OVERVIEW OF NASA IODINE HALL THRUSTER PROPULSION SYSTEM DEVELOPMENT

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ABSTRACT:

NASA is continuing to invest in advancing Hall thruster technologies for implementation in commercial and government missions. The most recent focus has been on increasing the power level for large-scale exploration applications. However, there has also been a similar push to examine applications of electric propulsion for small spacecraft in the range of 300 kg or less. There have been several recent iodine Hall propulsion system development activities performed by the team of the NASA Glenn Research Center, the NASA Marshall Space Flight Center, and Busek Co. Inc. In particular, the work focused on qualification of the Busek 200-W BHT-200-I and development of the 600-W BHT-600-I systems. This paper discusses the current status of iodine Hall propulsion system developments along with supporting technology development efforts.

1. BACKGROUND

Operational Hall thrusters currently demonstrate excellent mission performance for power levels between 1 and 10 kW using xenon gas. Unfortunately, the volume and high pressure requirements for xenon storage do not integrate well with small spacecraft. Low-power Hall thruster tests at Busek Co. Inc. found that Hall thruster performance with iodine is very similar to its performance with xenon; however, iodine is three times as dense as xenon and stores at subatmospheric pressures. This increase in storage density can lead to significant savings in spacecraft volume efficiencies, which can lead to significant ΔV over xenon propellant for a given electric propulsion system volume.

Test and analysis activities focus on four key areas have been undergoing—thruster, power processing unit (PPU), cathode, and feed system. The cathode activities have focused on cerium hexaboride, lanthanum hexaboride (LaB_6), and electride configurations. Feed system development focused on sublimation control, high-voltage isolation, and avoidance of propellant condensation. This paper summarizes evaluations of the Busek 200- and 600-W iodine propulsion systems conducted in NASA Glenn Research Center (GRC) vacuum facilities.

The use of iodine as an alternative to xenon has been studied for more than a decade [1,2,3,4,5]. Over that time there have been a wide range of studies from MicroSats (10 to 100 kg), which can perform significant orbit transfers including geostationary transfer orbit (GTO) to geostationary equatorial orbit (GEO) or deployment into a full constellation from a single launch. Studies a have also examined an Evolved Expendable Launch Vehicle (EELV), Secondary Payload Adaptor (ESPA), or ESPA Grande class spacecraft, which can perform more than 10 km/s of ΔV and perform orbit transfers from GTO to the Moon, Mars, Venus, and asteroids.

The first detailed concept design of a low-cost iodine Hall demonstration mission was completed by the Collaborative Modeling for Parametric Assessment of Space Systems (COMPASS) [6] team at GRC in 2012. The concept was a 6U spacecraft with a modified BHT-200 thruster and a repackaged compact PPU. Even though the initial concept was power starved, included aggressive assumptions, and required significant engineering development work, it showed the viability of a low cost and high value approach to flight demonstrate the iodine Hall technology. Multiple iterations of the concept followed, leading to the Iodine Satellite (iSAT) demonstration mission, which is also discussed in detail.

While iodine propellant has several advantages, in particular for low power volume constrained systems and at high power [7] there are challenges with propulsions system development, which must be addressed. As shown in the past with other elements, condensable propellants raise concerns with deposition on the spacecraft and operational complications. Iodine can be corrosive to materials both in the feed system and possibly on the spacecraft during flight. The feed system also has unique challenges, requiring very low pressure flow control and parasitic power burden to keep the propellant and propellant lines heated. Material compatibility considerations also apply to both the thruster and cathode when making decisions on the coatings and constituent materials.

1.1 Iodine Satellite Mission

NASA's Space Technology Mission Directorate (STMD), under the Small Spacecraft Technology Program (SSTP), approved the iodine satellite (iSat) flight project for a rapid demonstration of iodine Hall thruster technology in a 12U configuration [8,9,10]. The mission is a partnership between NASA Marshall Space Flight Center (MSFC), GRC, and Busek Co. Inc., with the U.S. Air Force supporting the propulsion technology maturation. The iSat mission will use a 200-W iodine Hall thruster propulsion system (Fig. 1) to demonstrate small spacecraft maneuverability and mitigate concerns regarding iodine deposition regardless of spacecraft size. The top-level objectives of the project are focused on validating the use of iodine for future missions while demonstrating high ΔV viability and capability on a secondary small spacecraft. The mission will validate in-space performance of the iodine Hall system, and demonstrate relatively high power and high-power density in a CubeSat form factor.

2. PROPULSION SYSTEMS

Development of iodine Hall thruster propulsion systems is progressing in two parallel and complimentary paths. A flight 200-W propulsion system, which includes the thruster, cathode, PPU, and feed system are in development to support the iSAT mission. A separate technology development effort is underway as part of the STMD Game Changing Development (GCD) program at the 600 W power level to examine the scale up potential of iodine. The 600-W system is not currently intended for flight but will leverage the lessons from the 200-W system so that it can readily be infused to a mission application.

2.1 BHT-200-I

The iSAT thruster is a derivative of the BHT-200 flight thruster (Fig. 2). The BHT-200 was the first American Hall effect thruster flown in space and was launched in 2006 as a part of the TacSat-2 project. The thruster has been studied extensively and provides a good benchmark for comparing performance variances from the iodine version of the thruster—the BHT-200-I. The iodine thruster is distinguished from the nominal BHT-200 by the materials of construction, geometry of the anode,

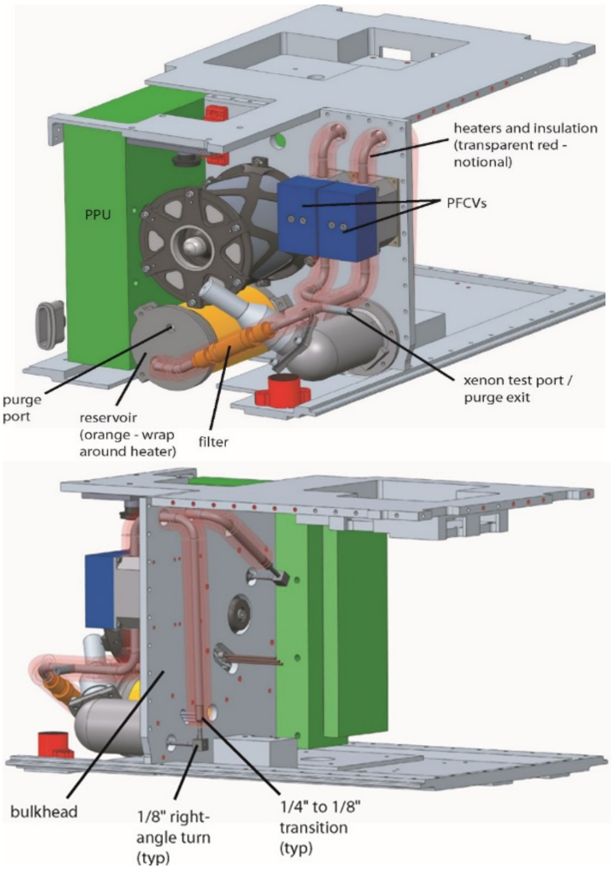

Figure 1. Current layout of the 200-W iodine propulsion system on the iSAT spacecraft. Top: External view of the propulsion system integrated into the iSAT spacecraft. Bottom: Internal view showing the propulsion feed system routing.

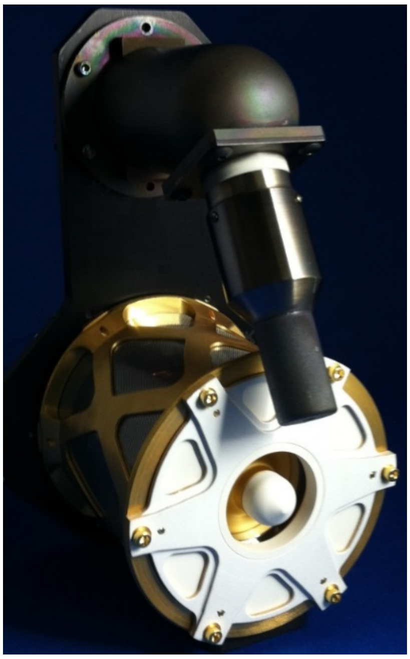

Figure 2. Iodine-fueled BHT-200-I thruster and cathode flight configuration.

and iodine-resistant coatings. The anode and gas flow lines are made from a nonmagnetic, iodine-resistant alloy. The propellant voltage isolator is made from iodine-resistant metals and brazes. The gas distributor was also completely redesigned to allow use of multiple materials.

2.2 BHT-600-I

The BHT-600 (Fig. 3) is a single stage Hall thruster designed to operate at a nominal discharge power of 600 W. The 600-W thruster is well sized for satellite station keeping and orbit maneuvering, either by itself or within a cluster. It also enables an integrated propulsion and power bus that could support both Earth centric and interplanetary missions. The discharge channel exit rings are made of boron nitride. The hollow cathode is located distal to the discharge. A high-voltage ceramic break electrically isolates the anode from the propellant line.

2.3 Cathode

Cathode activities have been focusing on cerium hexaboride, LaB_6 (Fig. 4.), and heaterless electride (Fig. 5) configurations. Key challenges to development of a cathode include the high ignition temperatures required and the impact of those temperatures on materials compatibility with iodine. Busek has demonstrated operation of an iodine LaB_6cathode for short duration [10] with iodine. However, long duration operation is required to avoid the additional complexity of implementing a xenon-cathode dual-propellant system. While a dual-propellant system may be acceptable at high power, the dual propellant with high-pressure xenon could eliminate the ability to deploy iodine Hall systems on low-cost small satellites. Multiple cathode design and emitter inserts have been evaluated with a down select planned for an option that provides the highest lifetime potential.

2.4 Power Processing Units (PPUs)

The initial plan was to develop a modular system that would scale from the 200 to 600 W. However, as more detailed requirements were developed for iSAT, this resulted in a configuration change requiring the development of separate units. The iSAT 200-W PPU includes a new topology for compact design. Both the 200- and 600-W PPUs have the same power requirements for operating a xenon thruster and can be used for future xenon mission applications. The iSAT 200-W PPU is also designed to include control of the feed system components described below. The intended functionality includes control of independent heater zones for the propellant lines, the tank heater, temperature sensors, and pressure transducers

Figure 3. BHT-600 engineering model.

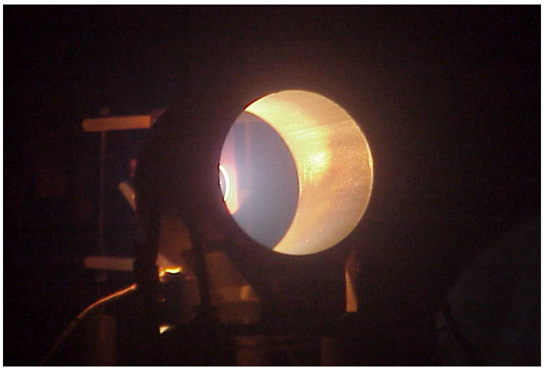

Figure 4. LaB_6 I_2 cathode discharging to anode.

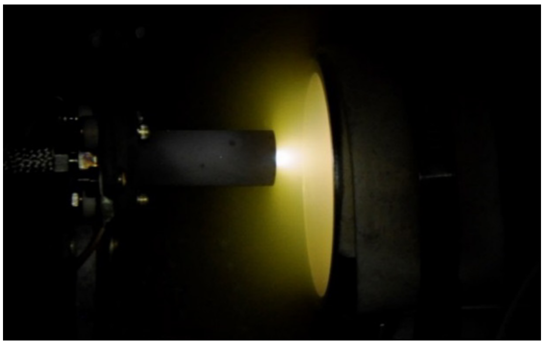

Figure 5. Calcium aluminate electride hollow cathode.

while also performing onboard closed loop flow control based on either discharge current or a pressure measurement. The PPU will use an RS422 interface, accept an input voltage range from 24 to 36 V, and leverage field programmable gate array-based control of outputs and telemetry.

2.5 Feed System

The iodine feed system [11] is designed similarly to the Advanced Xenon Feed System [12]. The core of the flow control is a pair of parallel flow paths with VACCO Industries proportional flow control valves (PFCVs). The new iodine PFCVs have been modified from the xenon qualification PFCV design to reduce the pressure drop, add internal heaters and temperature sensors, and change materials for iodine compatibility. NASA MSFC has been leading the iSAT mission feed system design, the lessons from which will be applicable to all scales of future iodine-based Hall thruster systems.

Traditional Hall feed systems rely on high pressures to ensure adequate mass flow to the cathode and thruster, and are mostly unaffected by gas buildup and small pressure drops in the lines. A low-pressure system, however, is very sensitive to all pressure differences, which can serve to overwhelm the tank pressure and prevent adequate flow or cause the flow to reverse. Designing a low-pressure sublimation-driven propellant feed system requires careful consideration of line pressure as well as design sensitivity to several factors, including temperature, physical line dimensions, filter choice, and tube materials. Both modeling and experiment characterization for the feed system design is continuing.

3. PROPULSION SYSTEM TESTING

NASA GRC is performing integrated tests of Busek's engineering model (EM) BHT-200-I and BHT-600-I iodine Hall thrusters. The Hall thrusters designed and manufactured by Busek will be tested at NASA GRC with GRC-designed iodine feed systems to assess the performance of the Hall thrusters, validate the design changes incorporated in the thrusters for iodine compatibility, and assess the lifetime capability of the thrusters.

This section summarizes the upgrades performed on one NASA GRC vacuum facility to make it iodine compatible and summarizes results from duration tests of the EM BHT-200-I and BHT-600-I thrusters.

4. NASA GRC VACUUM FACILITY 7

Propulsion system testing is being performed in GRC's Vacuum Facility 7 (VF–7) (Fig. 6)—an oil diffusion pump-evacuated facility that is 10 ft (3 m) in diameter and 15 ft (4.6 m) long.

The facility has been modified for compatibility with iodine propellant. During nominal operations V–F7 can reach base pressures down to 2x10^{-7} torr.

Currently, liquid nitrogen cooled chevrons are used to collect the expelled iodine propellant during thruster firing. After test completion, specially installed heating lamps are used to elevate the chevron temperatures to facilitate iodine propellant venting. A specially installed pumping train is used to exhaust the iodine propellant. In the near future a newly constructed cryotarget (shown in Fig. 6 bottom) will be installed to serve as a beam dump for the iodine plume.

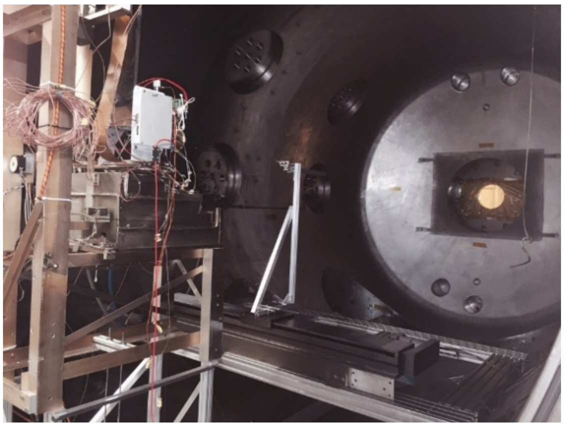

Figure 6. (Top) VF–7 10-ft (3-m) diameter facility will be used for long duration thruster tests and plasma diagnostics development and tests. (Bottom) Cryogenic-cooled iodine collection chevrons.

4.1 Inverted Pendulum Thrust Stand

A Null-type water-cooled inverted pendulum thrust stand [13] was implemented during thruster performance evaluation. The power cables were fed from the vacuum feed through to the thruster using a "water fall" configuration to minimize thermal drift of the thrust stand readings. In situ thrust stand calibrations were performed prior, during, and after thruster testing. The thruster was also periodically turned off during testing to measure the thrust stand thermal drift magnitude. Corrections were incorporated into the reported thrust data. Thrust measurement uncertainty was estimated at 2% of measured value.

5. THRUSTER PERFORMANCE AND DURATION TEST

5.1 BHT-200-I

The BHT-200-I EM thruster has undergone an 80-hr duration test in VF–7 (Fig. 7). The duration test is used to validate the design modifications of the EM thruster prior to building the qualification and flight model thrusters, map the performance of the thruster with both xenon and iodine over the thruster throttling range, map the plume of the thruster throughout the test duration, measure and record temperatures of selected thruster and feed system components for thermal model validation, and demonstrate robust and reliable iodine feed system components operation. Figure 8 presents a layout of the iodine feed system employed in this test campaign. The feed system setup allows the option of operating the thruster with xenon or iodine propellants. Xenon propellant operation is attained by opening solenoid valve S1 and closing solenoid valves S2 and S3 and also closing the PFCV. For iodine thruster operation, all solenoid valves are closed (S1, S2, and S3) and the PFCV is opened. The thruster's Busek barium oxide impregnated porous tungsten cathode was operated with xenon propellant. A MSFC-designed control board was used to control the PFCV and to power to the iodine tank heaters.

The thruster performance was baselined with xenon propellant. The measured thruster performance with xenon matched levels reported earlier by Busek. Next the thruster was operated with iodine propellant. The iodine tank temperature was set to approximately 90 ºC. The PFCV and propellant line temperature was set to approximately 110 ºC. For this test the iodine feed system was instrumented with seven thermocouples that included thermocouples on the PFCV, tank, filter, and propellant lines. The thruster was instrumented with six thermocouples that were placed on the inner electromagnet, propellant isolator, outer front pole, back pole, and thruster housing. In addition, optical probes were used to record the emission spectra of the thruster plume. After the prescribed iodine tank and propellant line temperatures were achieved, iodine propellant was introduced to the thruster by opening the PFCV. The PFCV applied voltage was varied to adjust the iodine flow rate until the desired discharge current was achieved. Figure 9 shows the thruster operating on iodine with the cathode operating on xenon.

The 80-hr thruster "on" duration was attained over 6 days of testing. Figure 10 presents the discharge current and voltage profiles during the test. The thruster was operated at a discharge voltage of 250 V

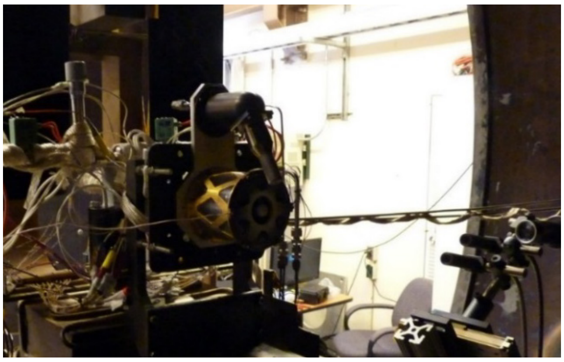

Figure 7. BHT-200 thruster and iodine feed system installed on the inverted pendulum thruster stand in VF–7. Optical probes are to the right of picture.

with a target discharge current of 0.8 A resulting in a thruster discharge power of 200 W. The xenon-propelled cathode was operated with a keeper current of 0.5 A. No closed-loop control on the PFCV was set up for this test, as such the thruster shutdowns occurred when the thruster discharge current drifted outside the limits set by the test operator. During day 2 of the duration test it was observed that the PFCV failed to close completely and iodine would flow through the PFCV even when it was commanded closed. Unfortunately, the inability to fully close the PFCV valve created uncertainty in the total iodine flow rate during thruster operation thus prohibiting an accurate calculation of the thruster's thrust efficiency and specific impulse. After test completion an investigation was performed to uncover the reasons for the PFCV failure. The root cause was found and Gen2 PFCVs are being designed and manufactured to preclude any future valve failure due to iodine exposure. The Gen2 PFCVs will be delivered in the fall of 2016 and incorporated in the integrated test of the qualification model BHT-200-I thruster.

Table 1 lists the thruster's thrust levels with xenon and iodine propellant at the beginning and end of the 80-hr test. Results in Table 1 indicate an almost identical thruster performance. For the 80-hr test approximately 300 g of iodine was consumed during the test as determined by measuring the iodine tank mass before and after the test. However, due to the PFCV failure not all the iodine propellant was exhausted during thruster operation.

Table 1 BHT-200-I thrust levels at the beginning and end of the 80-hr duration test.

	0-hr		80-hr	
	Xenon	Iodine	Xenon	Iodine
Discharge Voltage, V	250	250	250	250
Discharge Current, A	0.81	0.83	0.80	0.84
Thrust, mN	12.9	14.2	13.2	13.9

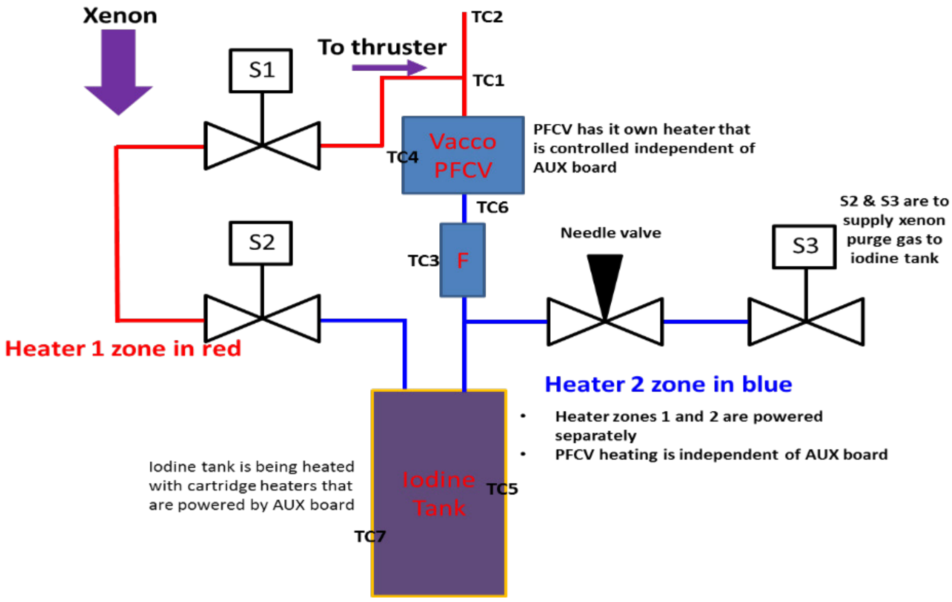

Figure 8. Iodine propellant feed system schematic showing the various components and thermocouple locations.

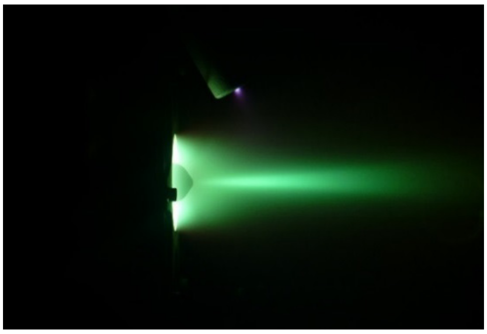

Figure 9. Photograph of the BHT-200 thruster operating with iodine and cathode operating on xenon.

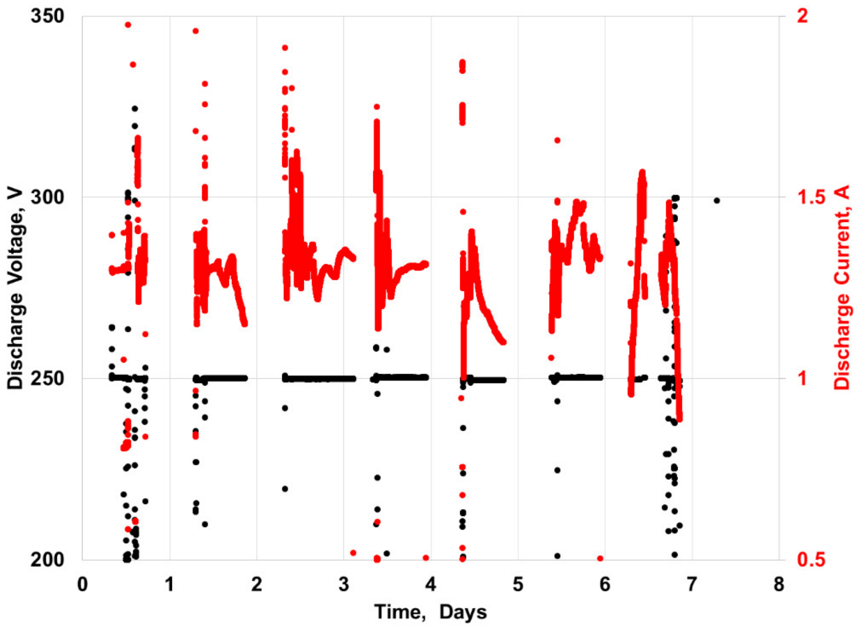

Figure 10. BHT-200-I discharge current and voltage profiles during the 80-hr test.

Detailed inspection of the BHT-200-I thruster was performed after removal of the thruster from VF–7. Photographic documentation of the thruster was performed at NASA GRC and the thruster was then returned to Busek for disassembly. Detailed inspection and documentation of the various thruster components including the propellant manifold assembly, magnetic circuit components, propellant isolator, and various component coatings was performed. Busek's detailed inspection revealed that the thruster's components did not show any evidence of degradation due to iodine exposure.

5.2 BHT-600-I

The BHT-600-I thruster was also tested at NASA GRC VF–7. The main objectives were to evaluate the performance of the thruster with both xenon and iodine propellants and perform duration tests with iodine propellant to uncover any degradation or change in thruster performance or components conditions due to extended exposure to iodine propellant. Two tests were performed with Test 1 taking 34 hr and Test 2 taking 46 hr in duration.

Test 1 was an attended test that utilized the same iodine feed system shown in Figure 8. The cathode assembly used in this test was a cerium hexaboride assembly developed by Busek and the cathode was operated on xenon propellant. Prior to testing with iodine, the thruster performance was baselined with xenon propellant. Thruster tests with xenon were performed at discharge power levels of 200, 300, 400, 500, and 600 W at discharge voltages of 200, 250, and 300 V. Then the thruster operation was transitioned to iodine propellant and the thruster was continuously operated for approximately 34 hr. Most of the thruster operation was performed at a discharge voltage of 300 V and a discharge current of 2 A. After exhausting all the iodine in the tank (~300 g), the thruster performance was re-evaluated with xenon propellant and test results indicated no change in the xenon thruster performance. Table 2 presents a summary of the thrust levels with xenon and iodine propellants at the beginning and end of the test.

Table 2 BHT-600-I thrust levels at the beginning and end of Test 1 (34-hr duration) with xenon and iodine propellants.

	0-hr		34-hr	
	Xenon	Iodine	Xenon	Iodine
Discharge Voltage, V	300	300	300	300
Discharge Current, A	2.0	2.0	1.98	2.0
Thrust, mN	38.4	39.2	38.4	~38.0

Test 2 was an unattended duration test. The feed system in this test campaign was a modified version of the feed system shown in Figure 8. The purge valves (S2 and S3) and two PFCV were removed. The PFCV was removed to undergo failure analysis at VACCO and the two purge valves were removed to eliminate any iodine flow paths where iodine loss could occur. In addition, the cathode unit utilized a barium oxide impregnated porous tungsten emitter. As with Test 1, the cathode was operated with xenon first and then iodine testing was initiated. Test 2 was run continuously and the test lasted for approximately 46 hr in duration. During the test the thruster was operated at a discharge voltage of 300 V with a discharge current target value of 2 A. Thermal throttling of the iodine tank temperature was the method used to try and regulate the iodine flow rate. As such the discharge current magnitude was mostly maintained around 2 A and started to drop towards the end of the test as the iodine propellant was depleted. After exhausting the iodine propellant, the thruster performance was again baselined with xenon propellant and results indicated an almost identical thruster performance when compared to start of the test. Results from Tests 1 and 2 are still being analyzed and will be presented at the 2016 AIAA Propulsion and Energy Conference.

6. FUTURE ACTIVITIES

Near-term future activities include additional tests of the EM BHT-200-I and BHT-600-I thrusters and standalone tests of iodine-compatible cathode and propellant isolators. The tests include

1. Performing additional duration tests of the BHT-600-I that will incorporate more advanced diagnostics, including a Fast Camera and a Faraday probe.
2. Performing standalone propellant isolator tests in a smaller iodine-ready vacuum chamber.
3. Performing standalone tests of iodine-compatible cathode assemblies. Busek and NASA GRC designed and manufactured cathode assemblies will be evaluated with iodine propellant and down selected promising assemblies will be duration tested.
4. Performing an integrated test of the EM BHT-200-I with an iodine-compatible cathode assembly. In this test both the thruster and cathode will be operated on iodine propellant. This test layout will incorporate two modified Gen 1 PFCVs and the feed system layout will be very similar to the iSAT spacecraft iodine feed system layout. This test will entail performing cycle tests on the BHT-200-I

thruster to simulate its operation on the iSAT spacecraft.
5. Implement additional upgrades to VF7 to reduce operation costs and enhance complete iodine removal after tests.
6. Perform an integrated test of the qualification model BHT-200-I thruster with the iSAT qualification iodine feed system.
7. Perform an integrated test of the BHT-600-I thruster with the PPU being developed by Busek.
8. Perform an extended duration test of the BHT-600-I thruster, time duration TBD.

7. SUMMARY

Due to the potential spacecraft and mission advantages, NASA is moving forward with development of Hall thrusters operating on iodine. The team of NASA Glenn Research Center, NASA Marshall Space Flight Center, and Busek Co. Inc. are working on both a flight mission and power level scale up designs with the work focused on qualification of the Busek 200-W BHT-200-I and development of the 600-W BHT-600-I systems. To date two series of 80-hr tests have been conducted at NASA GRC on the BHT-200-I and BHT-600-I. In each series of tests the performance was consistent with previous observed results and in-line with operation on xenon. Post inspection of the thrusters did not show any significant physical changes after operation with iodine. Future activities will focus on flight qualification of the BHT-200-I system including integrated testing on iodine with the feed system, cathode and power processing unit. Technology development will continue with the BHT-600-I to examine iodine operations at higher power, including planned extended duration testing with an engineering model propulsion system.

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