2018 Technology Demonstration Industry Day

Technology Title: 200 W Class Plasma Propulsion System for Small Spacecraft

Affiliation: Busek Co. Inc., Natick, MA

Assumptions: Technology required to be at TRL 5 by 2021

Technology Description, Current Performance Metrics, and Performance Goals

BHT-200 Hall Effect Propulsion System:

- Hall Effect Thruster
- Hollow Cathode
- Power Processing Unit (PPU)
- Thrust = 13 mN at Isp = 1375 s (discharge power = 200 W)
- Lifetime > 2,000 h

Efficient throttling to lower power
Xenon or Iodine fuel (Iodine reduces fuel volume by 2/3)

Current TRL

8 - 9

TRL By May 2021

8 - 9

Industry State of the Art Technology Performance

No comparably sized Hall effect thruster has been flown by US industry competitors

Foreign thruster with similar power, lower TRL, no iodine capability:

- KM-45 (Russia, Keldysh Research Center)
- Power range = 200 – 450 W
- Thrust= 10-28 mN at Isp = 1250 - 1500 s
- Lifetime = TBD
- Xenon fuel
- TRL 6 (qualified)

Technology Development Challenges to Meet TRL Goal

All-Xenon system is presently TRL 8-9 (thruster, cathode, PPU, feed system)

- First US developed Hall thruster to fly in space (on TacSat-2)
- PPU first flow on FalconSat-5

Iodine compatible thruster developed with NASA and USAF funding
Hybrid Iodine-Xenon (thruster-cathode) system is TRL 5-6

- Qualified flight model thruster (TRL 6) delivered to NASA for iSat TDM
- Iodine feed system developed by NASA MSFC for iSat TDM

All-Iodine system is TRL 3

- Iodine fueled cathode is TRL 3

Potential HPD Science Application (Optional)

Propulsion for a technology demonstration rideshare (up to ESPA class) launching with the IMAP

- Propulsion system is well sized for ESPA-class spacecraft & large CubeSats
- Orbit transfers from to Earth-Sun L1
- Station-keeping in L1

General applications: orbit maintenance including station-keeping, orbit raising, orbit lowering (including de-orbiting), phase changes, inclination changes and interplanetary transfers.

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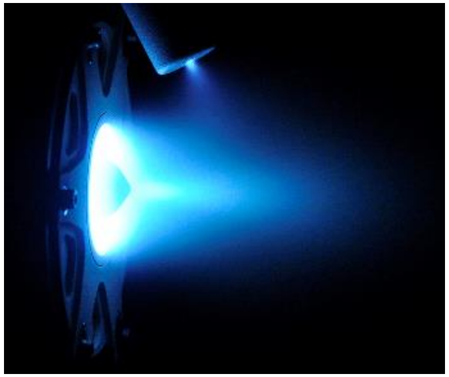
Additional Comments

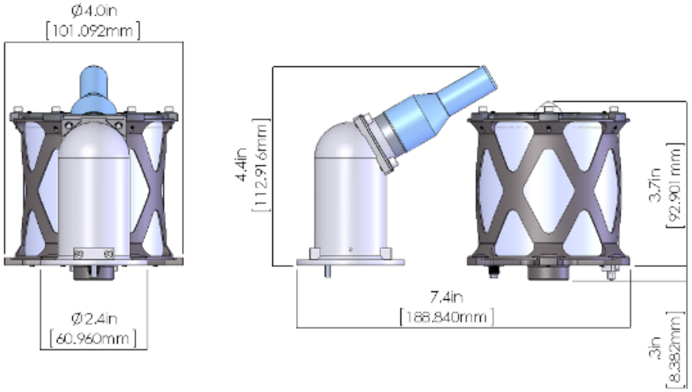
- BHT-200 system has flight heritage with xenon
- Iodine system developed for Iodine Satellite (iSat) Technology Demonstration Mission with USAF and NASA funding (mission status TBD)
- Hybrid Iodine-Xenon (thruster-cathode) system would provide many benefits (cost, volume, mass) with respect to all-xenon system and most benefits of all-iodine system with much less risk

BHT-200 Hall Thruster System

BHT-200

- Flight proven thruster, cathode, heritage PPU (compact PPU in development)
- Flight-proven Xenon feed system
- Xe system ground-tested 2,000 hours to-date, no major performance degradation
- Iodine compatible flight thrusters delivered to NASA
- Complete systems designed, integrated, tested, filled, delivered by Busek.
- Flight: TacSat 2, FalconSat-5
- Upcoming Flight: FalconSat-6 (Xe)





BHT-200: PERFORMANCE	
Nominal Thrust (mN)	13 (5-20)
Specific Impulse (s)	1,375 (1,000 – 1,500)
Thruster Power (W)	200
Thruster Mass (kg)	1.1*
Thruster Volume (U)	1*
Lifetime (hrs)	>1,800
Delta-v (m/s, 20kg spacecraft)	525
Propellants	Xe, I_2

* Excludes feed system & electronics

Science Mission Directorate

2018 Technology Demonstration Industry Day

Technology Demonstration MO

Technology Title: 600 W Class Plasma Propulsion System for Small Spacecraft

Affiliation: Busek Co. Inc., Natick, MA

Assumptions: Technology required to be at TRL 5 by 2021

Technology Description, Current Performance Metrics, and Performance Goals

BHT-600 Hall Effect Propulsion System:
- Hall Effect Thruster
- Hollow Cathode
- Power Processing Unit (PPU)
- Thrust = 38 mN at Isp = 1500 s (thruster power = 600 W)
- Lifetime (estimated) = 10,000 h

Efficient throttling from 300 W to 600 W
Specific impulse up to 1700 s
Xenon or Iodine fuel (Iodine reduces fuel volume by 2/3)

Current TRL

5

TRL By May 2021

6 - 8

Industry State of the Art Technology Performance

No comparably sized Hall effect thruster offered by US industry competitors

Russian thrusters offer similar performance, but with shorter lifetime and no iodine capability:
- SPT-70 (Russia, OKB Fakel)
- Thrust= 40 mN at Isp = 1500 s (nominal power = 700 W)
- Lifetime = 3100 h
- Xenon fuel
- TRL 9 (flew on-orbit)

Technology Development Challenges to Meet TRL Goal

All-Xenon system is presently TRL 5 (thruster, cathode, feed system)
- Not yet qualified for flight
- Xenon duration test (5,000 - 10,000 h) begins in 2018 (thruster, cathode)

PPU is Engineering Model (TRL 4-5) designed for high radiation environments
Hybrid Iodine-Xenon (thruster-cathode) system is TRL 4
- Iodine duration test (1200 h) completed (iodine thruster, xenon cathode)
- Iodine feed system is TRL 4 (flight system developed for iSat TDM)

All-Iodine system is TRL 3
- Iodine fueled cathode is TRL 3

Potential HPD Science Application (Optional)

Propulsion for a technology demonstration rideshare (up to ESPA class) launching with the IMAP
- Propulsion system is well sized for ESPA-class small spacecraft
- Orbit transfers from to Earth-Sun L1
- Station-keeping in L1

General applications: orbit maintenance including station-keeping, orbit raising, orbit lowering (including de-orbiting), phase changes, inclination changes and interplanetary transfers.

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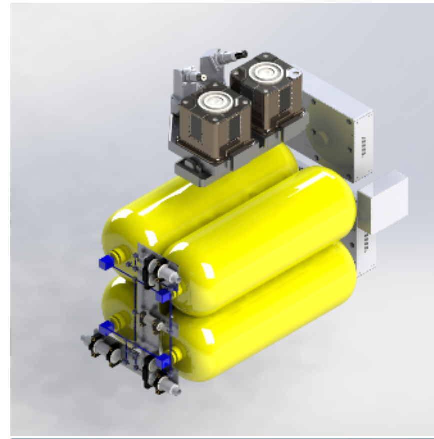
Additional Comments

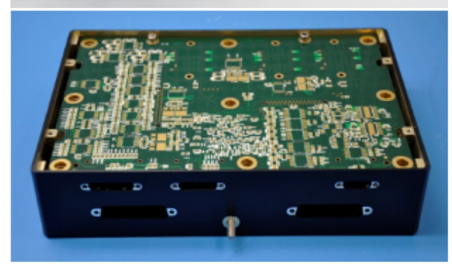
- BHT-600 system is being actively developed toward flight with USAF and NASA funding
- Delivery of flight qualified xenon fueled system to AFRL planned for 2020
- Hybrid Iodine-Xenon (thruster-cathode) system would provide many benefits (cost, volume, mass) with respect to all-xenon system

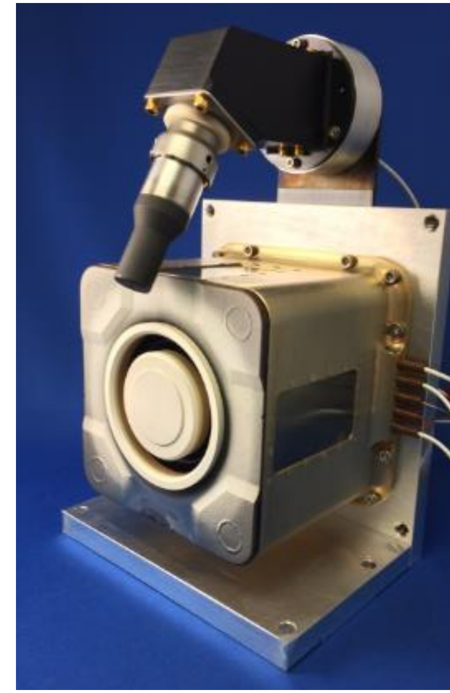
BHT-600 Hall Thruster System

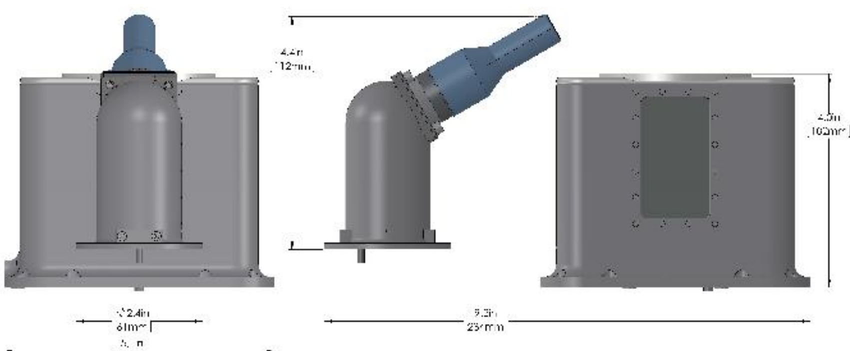
BHT-600 System

- High TRL with flight-proven components
- Compact PPU (BPU-600c) in development
- Flight-proven Xenon feed system
- Xe System undergoing >5k hour test beginning 2018
- Mission-enabling hybrid Xenon/Iodine thruster tested >1,200 hrs
- 100kRAD TID power processing unit with NASA-approved parts list.
- **Up to 6km/sec delta-V for ESPA-class missions**









BHT-600 Hall Effect Thruster & BHC-1500 Cathode

BHT-600: PERFORMANCE	
Nominal Thrust (mN)	9 – 38
Specific Impulse (s)	1,000 - 1,710
Thruster Power (W)	600 (700 input)
Thruster Mass (kg)	2.5*
Lifetime (hrs)	10,000**
Propellants	Xe, I_2

* Excludes feed system & electronics, **predicted

2018 Technology Demonstration Industry Day

Technology Title: BIT-3 Iodine RF Ion Propulsion System for CubeSats

Affiliation: Busek Co. Inc.

Assumptions: Technology required to be at TRL 5 by 2021

Technology Description, Current Performance Metrics, and Performance Goals

- BIT-3 is a compact, CubeSat friendly electric propulsion system using solid iodine as propellant. The system centers on a 2.5cm gridded ion engine using RF discharge. Complimentary subsystem technology includes the industry's first flight-ready iodine cathode (RF type), a miniature gimbal, a compact Power Processing Unit (PPU), and an ultra-lightweight iodine storage and feed system.
- BIT-3 system operates in the 55-80W range with thrust-to-power ratio around **15mN/kW**. Max thrust and Isp is 1.2mN and 2,300sec, respectively. Designed life of the thruster is >20,000 hours (theoretical); 4,000-hr test ongoing
- Future goals of BIT-3 include power upgrade and extended life test

Current TRL

5-6

TRL By May 2021

7 - 8

Industry State of the Art Technology Performance

- Ariane Group (Germany) RIT-µX gridded RF ion engine: 50W input, 0.5mN thrust **(10mN/kW)**, 3,000sec Isp, Xenon propellant
- JAXA/University of Tokyo (Japan) µ1 gridded microwave ion engine: 32W input, 0.3mN thrust **(9.4mN/kW)**, 1,200sec Isp, Xenon propellant
- ThrustMe (France) cathodeless gridded RF ion engine: 60W input, 0.7mN thrust **(11.7mN/kW)**, 1,000sec Isp, Xenon or Iodine propellant
- Busek (U.S.) BHT-200 Hall Effect thruster: 250W input, 12.8mN thrust (**51mN/kW**), 1,380sec Isp, Xenon or Iodine propellant

Technology Development Challenges to Meet TRL Goal

- BIT-3 technology can be further matured via long-duration ground testing and in-orbit demonstration
- Ground testing can be challenging due to potential interactions between iodine plume and vacuum facility (may cause pre-mature test hardware degradation)
- Current launch opportunity is still 2 years away (SLS EM-1); would be helpful to first prove the system out in a LEO demo mission in the near term

Potential HPD Science Application (Optional)

- BIT-3's high deltaV capability can enable small satellite (e.g. 6U CubeSat) flying to Earth-Sun L1 from GTO for long-duration solar observation
- BIT-3 can enable small "sun shade" satellite flying in front of a main space telescope (providing occultation) for observation of solar corona, with the spacecraft situated in LEO on a non-Keplerian orbit
- BIT-3 can enable formation flight in sun-synchronous orbit for distributed spatial or temporal solar measurements

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Additional Comments

- BIT-3 development program is sponsored by NASA Small Spacecraft Technology Program (SSTP) under Space Technology Mission Directorate (STMD)
- BIT-3 flight programs are sponsored by NASA Advanced Exploration System (AES) under Human Exploration and Operations Missions Directorate (HEOMD) and Science Mission Directorate (SMD)
- SBIR Ph2-X recently awarded for extended life (up to 4,000 hours) and integration testing

BIT-3 Iodine RF Ion Propulsion System

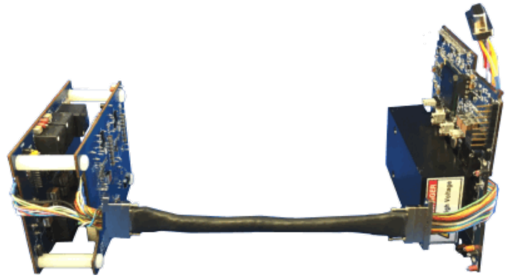
BUSEK
Space Propulsion and Systems

- Iodine-fueled BIT-3 systems will be flying on Lunar IceCube and LunaH-Map (SLS EM-1 launch in 2020)
  - 1.6U volume, 2.9kg wet mass
  - 2.5cm gridded RF ion thruster and 1cm RF cathode
  - 2-axis gimbal with +/- 10^{o} slew
  - Light weight, rad-tolerant ion propulsion PPU
  - Innovative iodine feed system w/ 1.5kg solid iodine propellant (zero-pressure launch)
  - Available 33kN-sec total impulse, SOTA
- Busek has proven iodine performance is on par with legacy EP propellant xenon
- Flight hardware deliveries beginning Summer 2018
- Endurance test up to 4,000 hrs commencing Summer 2018

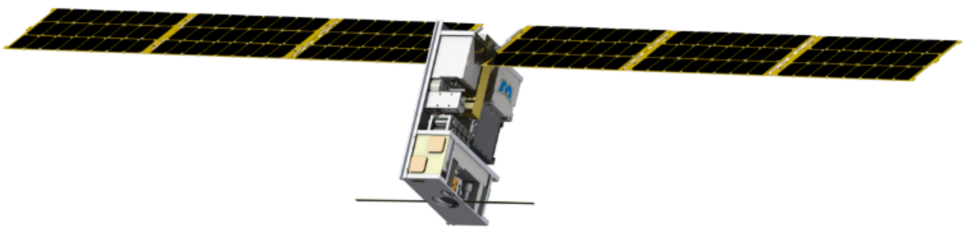
BIT-3 System Characteristics	
Thrust	0.88mN nominal, 1.2mN max
Total Isp	1,630 sec nominal, 2,300 sec max
Input power	65W nominal, 80W max
Mass	1.4kg dry / 2.9kg wet
Volume	1.6 U
Delta-V	~2 km/s for 6U CubeSats


BIT-3 Flight System


BIT-3 at Max Power on Iodine


Power Processing Unit (500g)


Iodine Feed System (450g Dry)


Lunar IceCube (6U CubeSat) in Flight Configurations
Photo Credit: Morehead State University

Science Mission Directorate

2018 Technology Demonstration Industry Day

Technology Demonstration MO

Technology Title: BET-300-P Multi-Axis Modular Electrospray Reaction Control System

Affiliation: Busek

Assumptions: Technology required to be at TRL 5 by 2021

Technology Description, Current Performance Metrics, and Performance Goals

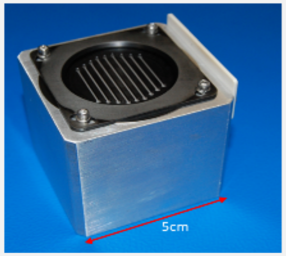
Modular (5cm cubed) thruster heads designed to provide unprecedented levels of position (μm scale) and attitude (milli-arcsecond) control to small spacecraft.

Currently measured metrics:

- 0 to 150μN of thrust via continuous or PWM control
- Minimum impulse bit <2.5μNs
- High thrust to power >55μN/W
- Thrust precision <0.4μN, thrust noise <0.1μN/$Hz^{1/2}$

Performance goals to be demonstrated:

- Total throughput of >135Ns per module (>1050Ns/U)



Current TRL

3

TRL By May 2021

5

Industry State of the Art Technology Performance

Primary competitors are cold gas thrusters and reaction wheels:

- *BET-300-P impulse density and thrust precision is significantly improved over cold gas thrusters*
  - Enables longer mission durations and enhanced precision
- *Reaction wheels induce significant vibration*
  - BET-300-P contains no moving parts, vibration eliminated
  - >10x improvement in torque noise and precision over SoA small-sat reaction wheels
- *Single system for ACS*
  - Eliminates need for reaction wheel desaturation via a secondary RCS or environmental forces

Technology Development Challenges to Meet TRL Goal

Lifetime (total impulse) is a primary challenge to all electrospray thrusters

- BET-300-P has demonstrated highest total impulse from a miniaturized electrospray thruster to date
- Ongoing funding (NASA GSFC) to address impulse-limiting issues

Inflight demonstration of critical features

- PPU design and charge neutralization

Potential HPD Science Application (Optional)

Precision body pointing to milli-arcsecond resolution

- Enables highly stable platforms and therefore long integration times; minimizing the need for large apertures

Precision position control to sub μm scales

- Numerous applications including on-demand/free-floating occultation, artificial guide stars and precisely spaced formation flights of distributed instruments

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Additional Comments

BET-300P (passive) Electrospray Thruster System

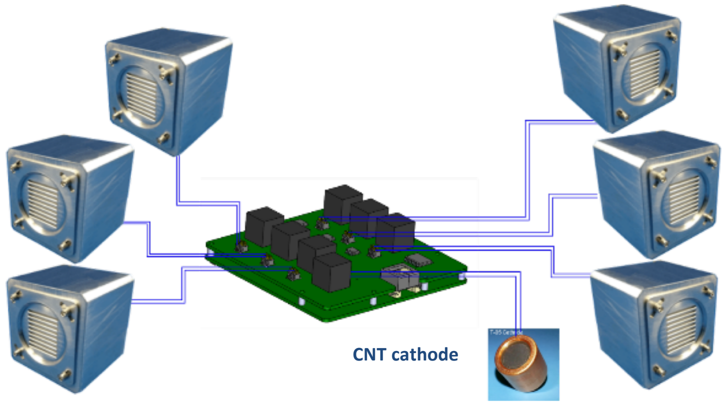
Specifications: ***Directly measured unless noted***

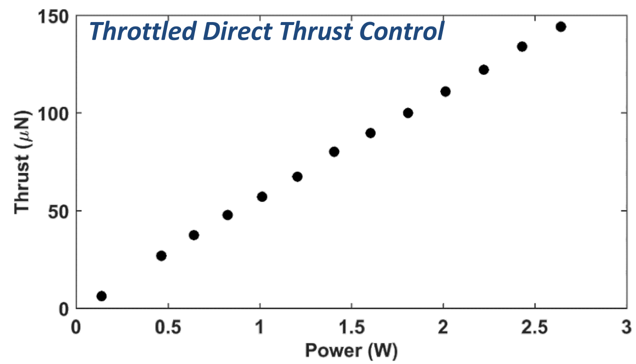
Thruster head size	~5 x 5 x 5 cm
Mass (wet)	~230g (not optimized) <150g anticipated
Propellant load	16 g
Total impulse	~135Ns*
Nominal thrust	~5-150 µN
Maximum thrust	300µN**
Control modes	Throttleable from <5µN to >150µN
Thrust control resolution	<500nN
Minimum impulse bit	<3µNs @ 30µN max set point <5µNs @ 65µN max set point
Minimum pulse duration	~50ms
Thruster head power (nom./max)	~2.5W / 6W
Neutralization	Busek CNT cathode, one per 6 BET-300-P
PPU Architecture (expected)	Simultaneous control of up to 6 axes Commanded thrust and/or PWM control
PPU Status	Conceptual; to be derived from TRL5/6 BET-100µN single axis PPU
Nominal system power (estimated)	~2-4W +3.5W per active thruster
PPU Size / mass (estimated)	~250g, 2 X 10cm x 10cm boards

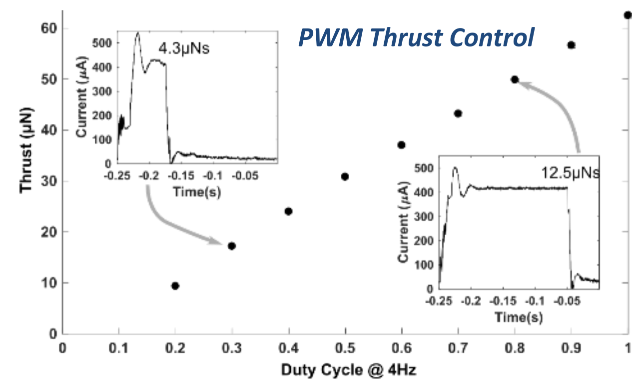
*Based on propellant load, lifetime not yet established

**300µN demonstrated on prototype system

Distributed Architecture







Electrospray Precision Attitude Control

BUSEK Space Propulsion and Systems

Precision Attitude Control

- Sub-milliarcsec control
- Ideal for long integrating stares
- Throttling by >25x supports fast slews
- Imaging, laser comms., scientific measurements

Precision Trajectory Control

- Ideal for high precision formation flight
  - Non Keplerian orbits
    - Occultation nanosats
    - Artificial stars
- Position control at nm scales
- Distributed apertures/instruments