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 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

Contact Information

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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)

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.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Thrust (mN)</td>
<td>13 (5-20)</td>
</tr>
<tr>
<td>Specific Impulse (s)</td>
<td>1,375 (1,000 – 1,500)</td>
</tr>
<tr>
<td>Thruster Power (W)</td>
<td>200</td>
</tr>
<tr>
<td>Thruster Mass (kg)</td>
<td>1.1*</td>
</tr>
<tr>
<td>Thruster Volume (U)</td>
<td>1*</td>
</tr>
<tr>
<td>Lifetime (hrs)</td>
<td>&gt;1,800</td>
</tr>
<tr>
<td>Delta-v (m/s, 20kg spacecraft)</td>
<td>525</td>
</tr>
<tr>
<td>Propellants</td>
<td>Xe, I₂</td>
</tr>
</tbody>
</table>

* Excludes feed system & electronics
## 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)

### 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.

### Contact Information

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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**

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**BHT-600: PERFORMANCE**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Thrust (mN)</td>
<td>9 – 38</td>
</tr>
<tr>
<td>Specific Impulse (s)</td>
<td>1,000 - 1,710</td>
</tr>
<tr>
<td>Thruster Power (W)</td>
<td>600 (700 input)</td>
</tr>
<tr>
<td>Thruster Mass (kg)</td>
<td>2.5*</td>
</tr>
<tr>
<td>Lifetime (hrs)</td>
<td>10,000**</td>
</tr>
<tr>
<td>Propellants</td>
<td>Xe, I₂</td>
</tr>
</tbody>
</table>

* Excludes feed system & electronics, **predicted
### 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

### 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

### Current TRL

<table>
<thead>
<tr>
<th>Technology</th>
<th>TRL By May 2021</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIT-3</td>
<td>7 - 8</td>
</tr>
</tbody>
</table>

### 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

### 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

- 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° 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

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

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

**Affiliation:** Busek

### 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)

### 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

### 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

### 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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# BET-300P (passive) Electrospray Thruster System

### Specifications: Directly measured unless noted

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thruster head size</td>
<td>~5 x 5 x 5 cm</td>
</tr>
<tr>
<td>Mass (wet)</td>
<td>~230g (not optimized)</td>
</tr>
<tr>
<td></td>
<td>&lt;150g anticipated</td>
</tr>
<tr>
<td>Propellant load</td>
<td>16 g</td>
</tr>
<tr>
<td>Total impulse</td>
<td>~135N*</td>
</tr>
<tr>
<td>Nominal thrust</td>
<td>~5-150 µN</td>
</tr>
<tr>
<td>Maximum thrust</td>
<td>300µN**</td>
</tr>
<tr>
<td>Control modes</td>
<td>Throttleable from &lt;5µN to &gt;150µN</td>
</tr>
<tr>
<td>Thrust control resolution</td>
<td>&lt;500nN</td>
</tr>
<tr>
<td>Minimum impulse bit</td>
<td>&lt;3µNs @ 30µN max set point</td>
</tr>
<tr>
<td></td>
<td>&lt;5µNs @ 65µN max set point</td>
</tr>
<tr>
<td>Minimum pulse duration</td>
<td>~50ms</td>
</tr>
<tr>
<td>Thruster head power (nom./max)</td>
<td>~2.5W / 6W</td>
</tr>
<tr>
<td>Neutralization</td>
<td>Busek CNT cathode, one per 6 BET-300-P</td>
</tr>
<tr>
<td>PPU Architecture (expected)</td>
<td>Simultaneous control of up to 6 axes</td>
</tr>
<tr>
<td></td>
<td>Commanded thrust and/or PWM control</td>
</tr>
<tr>
<td>PPU Status</td>
<td>Conceptual; to be derived from TRL5/6 BET-100µN single axis PPU</td>
</tr>
<tr>
<td>Nominal system power (estimated)</td>
<td>~2.4W + 3.5W per active thruster</td>
</tr>
<tr>
<td>PPU Size / mass (estimated)</td>
<td>~250g, 2 X 10cm x 10cm boards</td>
</tr>
</tbody>
</table>

*Based on propellant load, lifetime not yet established
**300µN demonstrated on prototype system
**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 Keplarian orbits
    - Occultation nanosats
    - Artificial stars
- Position control at nm scales
- Distributed apertures/instruments

Example inertial stare con-ops in LEO