Overview of Busek Electric Propulsion

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Abstract: Busek has been active in the fundamental research, development, manufacture, and flight of US solar electric propulsion (SEP) for over 30 years. Over the course of this time, the firm has contributed to the greater understanding and demonstration of multiple in-space propulsion technologies, and it continues to advance components, systems, and next generation propellants for future missions. Busek's present SEP focus is on three high-performance sub-disciplines; Hall effect, Electrospray, and Gridded Ion. The majority of Busek's portfolio and development status is described herein.

I. Introduction

United States' research in solar electric propulsion (SEP) has been an active field since the experiments of Dr. Robert Goddard in the early 1900's, later reinvigorated by Dr. Ernst Stuhlinger in the 1950's. Numerous in-space SEP technologies were studied, developed, and flown from the 1950's to the 1990's, including arc-jets, pulsed plasma thrusters, and gridded ion engines amongst others. For a variety of reasons, the US largely abandoned Hall thruster development in the late 1960's in favor of gridded ion engines, until Western interest was respawned after the fall of the Soviet Union.

Busek, founded in 1985 by Dr. Vlad Hruby, had an initial focus on energy conversion and plasma research. In the early 1990's, technical papers began to emerge describing the Hall thruster development and flight successes achieved during the Soviet space program. This revelation to the West highlighted a significant gap in US expertise and capabilities in space. At this time, several Western firms successfully gained access to former Soviet technology from leaders such as EDB Fakel and the Keldysh Research Center. Busek had neither the resources, clout, nor interest to pursue such technology transfers. Instead, Busek independently pursued the design and development of US-based EP.

Since the early 1990's, Busek's focus has been the design, development, and manufacture of wholly Domestic in-space thruster technology, with an emphasis on Hall effect propulsion. The departure point for Busek's work was the fundamental research performed by NASA in the 1960's, which was revived using a combination of funds from non-dilutive US Small Business Innovation Research Grants and private investment. By the mid 1990's, an early validation of Busek's work occurred when it was selected by the Teledesic constellation to provide Hall thruster technology for its then-planned 288 satellites. Due to relative size of Busek at the time (staff of ~12), and the large order, Busek issued a technology license to Primex Technologies (now Aerojet) for commercialization and production of thrusters. This license is the genesis of the Busek-Primex-Thruster line of product (e.g. BPT-4000, renamed XR-5). Ultimately, the Teledesic Constellation failed, having never launched a single spacecraft.

Work continued for another decade before Busek, with the Air Force Research Laboratory and Northrop Grumman were able to demonstrate for the first time a US Hall thruster in space. The mission was TacSat-2 (2006), which

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utilized a xenon propelled BHT-200 coupled with a Northrop Grumman power processing unit. TacSat-2 was followed by the Advanced Extremely High Frequency (AEHF-1) mission in 2010, which utilized the Aerojet-built BPT-4000, the first US operational mission with US Hall effect thrusters. Shortly after spacecraft tip-off, AEHF-1 experienced an anomaly in its chemical apogee engine, putting the spacecraft at risk of loss[1]. While AEHF-1's Hall thrusters were originally intended for north-south station-keeping in GEO stationary orbit, engineers rapidly implemented an electric orbit raise plan using the BPT-4000's. These mission-saving maneuvers represented the first US electric orbit raising and are seen as a turning-point for wider Hall thruster technology adoption in the US. Today, nearly all satellite Primes offer all-electric or hybrid electric propulsion solutions for GEO satellites, and most existing and proposed LEO constellations baseline SEP.

In its nearly three and a half decades of operation, Busek has developed what is today one of the largest in-space electric propulsion product portfolios in the United States. Present technologies including Hall effect, electrospray, radio frequency gridded ion, and pulsed plasma thrusters in effort to be a "one stop shop" for all advanced spacecraft propulsion. The firm's firsts include the first US Hall thruster in space (TacSat-2), the first micro-pulsed plasma thruster in space (FalconSat-3), and the first operational electrospray thrusters in space ESA LISA Pathfinder (AKA (NASA ST-7). Additional pioneering work has been the research and development of alternate propellants for EP, including iodine fueled RF ion engines and Hall thrusters, as well as air-breathing Hall thrusters.

Enabling the rapid development and testing of components and systems is Busek's extensive in-space propulsion infrastructure, modeling, and diagnostic tools built-up over decades of operation. Test capacity includes four large vacuum facilities, the largest capable of operating 10kW class thrusters, four dedicated electrospray chambers, two dedicated chambers for testing iodine-fueled RF ion engines, and numerous small vacuum chambers for testing at the subsystem and component level. Recent investments outside of test chamber capacity include AS-9100 certification, investment in fabrication and inspection equipment for streamlined vertical integration, and automation of test processes to support volume production of propulsion components and systems.

Present company efforts are split between the advancement of fundamental technologies, processes, and materials, new product development and qualification efforts, and scaling manufacturing capabilities to meet existing and anticipated thruster market needs.

II. Active & Passive Electrospray Thrusters

Busek spent nearly a decade developing and qualifying the first electrospray thrusters aboard the recently completed European Space Agency LISA Pathfinder (LPF) Mission. Working as part of the NASA Space Technology 7 (ST-7) Program with NASA's JPL, Busek advanced the technology from TRL-3 to flight. The effort spanned the creation of new flow control mechanisms, new ultra-high voltage electronics, mastering capillary emitters, and the flight qualification of an entirely new propellant. The past work serves as the ongoing foundation actively fed electrospray systems designed to enable the forthcoming LISA Mission. In addition, Busek has been leading the development and maturation of passively fed miniature electrospray systems for precision reaction control for small spacecraft.

Active Electrosprays

As part of the NASA Space Technology 7 (ST7) Disturbance Reduction System (DRS), Busek developed an electrospray or colloid-based micro-propulsion system that was flight demonstrated as part of the ESA LISA Pathfinder mission (Figure 1). These thrusters demonstrated precision thrust over the range of 5μN to 30μN, with unprecedented thrust resolution and noise ($<0.1\mu N\sqrt{Hz}$). The LPF technology demonstrator mission was a significant success, with the colloid thrusters meeting all system level requirements and demonstrating nearly 20,000 hours of operation across the eight thrusters on the LPF spacecraft. With key technologies demonstrated, work has commenced on the Laser Interferometer Space Antenna (LISA) mission, a space-based gravitational wave observatory mission.

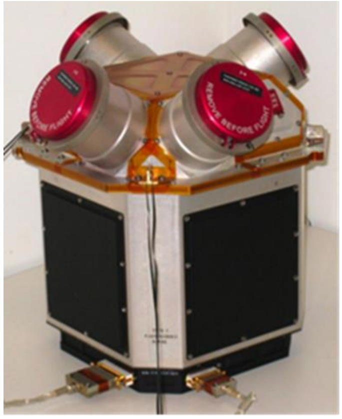

Figure 1: Colloid micro-thruster systems assembly as flown on LISA Pathfinder (ST7)

Lessons learned from the prior flight hardware build, qualification testing, on-orbit operations, as well as subsequent electrospray development work, have been compiled and dispositioned. From this list, it is evident that there are two major drivers of Colloid Micro-Thruster System (CMTS) design towards meeting LISA requirements, redundancy and life. In coordination with JPL, Busek has updated component-level designs towards meeting redundancy requirements, particularly with in the propellent feed system, such as adding series flow control valves and a redundant feed system string. These updated designs have been fabricated and have been subjected to environmental testing. For example, the latest generation Busek microvalve (**Error! Reference source not found.**, left) has successfully pass through both vibrational and thermal testing[2], demonstrating the required µL/min flow range, with pL/sec flow precision.

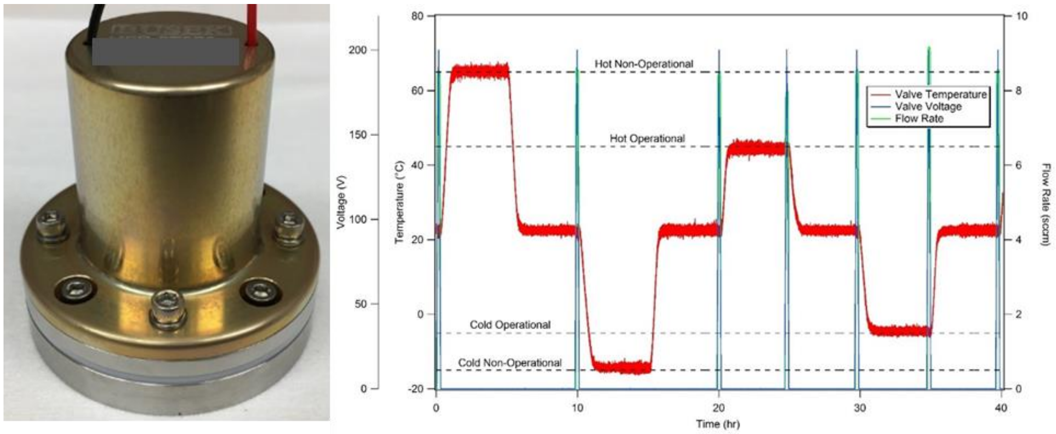

Figure 2: Busek 4th generation microvalve (left). Survival & operational thermal testing (right), demonstrating valve function.

In order for the CMTS technology to be a viable for the LISA mission, it must be raised back to TRL 6 by the ESA Mission Adoption Review. Towards this goal, next steps at Busek include integration of components into major subassemblies and additional environmental testing, followed by integrated testing of a complete Thruster String Assembly (TSA), culminating with a four-year life test.

Busek and JPL remain responsive to ESA LISA spacecraft designs initially drafted by the ESTEC Concurrent Design Facility that are in continued development. CMTS mass has been estimated as a function of the required thrust range. The primary function of the CMTS is to oppose the solar pressure applied to the spacecraft, thus the larger spacecraft proposed as part of the CDF study would necessitate increased thrust. The colloid thruster within the CMTS uses capillary-based emitters operated in parallel from a common propellant supply (9 emitters for LPF), thus thrust can be readily scaled to meet new thrust requirements by adding more emitters to the same general thruster head design. As shown in Figure 3, the dry and wet mass of a primary-redundant CMTS has been estimated based on the number of capillary emitters used and achievable maximum thrust. While there are likely no significant dry mass savings with regards to the cold gas thruster competing technology, there are considerable wet mass savings due to the higher specific impulse operation of the colloid thrusters (150sec to 250sec) versus cold gas (45sec to 60sec). Given these advantages, the Busek CMTS technology is a strong candidate for adoption for the LISA mission.

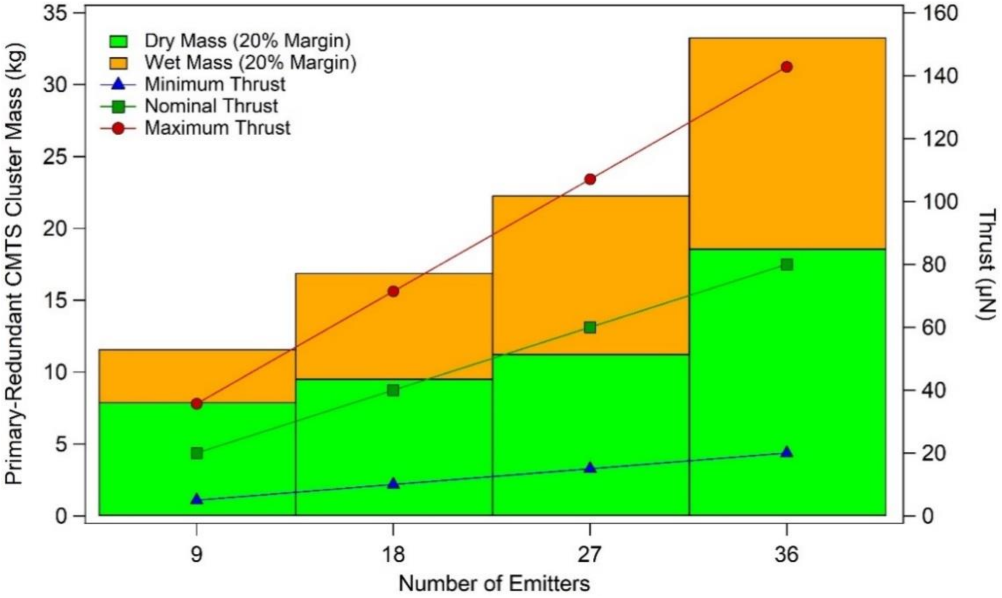

Figure 3. CMTS mass versus number of emitters and thrust range. Image taken from ref 2.

Passive Electrosprays

Busek's BET-300-P passively fed electrospray thruster, Figure 4 (left), is being actively developed as part of a high precision reaction control system (RCS). The complete system, referred to as the BET-MAX Figure 4 (right). Up to four 125cm^3 BET-300-P thrusters per centralized PPU can be integrated as desired to provide attitude or orbital control within a wide range of spacecraft platforms. Each thruster can provide throttled continuous thrust from <1µN up to 150µN at <2.5W of thruster power with sub-µN resolution over the full range[3]. Thrust noise characterizations are ongoing with preliminary results indicating noise predominantly under 0.1µN/Hz$^{1/2}$ from 10mHz through to several kHz[4].

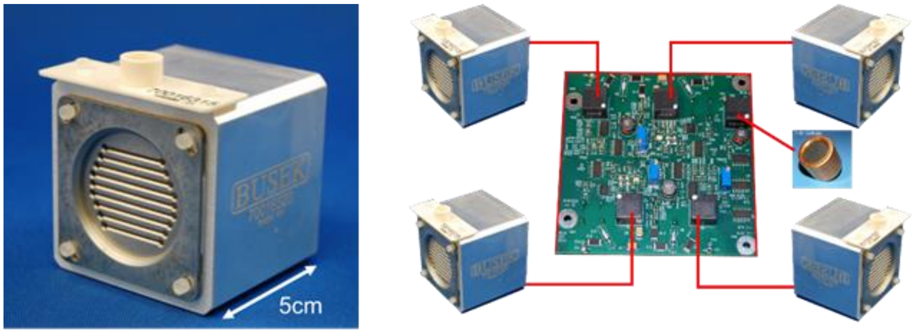

Figure 4: Busek BET-300-P passively fed electrospray thruster (left); BET-MAX, multi-axis electrospray reaction control system for small spacecraft (right).

Passively fed electrospray thrusters have previously been shown to yield high specific impulse estimates, by way of an enhanced ion content compared with droplet dominated colloid thrusters[5,6]. Due to the large throttling range of these thrusters, lifetimes (in hours for example) are an ambiguous measure of the thruster's true capabilities. Rather total impulse is a preferred metric, with existing published results at the time of writing limited to less than 10Ns in

Ref. [7]. This can be contrasted with the many 10's of kNs required to achieve many primary ΔV mission objectives[8]. However, 10's of Ns from a compact electrospray thruster would provide an impulse density comparable to available small-sat cold-gas precision thrusters[9]; while also providing significant precision control improvements. Referring toFigure 5 Figure 5, Busek's BET-300-P development program has emphasized total impulse improvements culminating in over 70Ns demonstrated to date. Here throughput measurements are made by means of periodic direct thrust measurement sweeps (versus time of flight) used to constantly update an empirical expression for instantaneous thrust. See Ref. [10] for further details.

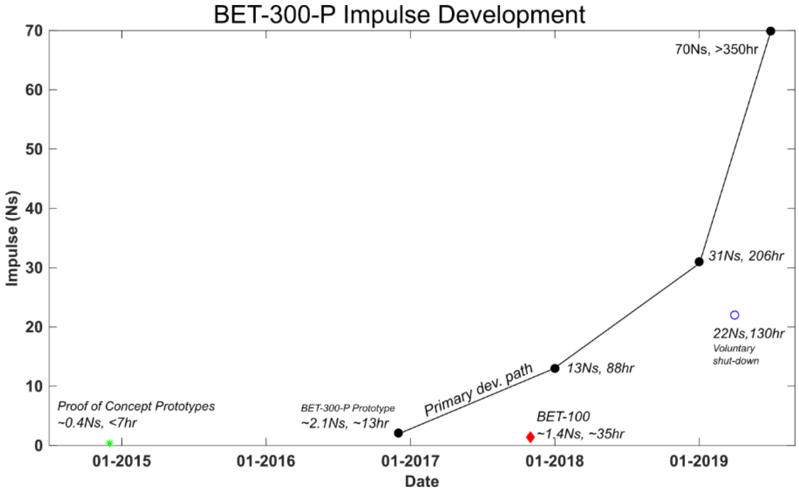

Figure 5: Evolution of the BET-300-P demonstrated impulse throughput based on direct thrust measurements.

III. Radio Frequency Ion Engines

Busek has developed a family of gridded RF ion thrusters ranging from 1cm to 7cm in grid diameter, with thruster power up to 400W. Currently the 3cm model "BIT-3" is the most mature, and it is slated for flight delivery in 2019 to multiple customers including two 6U/14kg CubeSat missions that will be launched on NASA's SLS EM-1. Figure 6 shows integrated unit firing on iodine as well as a completed QM unit. The fully integrated BIT-3 propulsion system represents a significant technological achievement as it is one of the first solid iodine-fueled, flight-ready EP systems, and it will enable a multitude of deep space CubeSat missions.

Figure 6: Integrated BIT-3 operating on iodine propellant (left); integrated thruster system (right)

The iodine BIT-3 system has a physical envelope of 180×88×102mm (~1.6L or 1.6U), 1.4kg dry mass and 2.9kg wet mass. In addition to the thruster head, other notable subsystem components include an innovative RF cathode, a 2-axis thruster gimbal capable of ±10° slew, a highly miniaturized and >83% efficient PPU, and a lightweight, rectangular-shaped iodine propellant tank. A full propellant load translates to over 32kN-s of total impulse from a compact 1.6U wet system volume. This level of impulse, once demonstrated, would be an unprecedented for a CubeSat compatible system. It would enable 6-12U cubesats to perform numerous high deltaV missions, examples of which include 1) low-altitude (<300km), drag-less flight for Earth observation or telecommunication, 2) orbit raising (i.e. from GTO to GEO), 3) inflight plane change or re-tasking, and 4) interplanetary orbit transfer. System performance is listed in Figure 7.

Input Power, W	Thrust, mN	Total Isp, sec
55	0.66	1190
60	0.83	1490
65	0.94	1690
70	1.05	1890
75	1.16	2090
80	1.27	2290

Figure 7: BIT-3 system performance

IV. Hall Effect Thrusters

Over the last two decades, Busek has matured a wide variety of Hall thrusters ranging in nominal power from 100 W to 20 kW. Most are highly throttle-able in terms of power, thrust, and specific impulse. Busek has developed Domestic designs for five pole and two pole thrusters (Figure 8). A number of Busek's thrusters incorporate patented "U" shape magnetic shunts as well as thermal management features that allow high power density operation. The former originated what is now called 'magnetic shielding' by JPL. Several of the models described below are amidst qualification and flight programs.

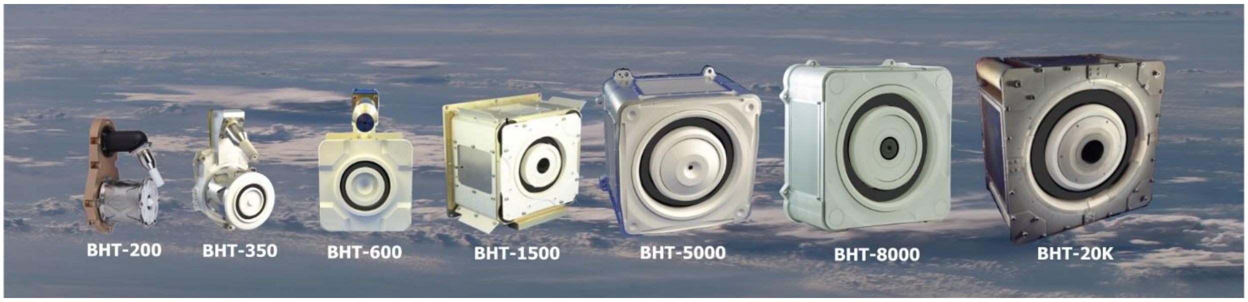

Figure 8: Busek Hall thruster Portfolio

BHT-100

The BHT-100 (not pictured above) is a nominal 100-W thruster designed for long-life, low-power, small satellite applications, including CubeSats as small as 12U. At present, the BHT-100 is at TRL 4-5. At 100 to 150 W, the ratio of thrust to power ranges from 53 to 63 mN/kW, and I_{sp} ranges from 1000 to 1200 seconds, [11] Figure 9 shows the BHT-100 operating on xenon. An iodine compatible version of the thruster has also been developed and tested.

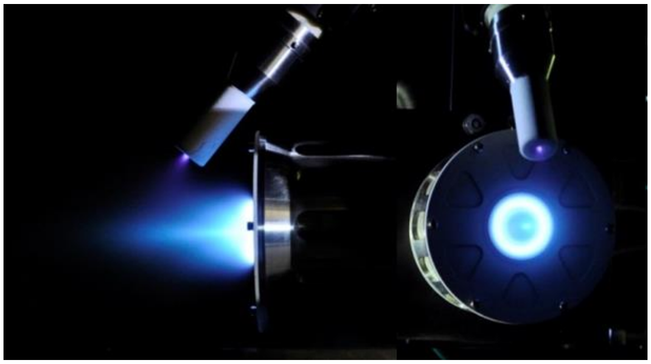

Figure 9: BHT-100 operating on Xenon Propellant

BHT-200

The BHT-200 (Figure 10) is one of the most extensively studied Hall thrusters in the US, and laboratory models of this thruster have been used to train a generation of students in Hall thruster technology. The body of research around the device and resulting large data sets have contributed greatly to US scientific understanding of small Hall effect thrusters. Flight programs for the thruster include TacSat-2, [12], the first US Hall thruster in space, FalconSat-5, and FalconSat-6. The latest launch of a 200W system occurred in December 2019, and the device is at TRL 9 as defined by Mankins.[13]

Figure 10: BHT-200 operating on Xenon propellant (left); static (right)

For the FalconSat missions, the BHT-200 was powered by a Busek Power Processing Unit (PPU). At 200 W, the BHT-200 produces 13 mN of thrust at a specific impulse of1390 seconds. The demonstrated lifetime is over 1800 h, for a demonstrated propellant throughput of > 6 kg. The device is shown in Figure 10, with the cathode being distal to the discharge channel. Iodine compatible versions of the BHT-200 have been delivered to NASA for the iSat mission, but the mission has not yet flown.[14],[15]

BHT-600

An engineering model BHT-600 is presently being duration tested at NASA GRC with the cathode in the external position. The fuel is xenon. Thus far, the thruster has run for > 5,000 hours, mostly at the nominal 600 W operating point. Demonstrated throughput is > 48 kg, and demonstrated total impulse is > 700 kN-s. Over the course of the xenon duration test, thrust and specific impulse (I_{sp}) have remained essentially invariant, within experimental uncertainty. Figure 11 plots specific impulse against time for the first 4500 h of the test.

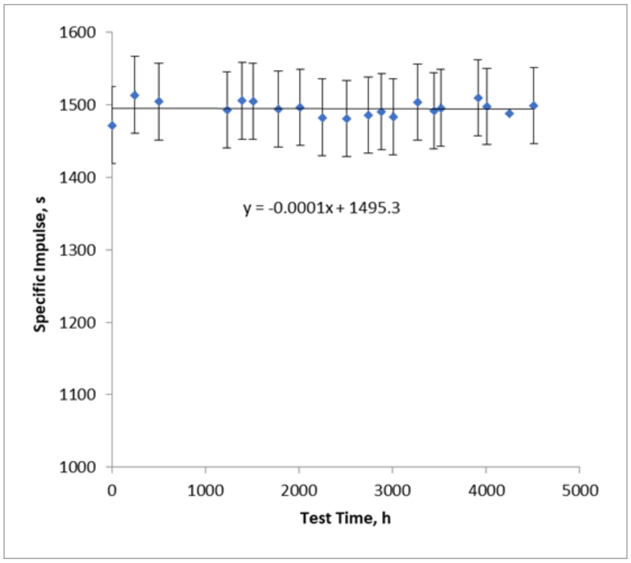

Figure 11: Measured Isp vs. time for BHT-600 through 4500 h (Xe)

In 2017 – 2018, the same engineering model thruster was tested with an internal cathode. This testing took place at low background pressure (e.g. 6 x 10^{-6} Torr), and measured performance was very similar to that measured with the external cathode. An iodine compatible version of the BHT-600 has also been developed. The iodine compatible BHT-600-I demonstrated over 1200 hours of cumulative operation in three discrete segments totaling 34, 46 and 1175 hours.[16] Figure 12 shows the BHT-600 operating on xenon and BHT-600-I (iodine) as delivered to NASA GRC in 2015.

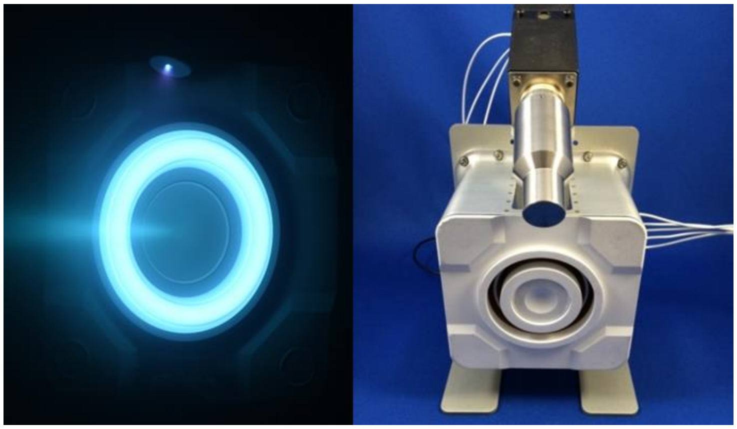

Figure 12: BHT-600 operating on Xenon propellant (left); Iodine Compatible BHT-600-I unit (right)

With xenon or with iodine, the BHT-600 is optimized for small spacecraft, including ESPA or ½ ESPA class. Demonstrated xenon throughput for a single thruster at I_{sp} ~ 1500 s is sufficient to lift a 140 kg spacecraft from LEO to GEO, including a 28 degree inclination change – a maneuver which requires a total delta V of approximately 6.0 km/s. With two thrusters, the spacecraft mass can exceed 250 kg with margin. This capability opens an unprecedented new range of smallsat missions deploying from rideshares or dedicated smallsat launches.

The BHT-600 was designed to operate at 600 W.[17] With xenon at 600 W, the BHT-600 produces 39 mN of thrust at a specific impulse of 1495 s. Nominal specifications are found in Table 1.

Table 1: Nominal Performance Specifications for BHT-600 (Xenon Fuel)

Parameter	Value
Disharge Potential	300 V
Discharge Current	2.0 A
Discharge Power	600 W
Thrust (Xenon)	39 mN
Specific Impulse (Xenon)	1495 s
Lifetime (Demonstrated)	>5,000 h
Througput (Demonstrated)	>48 kg
Total Impulse (Demonstrated)	>700 kN-s

BHT-1500

The BHT-1500 has a throttling range from <1 kW to >2 kW, but the designed operating point is 1.5 kW. Estimated lifetime is > 10,000 hours at nominal conditions. In 2008, the BHT-1500 was redesigned to locate the cathode along the geometrical thruster axis, resulting in the BHT-1500-C. A unit was delivered to the Air Force Institute of Technology (AFIT), where it was studied with xenon, with results published in 2009.[18]

Significant private resources were invested in the development of a qualification model, known as the BHT-1500-E, which retains the internal cathode. Testing at the Aerospace Corporation confirmed excellent performance.[19] At

1.8 kW, the BHT-1500 provides 103 mN thrust at a specific impulse of 1,820 seconds. Additional data points at 1.5 and 1.8 kW are found in Table 2.

Table 2. Performance of BHT-1500-E with xenon (Data from Ref. 19)

Gas	Power (Watts)	Discharge Potential (Volts)	Specific Impulse (s)	Efficiency (%)	P Background (Torr)
Xe	1.5	300	1710	55.4	7.8E-06
	1.5	400	1878	51.8	6.0E-06
	1.8	300	1763	57.1	8.8E-06
	1.8	400	1942	53.6	7.1E-06

Various versions of the BHT-1500 have been used to investigate alternate propellants. The list of propellants includes noble gases such as krypton,[20] metals such as bismuth,[21] zinc,[22] and magnesium[23], and molecules such as CO_2 and N_2.

BHT-5000

Busek Co. Inc. is developing a 5kW class Hall Effect Thruster (HET) designated as BHT-5000 (Figure 13). The effort is funded and guided by Maxar. The program goal is to qualify a high performance, multi-kW, long life thruster that operates in multimode fashion at high Isp for station keeping and high thrust for orbit raising. To achieve the program goals, which includes lower plume divergence and insensitivity to vacuum tank pressure, the thruster incorporates a center mounted cathode, which Busek pioneered in its 1.5kW and 8kW thrusters.

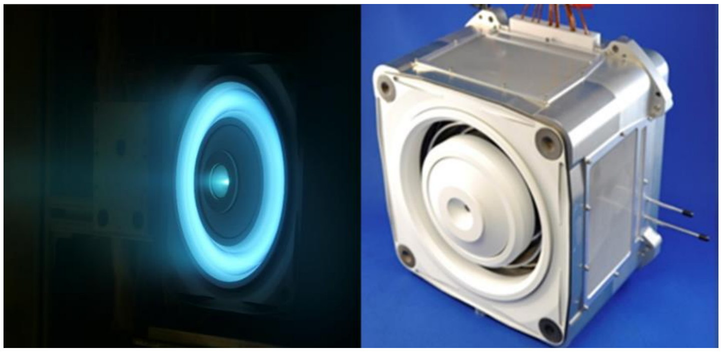

Figure 13: BHT-5000 operating on Xenon propellant (left) with center-cathode plume visible; static (right).

The BHT-5000 has excellent performance in the 3-6kW power range; exceeding 60% total efficiency and having a predicted lifetime greater than 20,000 hours which has been determined by erosion modeling and currently verified by accelerated life testing. At 5kW and 300V discharge which represents the high thrust mode, the thruster delivers T>310mN and Isp>2,000sec with efficiency> 61% total efficiency. Operating attributes are listed in Table 3.

Table 3: BHT-5000 dual-mode attributes

Operating Mode (Xe)	Orbit Raising	Station Keeping
Discharge Power (Watts)	5,000	3,000
Discharge Voltage (Volts)	300	400
Thrust (mN)	311	174
Isp (s)	2009	2044

The current development status is that the thruster passed CDR, successfully completed qualification level environmental tests, completed a separate life test of two center mounted cathodes, and is in the third segment of a four-segment accelerated life test that is focused on demonstrating mission start/stop cycles in the high Isp mode. The completion of the fourth segment is scheduled for late 2019. The completed cathode life test included two hollow cathodes, one operating in steady state at 20A demonstrating accumulation of emitted Coulombs per mission requirements and the other demonstrating 10,000 heat up, emission and cool down cycles applicable to station keeping.

BHT-8000

The BHT-8000 was designed to operate at 8 kW and features a centrally mounted cathode shown to reduce beam divergence and maximize efficiency[24] The BHT-8000 has been tested with xenon, krypton, iodine and other propellants.[25], [26] With xenon at 8.0 kW, the BHT-8000 produces 449 mN of thrust at a specific impulse of 2,210 seconds. Figure 14 shows the laboratory model operating on krypton and the present engineering model thruster.

Figure 14: BHT-8000 operating on Krypton propellant (left), with center-cathode plume visible; static (right).

BHT-20K

Busek's largest thruster is the BHT-20K, a noble gas thruster that was designed to operate at power levels of 5 to 20 kW and discharge potentials up to 700 V. The cathode is internal. The BHT-20K is at TRL 5. Full power testing has taken place at Busek, the Arnold Engineering Development Center (AEDC), and NASA Glenn Research Center.[27] At 20 kW, the BHT-20K produces 980 mN of thrust at a specific impulse of 2630 s.

V. Alternate Propellants

Busek has demonstrated a range of propellants in electric propulsion devices (Figure 15) and is a pioneer in the field iodine electric propulsion (IEP). Iodine is easy to ionize, has an atomic mass similar to that of xenon, and stores in the solid phase at low pressure and roughly three times the density of high-pressure xenon. In performance testing of Hall thrusters at widely disparate power levels, little or no performance penalty from using iodine instead of xenon was observed.[28,29]

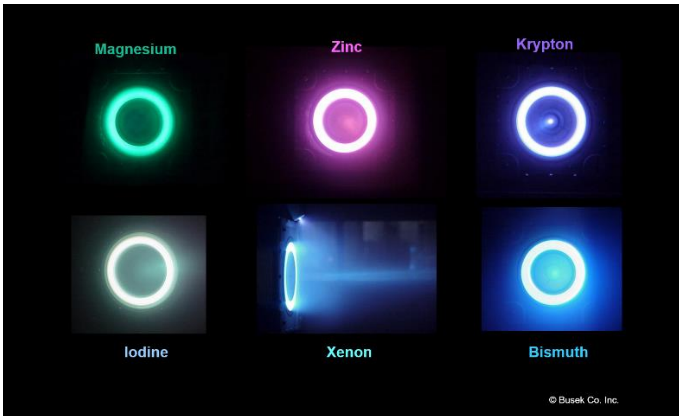

Figure 15: Alternate EP Propellants

Busek has commitments for several all-iodine fueled RF ion engine flight programs for its BIT-3 system, including two lunar missions due to launch on SLS EM-1 (Morehead State University's Lunar Ice Cube, and Arizona State University's LunaH-Map). As with any plasma propulsion system, 100% ionization within is not expected. Accordingly, a neutral flux downstream of the thruster will occur. The BIT-3 operates on iodine propellant which has a vapor pressure[30] of ~10 mTorr at 0°C and therefore is expected to sublimate – to a degree – from moderately cold surfaces in a space (high vacuum) environment. However, while this propellant has been extensively studied from an electric propulsion performance perspective in recent years, questions regarding contamination risk have not been experimentally evaluated.

VI. Flight Programs

A sample of Busek's past and present flight programs are depicted in Figure 16 below.

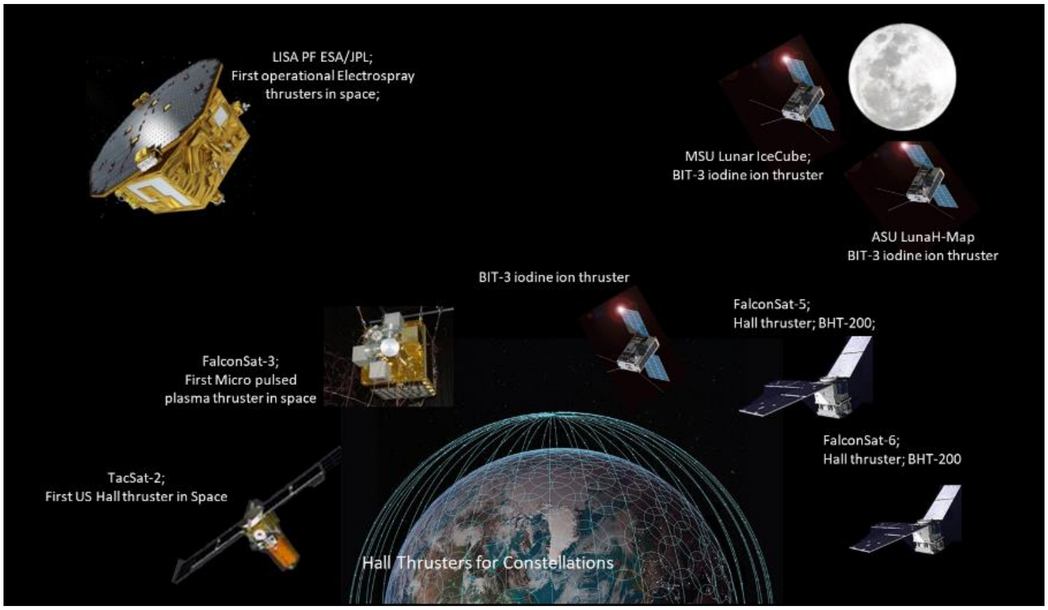

Figure 16: Select past and present flight programs

Acknowledgments

The BHT-600 duration test is being conducted by NASA GRC personnel under a Space Act Agreement. Busek acknowledges the support and collaboration of NASA and AFRL, as well as the customers who give us the opportunities to demonstrate success.

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