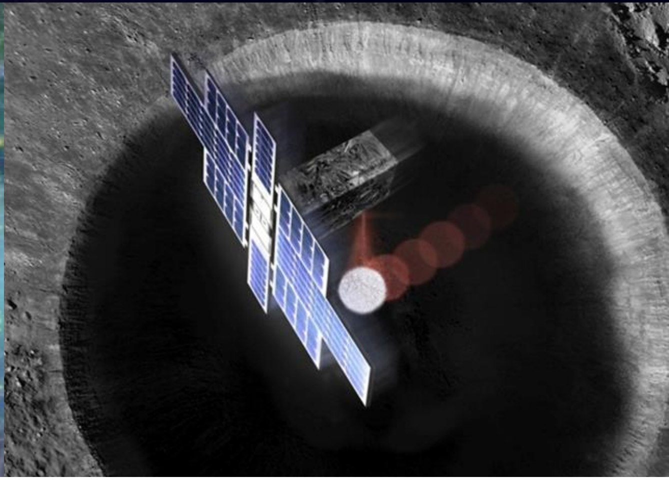

EMERGING LOW TOXICITY “GREEN” CHEMICAL PROPULSION TECHNOLOGIES FOR SMALLSATS

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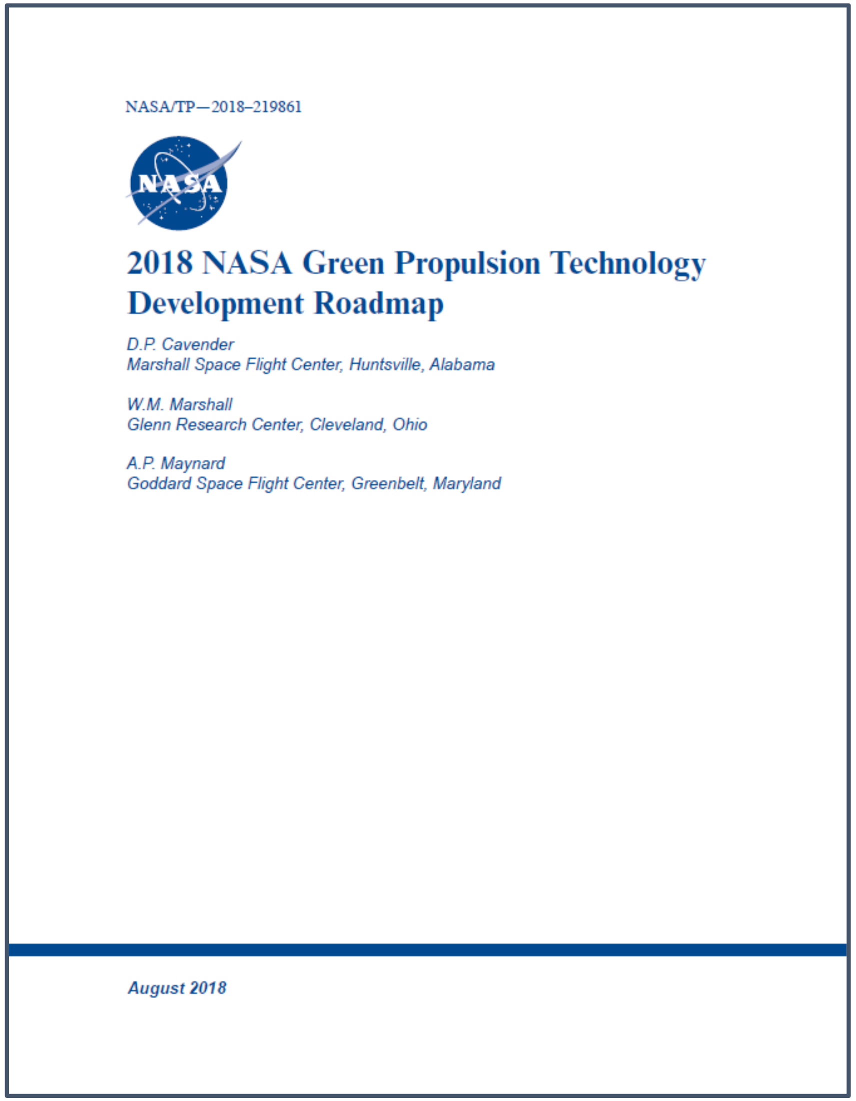
The NASA Green Propulsion Working Group (GPWG)

- Tasked by the NASA Chemical Propulsion Subcapabilities Management (CPSM) with the development of a NASA Green Propulsion Technologies Development Roadmap.
  - Comprising reps from MSFC, GRC & GSFC, JPL, ARC, and KSC
- Specifically chartered with:
  (1) Developing and maintaining an Agency Green Propulsion Roadmap to address technological gaps within green propulsion
  (2) Developing and maintaining a list of green propulsion technology development efforts being pursued by members' respective Centers or Agencies
  (3) Identifying and maintaining an assessment of green propulsion test facilities and Center competencies related to green propulsion for the Agency.
- Typically focus on ionic liquid (IL) propellants.

NASA Green Propulsion Technology Development Roadmap

- NASA TP-NASA/TP-2018-219861
- Lays out 4 "Technology Development Areas" or TDA's addressing aspects for technology maturation
  - TDA 1 – Thruster Hardware Development
  - TDA 2 – Modeling & Tools Development
  - TDA 3 – Materials Properties & Characterization
  - TDA 4 – Propellant Development
- Highlights Partnerships as Key:
  - Intra-NASA (Centers, MDs, NSTGROs, Etc.)
  - Inter-Agency (NASA, AF, Navy, Nat'l Labs)
  - Public-Private (SBIR/STTR, ACOs, CANs, Academia, Industry)
  - Collaborative Bodies (JANNAF, S3VI, Etc.)
  - International (ESA, SSC, JAXA, Etc.)


NASA/TP—2018–219861

2018 NASA Green Propulsion Technology Development Roadmap

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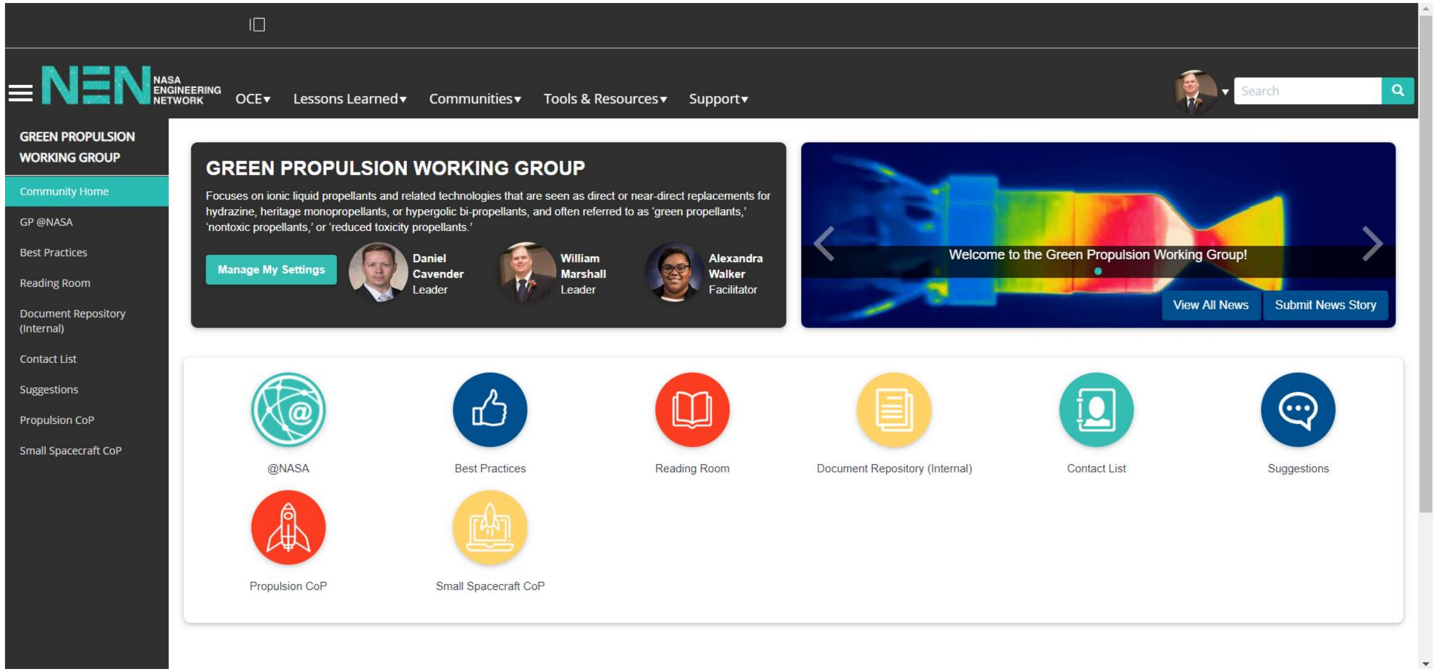
August 2018

GPWG's NASA Engineering Network (NEN) Page

- Partially supports 2nd chartered purpose – to develop and maintain a list of green propulsion technology development efforts being pursued by members' respective Centers or Agencies
- Cross-linked to Chemical Propulsion TDT and links to Small Satellite's NEN sites
- Includes references to a number of scholarly papers about green propulsion (Reading Room)



Purpose of This Presentation

- This presentation is to provide Mission Planners with a quick reference guide to selecting green propulsion systems that are flight ready, and those that are positioned for flight readiness with little additional investment.
- This presentation, focuses on the two most prominent ionic liquid blends, frequently referred to as “green monopropellants” (i.e AF-M315E (ASCENT), LMP-103S, etc).
- It is a survey of green propulsion technologies as discussed in open literature and does not intend to be a primary, original source.
- We recognize that a greater wealth of knowledge is covered under limited distribution or restricted (e.g. export controlled) formats.
- This Presentation also offers the Author’s opinions on the state of the SmallSat propulsion industry, where progress is being made, and where attention is needed.

Progress to Mission Infusion (PMI) Definitions

- TRL assessments are based upon recommendations in "JANNAF Guidelines for the Application of Technology Readiness Levels (TRLs) to Micro-Propulsion Systems".
- An accurate TRL assessment, includes understanding of mission-specific environments, interfaces, and verification history.
- To simplify understanding of TRL assessments, this presentation uses Progress to Mission Infusion (PMI).
- These are described in detail in a 2020 revision of the Small Satellite SOA report's propulsion chapter.
- This classification system is intended to provide end users easier to digest assessments of the SOA to understand the device and system maturities
- This novel classification system is not intended to replace TRLs

TRL 1

Concept, 'C'
- At minimum, an idea has been established as scientifically feasible.
- May even include experimental verification of the underlying physics.
- May even include notional device designs.
- Approximately aligns to NASA TRL 1-3

In-Development, 'D'
- At minimum, a low-fidelity device that has been operated in an appropriate environment to demonstrate the basic functionality and predict the ultimate capabilities.
- May even be a medium- or high-fidelity device operated in a simulated final environment, but the device lacks a specific mission pull to define requirements and a qualification program.
- May even be a medium- or high-fidelity device operated in a flight demonstration, but the device lacks sufficient fidelity or demonstrated capability to reflect the anticipated final product.
- Approximately aligns to NASA TRL 4-5

Engineering-to-Flight, 'E'
- At minimum, a medium-fidelity device that has been operated in a simulated final environment and demonstrates key capabilities relative to the requirements of a specific mission.
- May even include a qualification program in-progress or completed.
- May even include a spaceflight, but the device fails to demonstrate key capabilities.
- May even include a successful spaceflight, but the device is now being applied in a new environment or platform, necessitating a delta-qualification.
- A specific mission opportunity must be identified in open literature.
- Approximately aligns to NASA TRL 5-6

Flight-Demonstrated, 'F'
- At minimum, a high-fidelity component or system (fit, form, and function) that has been operated in the intended in-space environment (e.g., LEO, GEO, deep space) on an appropriate platform, where key capabilities have been successfully demonstrated.
- May even be a final product that has completed a mission (not strictly a technology demonstration).
- May even be a product in repeat production and routine use for a number of missions.
- A successful spaceflight must be identified and the outcome described in open literature.
- Approximately aligns to NASA TRL 7-9

TRL 9

GPWG State of the Art (SOA) Report

- Presented at JANNAF In Space Chem Prop TIM yesterday (7473).
- Majority of document references ionic liquid blends, frequently referred to as "green monopropellants" (i.e AF-M315E (ASCENT), LMP-103S, etc)
- A survey of green propulsion technologies as discussed in open literature
  - Does not intend to be a primary, original source
  - End users should consult primary sources for specifics on performance or capabilities
- This work only considers literature in the public domain to identify and classify devices and is intended to be a open, publically available document
  - Commonly used sources for data include manufacturer datasheets, conference papers, journal papers, filings with government agencies, and news articles
  - The GPWG recognizes that a greater wealth of knowledge is covered under limited distribution or restricted (e.g. export controlled) formats. Where feasible we will reference general technologies for awareness without divulging restricted specific content

GPWG State of the Art (SOA) Report

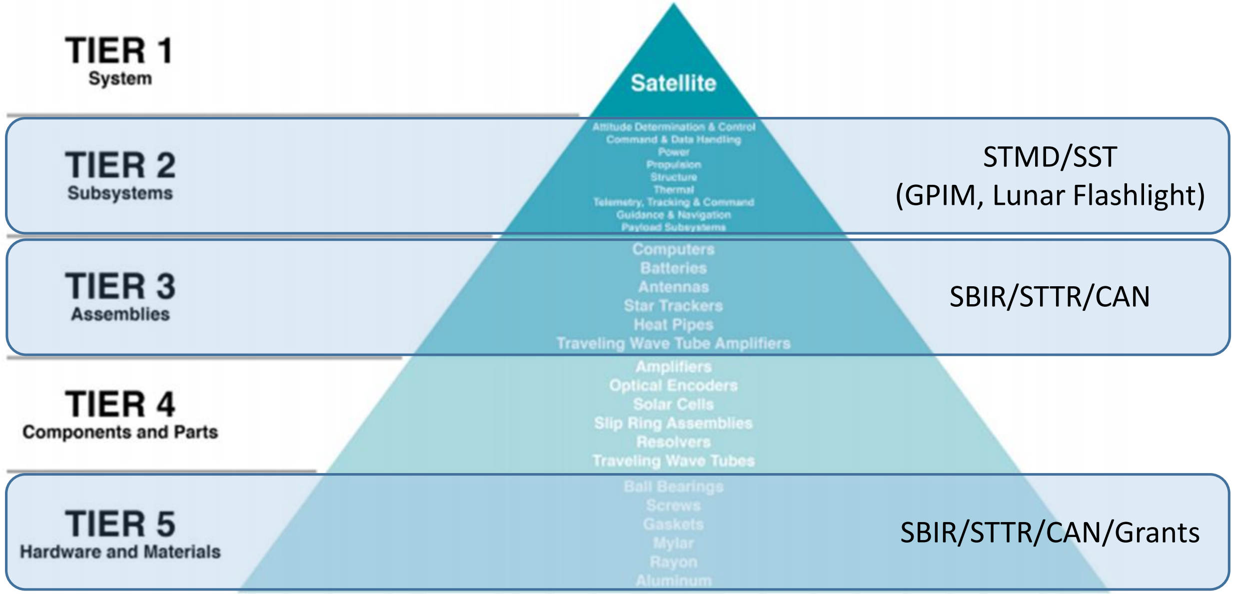
- The primary sources of data are literature produced by device manufacturer
  - To the greatest extent practical, only publically available sources are used
  - Performance and capabilities described may be speculative or otherwise based on limited data
  - Do not assume independent verification of device performance and capabilities
    - Some capabilities may be restricted from public discussion
- No discussion of technologies or specific devices herein is an endorsement by the U.S. Government
- The authors intend to regularly update this work, and current technologies that are inadvertently missed will be identified and included in future releases
  - Failure to include any specific publically identified products or technologies that might be considered relevant under a particular topic is unintentional

SmallSat Supply Chain ‘Tier-by-Tier’ Structure

- Tier 1: Spacecraft/Satellite
- Tier 2: Propulsion Systems
- Tier 3: Subassemblies / Components
  - Thrusters
  - Valves
  - Pumps
  - Propellants
  - Controllers
  - Software/Firmware

NASA/DoD has heavily incentivized GP development in this Tier.

- Tier 4/5: Components/Parts/Materials
  - Propellant Constituents
  - EEE Parts/Sensors
  - Screws/Fasteners/Etc.
  - Raw Stock/Gases/Etc.



Smith, P. M., Dolgopolov, A., & Doom, T. (2017). New Kids on the Block: The Impact of New Start-up Space Companies on the US Space Industry Supply Chain. In AIAA SPACE and Astronautics Forum and Exposition (p. 5354).

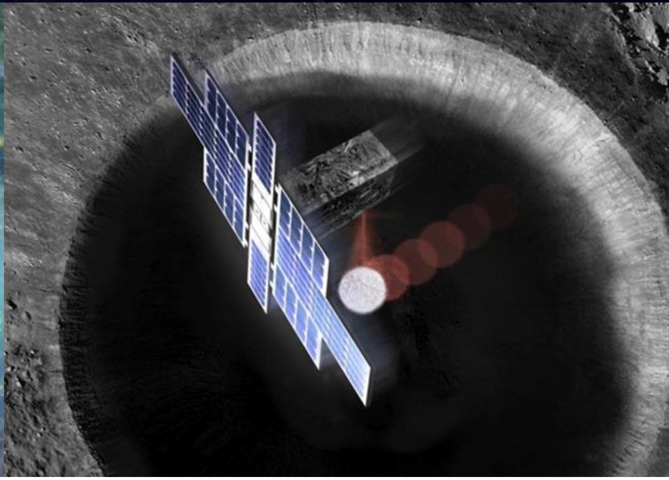
An increasingly important feature of the start-up space investment landscape is the ***enabling role played by the government****, both as a source of* ***direct funding*** *and a* ***perceived stamp of approval*** *that builds confidence among private investors.*

Opinion: Where the SmallSat Propulsion Market Stands

- Tier 4/5:
  - Reliance/Dependence on geo-political, & other global market forces (e.g. prop ingredients, rare Earth metals)
  - Small market players continue to struggle with priority & lead times for manufacturing. (e.g. sensors, fabricators)
- Tier 3:
  - More growth in this area in last few years; bolstered by SBIR/STTR/IRAD/Grants/Tech Transfer.
  - Emerging commodity markets (thrusters, valves, pumps, controllers, etc.).
  - More development/expansion needed to provide full spectrum of components for Tier 2. (tanks, valves, etc.)
  - Items are qualified for specific mission applications; delta qualifications required to expand applications.
- Tier 2:
  - Very few players; even fewer with spaceflight heritage systems
  - Majority of systems are 'one-offs' with unique requirements.
  - Still "Artisan" in nature.
  - Government SBIR/STTR programs should start to focus here; help establish green prop system providers.
- Tier 1:
  - No market players that provide/operate spacecraft with green monopropellant systems to market at large.

Emerging Trends In SmallSats

- Vertical Integration:
  - Some start-up space firms are vertically integrated, an approach being pursued to ensure supply chain control and keep costs down.
- Maker and Small Team Innovation:
  - Spurred by advances in materials and miniaturized electronics
  - Start-up space companies and universities have expanded the industry beyond traditional space system manufacturing centers in terms of innovations in design, manufacturing, and provision of services.
- Leveraging COTS:
  - Commercial-off-the-shelf (COTS) components are a popular option for start-up space companies.
  - Attractive because the components selected are low cost and have proven reliability in other industries.
- Warehousing (maintaining an inventory):
  - The space industry has always been more of an "artisan," built-to-order industry than one characterized by mass production like the automotive industry.
  - *Not seeing this in propulsion, but will be needed to support desired mission/launch cadences.*
- Additive Manufacturing:
  - Though potentially a major technology improvement for the industry, it is still an emerging capability and uncertainties remain about quality control and performance.



PROPELLANTS, THRUSTERS, COMPONENTS, SYSTEMS & SUPPORT SERVICES

Propellants

- Propellants are either blends of the ionic salts Hydroxylammonium Nitrate (HAN) or Ammonium dinitramide (ADN)
  - These salts are then dissolved into solution with other constituents & water to form a “monopropellant”
  - While not a true monopropellant (there are fuel & oxidizer components that combust), they do behave and are treated like a conventional monopropellant (e.g. hydrazine)
- A number of propellant blends exist or are in-work:

Propellant	Primary Salt	Country of Origin	Major Developer	Density (g/cm^3)	Specific Impulse (s)	PMI	Reference Mission (E/F only)	Reference
AF-M315E (ASCENT)	HAN	United States	AFRL/DSSP	1.4	235-250	F	GPIM	[1]
LMP-103S	ADN	Sweden	ECAPS	1.24	200-285	F	PRISMA/ Skybox	[2]
SHP-163	HAN	Japan	JAXA	1.4	N/A	E	RAPIS-1	[3,4]
“green monopropellant”	N/A	N/A	RocketLab	N/A	N/A	F	KickStage (“Still Testing”)	[5]
Green Electrical Monopropellant (GEM)	HAN	United States	DSSP	N/A	N/A	D	-	[6,7]

Propellants

	AF-M315E	LMP-103S
Developer	Air Force Research Laboratory	ECAPS / SSC (Swedish Space Corporation)
Spaceflight Heritage	NASA GPIM	Prisma / SkySats
Hazard Classification	Critical (Per NASA SLS PSRP & AF STP-2)	Catastrophic (Per NASA SLS PSRP)
Viscosity & Surface Tension Data	Data Sets Exist; Developed by NASA	Data Sets Exist; Developed by ECAPS
Radiation Tolerance	To Be Tested	Data Sets Exist; Developed by ECAPS
Thermal Range	Characterized; Viscosity is Challenge	Characterized; Precipitation is Challenge
Decomposition/Combustion Dynamics	Modelling Efforts Continue	Modelling Efforts Continue
Aerospace Matl's Compatibility Data	Extensive Data Sets Exists in Various Sources	Extensive Data Sets Exists in Various Sources
Suppler	Digital Solid State Propulsion (DSSP) & AFRL	Bradford ECAPS (Seeks License Manufacturing)
Supporting Tech (Thrusters, Etc.)	Various in Qualification & Development	Various in Qualification & Development

Thrusters

- List of known Ionic Liquid (IL) "Green" monoprop thruster developments

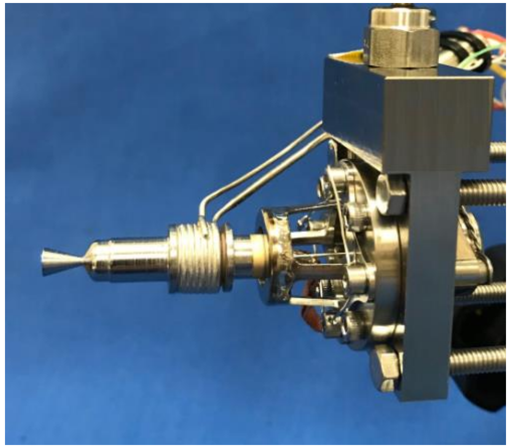
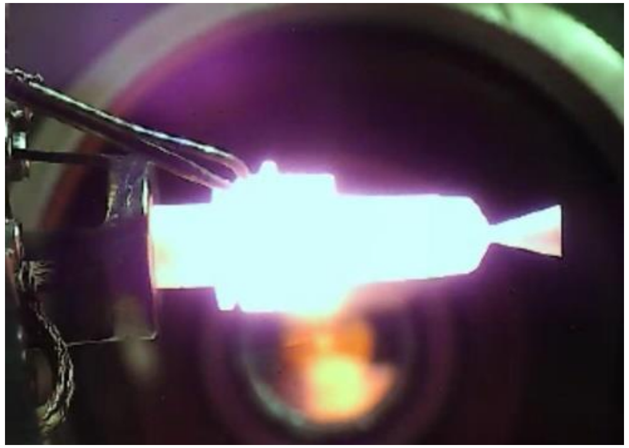
Manufacturer	Thruster	Propellant	Thrust per thruster (Quantity)	Specific Impulse	Total Impulse	Mass	Power	PMI	Reference Missions (E/F only)	Reference
---	---	---	[N]	[s]	[kN-s]	[kg]	[W]	C,D,E,F	---	
Aerojet Rocketdyne	GR-1	ASCENT	0.4-1.1	231	23	N/A	12	F	GPIM	[1]
Aerojet Rocketdyne	GR-22	ASCENT	8.0-25	248	74	N/A	28	E	GPIM	[1]
Bradford-ECAPS	0.1N HPGP	LMP-103S	0.03 – 0.10	196-209	N/A	0.04 excl. FCV	6.3 – 8	E	ArgoMoon	[9]
Bradford-ECAPS	1N HPGP	LMP-103S	0.25 – 1.0	204 – 235	N/A	0.38	8-10	F	SkySat	[9]
Bradford-ECAPS	1N GP	LMP-103S/LT	0.25 – 1.0	194 - 227	N/A	0.38	8-10	D	-	[10]
Bradford-ECAPS	5N HPGP	LMP-103S	1.5 - 5.5	239 -253	N/A	0.48	15-25	D	-	[9]
Bradford-ECAPS	22N HPGP	LMP-103S	5.5 - 22	243 -255	N/A	1.1	25-50	D	-	[9]
Busek	BGT-X1	ASCENT	0.02 – 0.18	214	N/A	N/A	4.5	D	-	[11]
Busek	BGT-X5	ASCENT	0.05 - 0.50	220 - 225	0.56	N/A	20	D	-	[11]
Busek	BGT-5	ASCENT	1.0 – 6.0	> 230	N/A	N/A	50	D	-	[11]
NanoAvionics	EPSS-C1	ADN-blend	0.22-1.0	213	>0.4	N/A	9.6 (preheat) 1.7 (firing)	F	Lituanica-2	[12]
Plasma Processes	100mN (PP3490-B)	ASCENT	0.1 – 0.17	195 - 208	N/A	.08	7.5 - 10	E	Lunar Flashlight	[13]
Rocket Lab	Curie Engine	unknown	120	N/A	N/A	N/A	N/A	F	Electron 'Still Testing'	[5,14]

Plasma Processes Thrusters (AF-M315E)

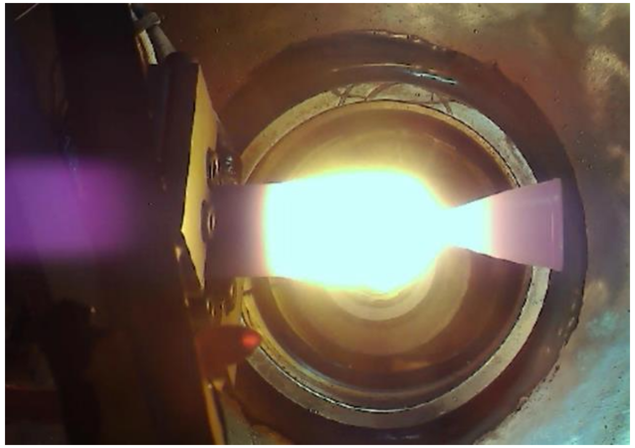
- 100mN Thrusters (PP3490) [PMI-E]
  - Throughput: 330 grams (mission: 350 g, qualification: 530 g)
  - Steady state Isp: 220s; Pulse mode Isp: 195 s
  - Minimum impulse bit: 0.4 mNs
  - Thrust level: ~ 80-150 mN (depending on feed pressure)
  - Longest duration firing: 35 minutes
  - Number of accumulated pulses: ~ 7500
  - Pre-heat power: 8-10 W
  - Weight: ~ 70 grams (without flow control valve)

Qualification of the flight design thruster is planned to be performed in Nov-Dec 2020

- 5N Thrusters (PP3614 – EDM) [PMI-D]
  - Propellant throughput: 1.13 kg
  - Pulse mode Isp: 210 s
  - Steady state Isp: 250 s
  - Minimum impulse bit: < 0.1 Ns
  - Thrust level: 5N
  - Flow rate: ~ 2.2 g/s
  - Longest duration firing: 280 s
  - Accumulated burn time: 515 s (~9 min)
  - Number of accumulated pulses: 400
  - Pre-heat power: 75W

100 mN Flight Design Thruster

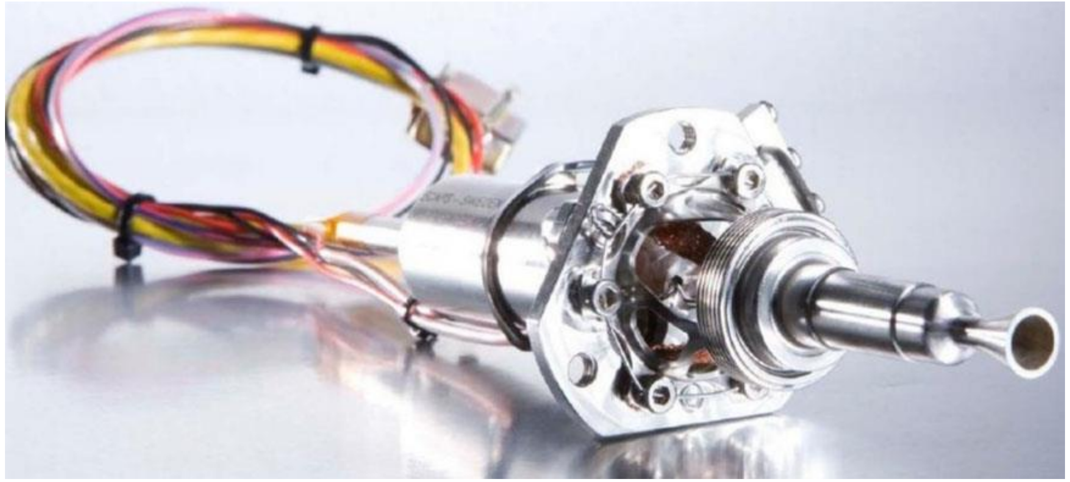
5N EDU Thruster

Bradford ECAPS Thrusters (LMP-103S)

- 100mN Thrusters (Flight) [PMI-E]
  - Throughput: ~400g (qualification)
  - Steady state Isp: 209s; Pulse mode Isp: 196s
  - Minimum impulse bit: <5mNs
  - Thrust level: ~ 30-100 mN (depending on feed pressure)
  - Longest duration firing: 30 minutes
  - Number of accumulated pulses: ~ 6,696
  - Pre-heat power: 6.3 - 8W
  - Weight: ~ 40 grams (without flow control valve)

100 mN Flight Design Thruster

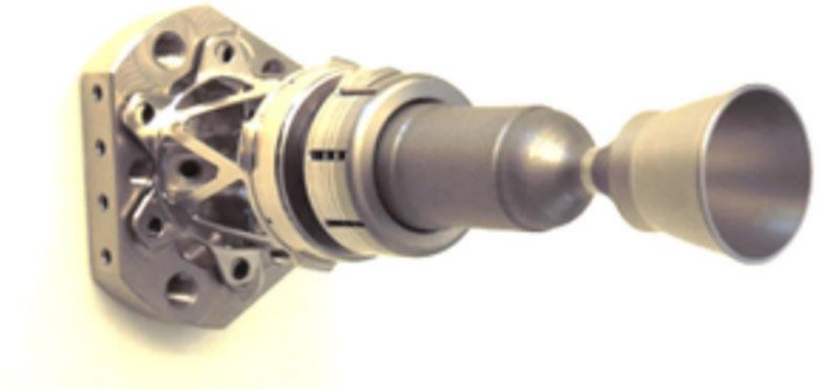
- 1N HPGP Thrusters (Flight) [PMI-F]
  - Throughput: 24kg (qualification)
  - Steady state Isp: 231s; Pulse mode Isp: 204s
  - Minimum impulse bit: <5mNs
  - Thrust level: ~ .25 - 1N (depending on feed pressure)
  - Longest duration firing: 1.5 hrs
  - Number of accumulated pulses: ~ 60,000
  - Pre-heat power: 8 - 10W
  - Weight: ~ .38kg



1N Flight Thruster

Bradford ECAPS Thrusters (LMP-103S)

- 5N HPGP Thrusters (EQM) [PMI-D]
  - Throughput: ~5kg
  - Steady state Isp: 253s; Pulse mode Isp: 239s
  - Minimum impulse bit: <.1mNs
  - Thrust level: ~ 1.5 – 5.5N (depending on feed pressure)
  - Longest duration firing: 1 minutes
  - Number of accumulated pulses: ~ 10,000
  - Pre-heat power: 15 - 25W
  - Weight: ~ .48kg (without flow control valve)



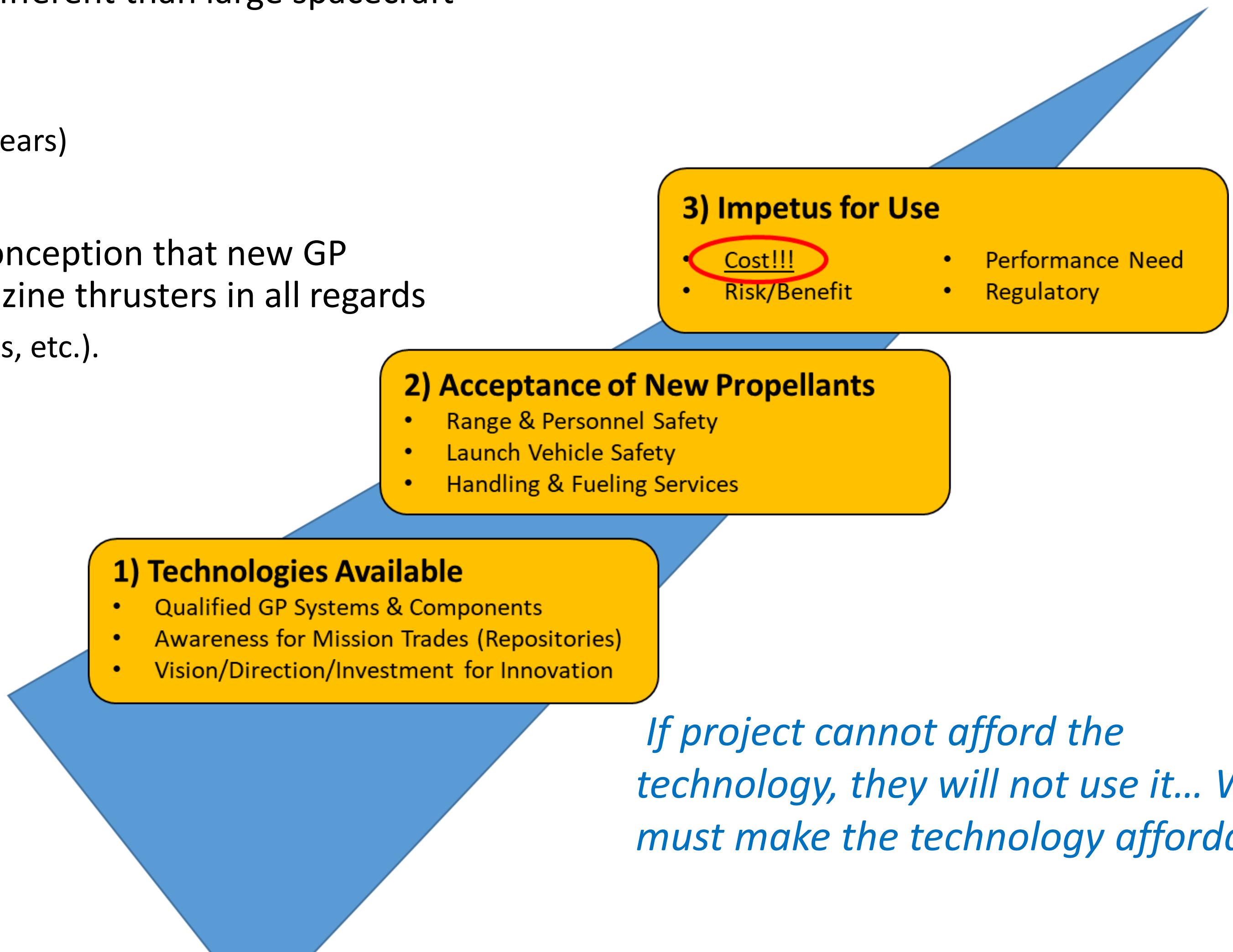
5N EDU Thruster

- 22N HPGP Thrusters (EQM) [PMI-D]
  - Throughput: 53kg
  - Steady state Isp: 255s; Pulse mode Isp: 243s
  - Minimum impulse bit: <.44Ns
  - Thrust level: ~ 5.5 - 22N (depending on feed pressure)
  - Longest duration firing: 38 minutes
  - Number of accumulated pulses: ~ 26,481
  - Pre-heat power: 25 - 50W
  - Weight: ~ 1.1kg

22N EDU Thruster

Divergent Thruster Requirements

- SmallSat Propulsion Performance Needs are different than large spacecraft
  - Can only carry so much fuel (Performance)
  - Are generally Secondary Payloads (Safety)
  - Are generally short in duration (months; not years)
  - Accept more risk for bigger potential benefits
- But, manufacturers are beholden to the misconception that new GP thruster must be as good or better than hydrazine thrusters in all regards
  - (e.g. Isp, throughput, total impulse, duty cycles, etc.).
- Known Infusions Barriers:
  - Technologies Available.
  - Acceptance of New Propellants.
  - Impetus for Use.
- It ultimately comes down to Cost…



If project cannot afford the technology, they will not use it… We must make the technology affordable.

Divergent Thruster Requirements

- Cost Green Propellants: $1K - $2K per Liter
  - Relatively small cost for SmallSat missions.
- Cost of Thrusters & Components are significant Hardware cost
  - Raw Materials Costs (refractory metals, rare Earth metals, fabrication processes)
- Majority of recent NASA trade studies have shown:
  - That a majority of missions can be accomplished with far lower throughput targets than manufacturers have been targeting.
  - That cost caps have pushed some mission away from GP solutions, and to compromise on mission scope (destination access and/or science value).
- This divergence in performance need shows a disconnect between what the market needs and what manufacturers are pursuing.
- Near term efforts with NASA and GP thruster manufacturers is pushing to address more immediate needs for 'Short Life' thruster variants, and greatly reduced price (cost conscious design attributes).
  - Super alloy chambers, not refractory metal
  - Iridium alternatives within catalysts

Proposed Short Life vs Long Life Throughput Requirement Targets

Thrust	Throughput	
	Short Life	Long Life
1N	5kg	>20kg
5N	5kg	>50kg
22N	25kg	>150kg

FY21-22 Public-Private Partnership efforts will bring Short Life 5N & 22N variants to market in FY22 time frame.

Components – Some of What is Out There

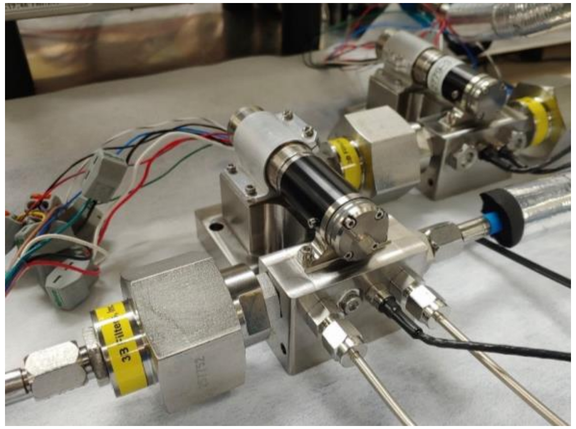
- Its not quite like building your own PC, but its getting there.
- Awareness of available options is challenge:
  - Sensors – Lab and auto-grade/COTS components
  - Thrusters – Some are there, other are closing in.
  - Valves – Scattered options; NASA tech transfer
  - Pressure on Demand – Some options
  - Controllers – Scattered options; NASA tech transfer
- Encourage vendors to leverage SPOONs database.

Components - Pumps and Valves

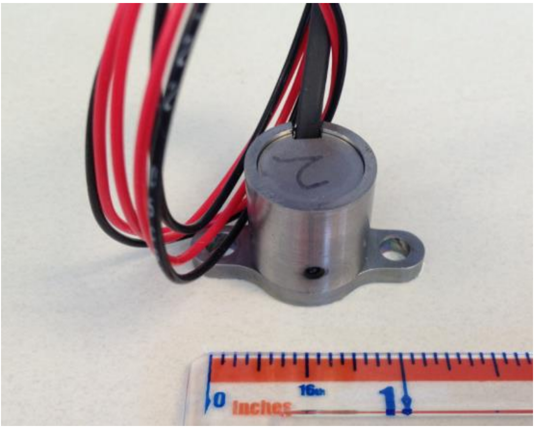
- Flight Works Inc. Micro-Pump (Flight) [PMI-E]
  - Nominal flow: min 45 ml/min @ 375 psia
  - Power: 5.0 – 10W @ nominal flow
  - Inlet pressures: from 3 psia to 60 psia
  - Compatible with AF-M315E
  - Flight Life: > 10 hours
  - Cycles: >500
  - Single duration continuous operation: 60 min

Design Recently Passed Qualification for Lunar Flashlight mission. Flight pump delivered to NASA.

- NASA MSFC Solenoid & Fill/Drain Valves (Flight) [PMI-E]
  - Voltage: 9-12.6VDC (pick); 3.3V (Hold)
  - Power: 9.9W (opening); 1.4W (holding)
  - Max Design Pressure: 500 psia
  - Temperature Range: -15C – 60C.
  - Cycles: >50,000
  - Application: Isolation (ISO) / Flow Control Valve (FCV)
- NASA MSFC Fill/Drain Valves (Flight) [PMI-E]
  - Max Design Pressure: 500psia
  - Cycles: >100
  - Propellant/Pressurant Loading/Off-Loading

Flight Works Inc. Micro-Pump



Solenoid Valve

F/D Valve Flight Half

Components – Propellant Tanks

- Northrop Grumman (NGC) (80588, EQM) [PMI-D] [23]
  - Prop Volume: 1.8L
  - Material: AM Ti-AL6-V4 (Grade 5 titanium)
  - Diaphragm: (AF-E-332) rubber diaphragm
  - Max Design Pressure: 500psig

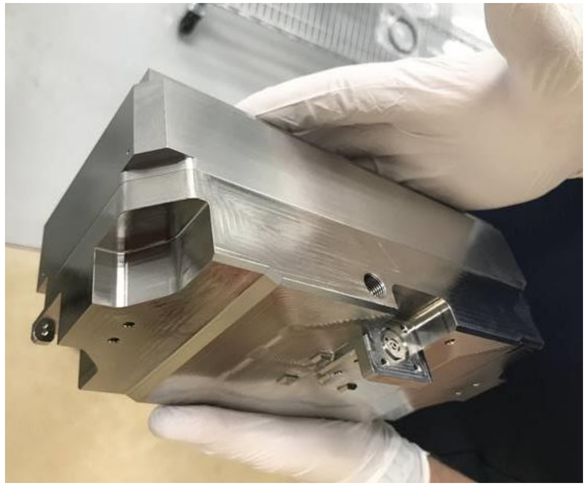
- NGC/ATK 19” Spherical Diaphragm Tank (80512-1 - Flight) [PMI-F] [24]
  - Prop Volume: 45L
  - Material Ti-AL6-V4 (Grade 5 titanium)
  - Diaphragm: (AF-E-332) rubber diaphragm
  - Max Design Pressure: 500psig
  - Qualified: GSFC-STD-7000 levels

NGC 1.8L Prop Tank EQM

NGC 45L Flight Qualified Prop Tank

Components – Propellant Tanks

- No COTS prop tanks available; nearly all are custom builds
- Perpetual Non-Recurring Engineering (NRE) costs to project
- CubeSats primarily volume constrained; more so than mass
- Packaging is a major driver to non-typical tank geometries
    - Propellant management/acquisition is non-trival.
- Safety considerations drive projects to 'Fracture Critical' prop tank requirements, driving NRE higher.
- Some efforts to make standard tanks on this scale, but this problem has been primarily addressed by prop system developers (@ Tier 2).
- Additive Manufacturing starts to address some design challenges here, but qualification of AM structures is on-going challenge itself.



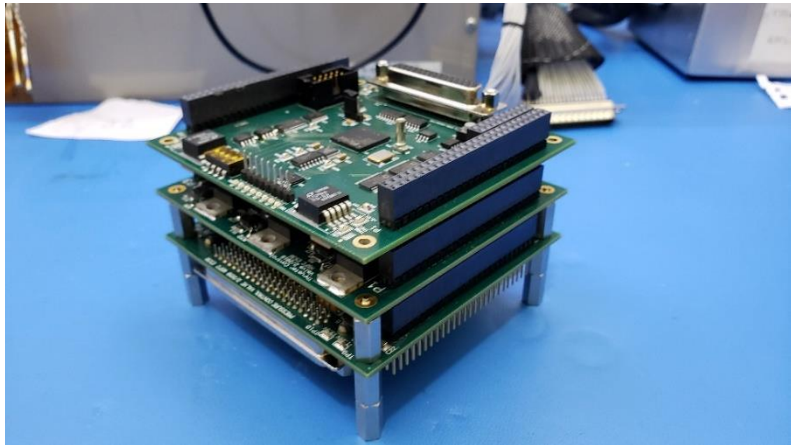
LFPS Prop Tank (MSFC/GT)

Low Cost Dev Tank (MSFC/USU)

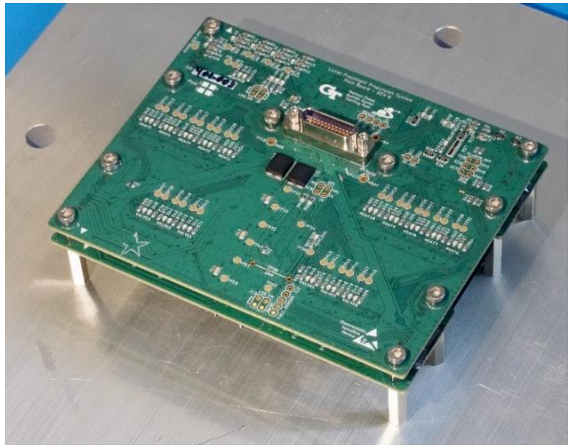
ECAPS SkySat Prop Tank [22]

Components - Controllers

- NASA MSFC Prop System Controller [PMI-E]
  - FPGA Based
  - Pressure Regulated Systems
  - Split bus: 5V for sensors; 12/28V for valves & heaters
  - 6 valve drivers; 6 heater drivers; 8 thermocouple channels
  - >30kRad radiation tolerance
  - Tech transfer available
- NASA MSFC/GT Prop System Controller [PMI-E]
  - Microprocessor Based
  - Pump-fed Systems
  - Split bus: 5V for sensors; 12V for valves & heaters
  - 6 valve drivers; 11 heater drivers; 9 thermocouple channels
  - >30kRad radiation tolerance
- Unknown if COTS options are available.
  - Lots of independent developed solution
  - Generally by Tier 2 (solution specific), and academia.
- Electrical interfaces between systems is non-standard.
  - Telemetry byte structures/formats/rates/etc.
  - Software/Firmware development/modification/negotiation
- Another example of perpetual NRE costs.



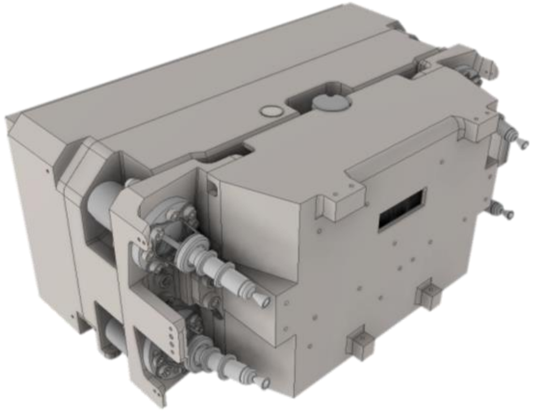
NASA MSFC Prop System Controller [PMI-E]



MSFC/GT Prop System Controller [PMI-E]

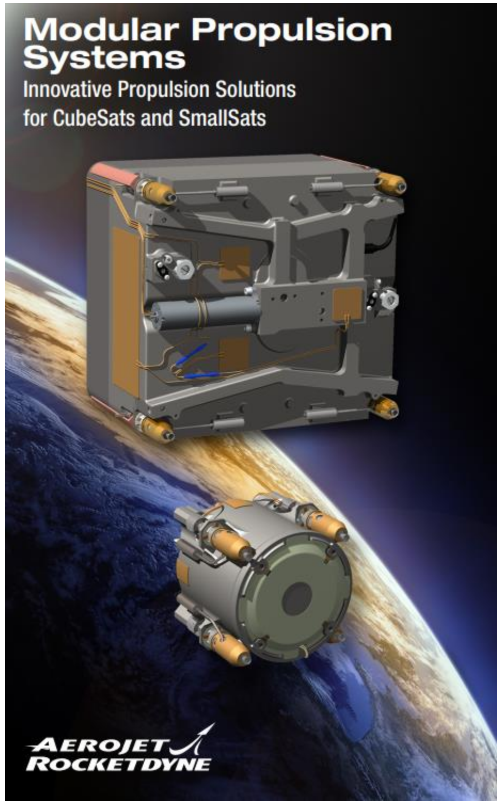
Integrated Propulsion Systems

Bradford ECAPS - Skysat



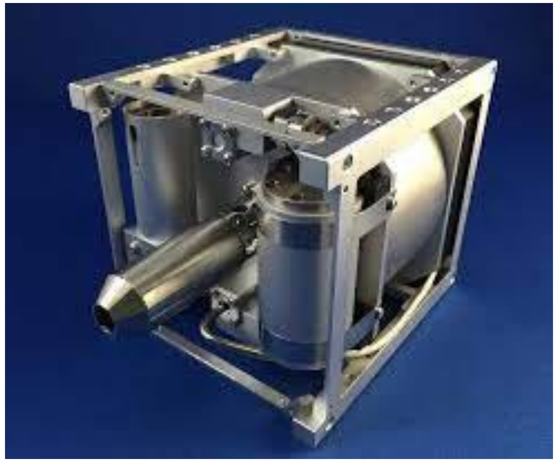
MSFC/GT LFPS

Rocket Lab
"Kick Stage"



Aerojet MP-130/135

VACCO IPS



Busek AMAC

NanoAvionics EPSS C1K

Integrated Propulsion Systems

Manufacturer	Product	Propellant	Thrust per thruster (Quantity)	Specific Impulse	Total Impulse	Mass	Envelope	Power	ACS	PMI	Reference Missions (E/F only)	Reference
---	---	---	[N]	[s]	[kN-s]	[kg]	[cm^3 or U]	[W]	Y/N	C,D,E,F	---	---
Aerojet Rocketdyne	MPS-130	ASCENT	0.25-1.0 (4)	N/A	>2.7 (2U) >1.1 (1U)	1.7 – 2.8 † 1.1 - 1.4 ‡	1U – 2U	N/A	Y	D	-	[15]
Aerojet Rocketdyne	MPS-135	ASCENT	0.25-1.0 (4)	N/A	>19 (8U) >13.7 (6U) >7.3 (4U)	7.2 - 14.7 † 3.5 – 5.1 ‡	4U – 8U	N/A	Y	D	-	[15]
Bradford-ECAPS	Skysat 1N HPGP Propulsion System	LMP-103S	1.0 (4)	200	>17	17	27U	10	Y	F	Skysat, PRISMA	[16]
Busek	AMAC	ASCENT	0.5 (1)	225	0.56	1.5 †	1U	N/A	N	D	-	[17]
Busek	BGT-X5 System	ASCENT	0.5	220-225	N/A	1.5 (BOL)	1U	20	N	D	-	[18]
Moog	Monopropellant Propulsion Module	Green or 'Traditional'	0.5 (1)	224	0.5	1.01†	1U (baseline, scalable)	2 x 22.5 W/Thruster	N	D	-	[19]
MSFC/Plasma Processes/GT	LFPS	ASCENT	0.1 (4)	N/A	N/A	N/A	N/A	N/A	Y	E	Lunar Flashlight	[13]
NanoAvionics	EPSS C1K	ADN-blend	1.0 (1) BOL 0.22 (1) EOL	213	>0.4	1.2 † 1.0 ‡	1.3U	0.19 (monitor) 9.6 (preheat) 1.7 (firing)	N	F	Lituanica-2	[12]
Rocket Lab	Kick Stage	Unknown	120	N/A	N/A	N/A	N/A	N/A	Y	F	Electron 'Still Testing'	[5,14]
VACCO	ArgoMoon Hybrid MiPS	LMP-103S/ cold-gas	0.1 (1)	190	1	14.7 † 9 ‡	~1.3U	13.6 20 (max)	Y	E	ArgoMoon	[20]
VACCO	Green Propulsion System (MiPS)	LMP-103S	0.1 (4)	190	4.5	5 † 3 ‡	~3U	15 (max)	Y	D	-	[21]
VACCO	Integrated Propulsion System	LMP-103S	1.0 (4)	200	12.5	14.7 † 9 ‡	~1U – 19,000 cm^3	15-50 (max)	Y	D	-	[21]

Support Systems – Fueling Services

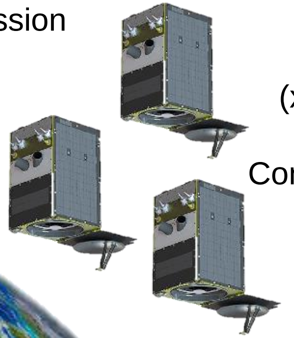
- No commercial green prop fueling services exists
- Currently, missions are left to develop their own solutions
- This is an area of needed commercialization to support future

Bradford ECAPS Fueling System

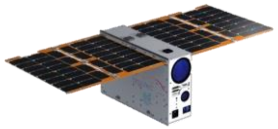
NASA MSFC Fueling System

Green Prop Flight Demonstrations (as of 2020)

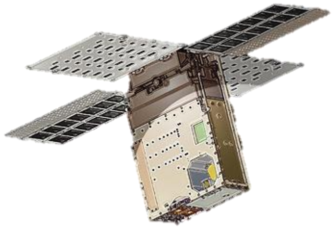
"PRISMA"
Swedish National Space Board
(SNSB)
ECAPS 1-N HPGP
(x 2 thrusters)
(**LMP-103S**)
Prototype/Demonstration Mission
2009 - 2011



"SkySat"
Planet
ECAPS 1-N HPGP
(x4 thrusters per S/C)
(**LMP-103S**)
Commercial Development
(11+ units)
2018 +



"ArgoMoon"
ESA/ASI
100 mN VACCO MiPS
(x1 thruster per S/C
w/ cold-gas RCS)
(**LMP-103S**)
Artemis-1
2021 (?)



"Lunar Flashlight"
NASA / JPL
100 mN LFPS
(x4 thrusters per S/C)
(**AF-M315E/ASCENT**)
SMD Mission/Artemis-1
2021 (?)

"GPIM"
NASA / Ball Aerospace
1-N Aerojet GR-1
(x5 thrusters per S/C)
(**AF-M315E**)
STMD TDM Mission
2019 - 2020

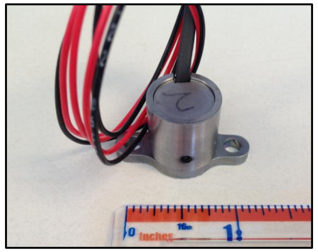
"Kick Stage"
Rocket Lab
120-N Curie Engine
(x1 thruster per S/C
w/ cold-gas RCS)
(**"green" monopropellant**)
Commercial Development
"Still Testing" Mission & others
2018 +

Return on Investments – Lunar Flashlight Prop System

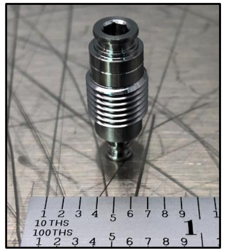
- Perfection is not the objective…
  - On time, on budget, and at the requisite quality, and risk tolerance is.
  - Do not risk success by holding out for perfection, especially in the 1st gen design.
- 'Due Diligence' Is Not The Same As 'Duly Diligent'.
  - It means be properly, or appropriately suitable, or proper in the circumstance.
- 7120.8's Shouldn't Act Like 7120.5's.
  - Right size the process rigor. Consult with Stakeholders/Sponsors.
  - Not all Space Flight Hardware is made equal, and should not be.
  - We act like a "Class D", but we are on the far bottom edge of that scale.
- We have a Choice in The Hazards We Face.
  - The overhead involved with 'Catastrophic' vs 'Non-Catastrophic' hazards (Pressure & Propellants).
  - You can select technologies, configurations, and other features that will limit mitigation requirements.
  - Designed for minimum bureaucracy.
- We Are Charting A Course; not just Navigating It.
  - Other will follow. We want others to follow. So, leave a trail (Document!)
  - Helped to establish vendor manufacturing & testing capabilities along the way.
- Time, Cost, & Quality Are Commodities; Treat them AS Such.
  - We don't like to think of Quality as a commodity, but it is. Not everything needs to be 'Top Shelf'.
  - For projects like these, it is more important to deliver on time and on budget.
- Know what is important to the success of the project/business.

Return on Investments – Lunar Flashlight Prop System

- The Future Requires Investments.
  - Small Business Innovative Research (SBIR)
  - Cooperative Agreements (CANs)
  - Internal Research & Development (IRAD)
- Stay Updated on State of Technologies:
  - Propellants, Components, Industry and Academia Successes.
  - Community Networks, Conference Papers/Presentations
- Are There Promising Technologies Ready?
  - Talk with Tech Monitors & Subject Matter Experts

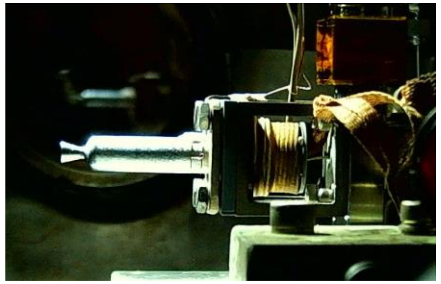


IRAD Solenoid Valve Development Moved to Flight Qual

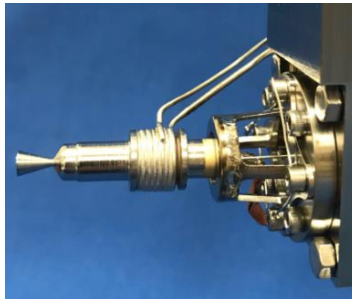


F/D Valve Moved From TRL2 to 8 in 14 months.

SBIR Phase I



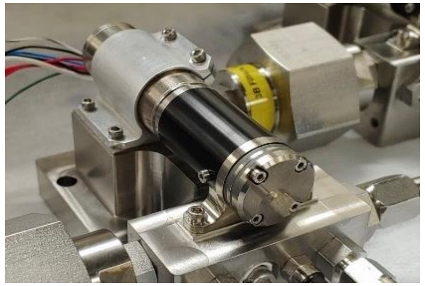
SBIR Phase II/III



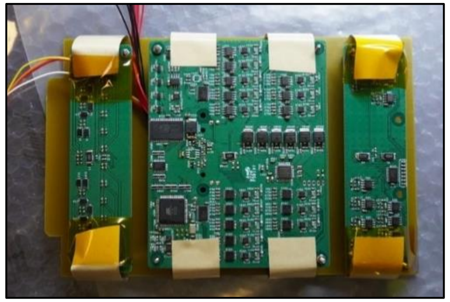
3D Printed CubeSat Prop Demos

SBIR Dev Pump 2019

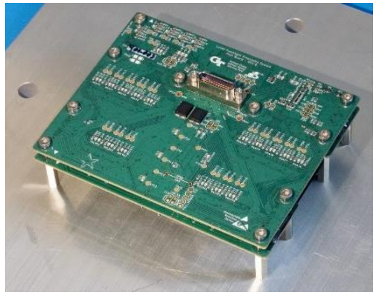
Flight Pump 2020



CAN Prototype 2019



Qual Unit 2020



Forward Thinking; Supporting Future Endeavors

Strategic Investment Targets in Green Chemical Propulsion Supporting Goals; Next 5 Years.

2020 Thru 2022

2023 thru 2025

Prop System	Thruster(s)	Pressurization	Valve(s)	Controller	PMD	System I&T
Lunar Flashlight Propulsion System (LFPS)	100mN X 4 (SBIR PII/IIE/III)	Pump (SBIR PII/III)	MSFC MSV	MSFC/GT (CAN)	Sponge & Ribbon IRAD (MSFC/GRC)	GT – Grant
Bimodal Propulsion	100mN X 1 (SBIR PIII)	Pump (SBIR PIII)	MSFC MSV (Tech Transfer)	MSFC/GT Derivative (Grant/STTR PII)	Sponge & Ribbon IRAD (MSFC/GRC)	STTR PII
	Electro-Spray (CAN/SBIR PII)					SBIR PII
Deep Space CubeSat Prop	1N X TBD (SBIR PII/CAN)	Pump (SBIR PIII)	MSFC MSV (Tech Transfer)	MSFC/GT Derivative (Grant/STTP PII)	CAN	SBIR PIII
Deep Space SmallSat Prop	5N X 4 (SBIR PII/III)	Pressurant or Pump	IRAD	SBIR PIII	?	SBIR PIII
Complex, Deep Space SmallSat (ESPA) Prop (Mothership/CubeSats)	5N X 4 (SBIR PII/III)	Pressurant or Pump	IRAD	SBIR PIII	?	SBIR PIII
	100mN X 4 (SBIR PIII)	Pump (SBIR PIII)	MSFC MSV (Tech Transfer)	SBIR PIII	CAN	SBIR PIII
Other ESPA Prop	22N (CAN)	Pressurant or Pump	COTS	?	?	?

Stat of the Art; High Maturity (≥TRL6)

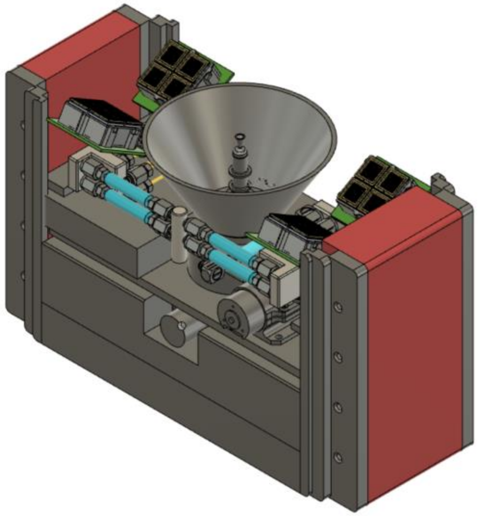
Delta Qualification High Maturity (≥TRL6)

Investment Planned Med Maturity (TRL4-5)

Investment Needed Low Maturity (≤TRL3)

Gov't or Industry; Prime Contractor

Future Applications of GP Technologies?



Dual Mode Systems
Chemical & Electrospray

Mars Sample Return Vehicle
Reaction Control System (RCS)

Thanks for Your Time! Questions?

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BACK-UP

Pre-Webinar Questions

1. I'm trying to determine if any orbit environment lifespan testing/analysis is underway or complete for Green Propellants. Some of these propellants, namely BMIM-BF4 appear to have resilience to radiation exposure, vacuum, and temperature swings. In the event of a breakup, I'm guessing volatile compounds in AF-M315E will facilitate breakdown of the liquid, but I'm not so sure about BMIM-BF4. Is there any work out there that addresses this concern?

2. When should a NASA mission planner consider the use of electric propulsion instead of green chemical propulsion?