# Propulsion System Development for the Iodine Satellite (iSAT) Demonstration Mission

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**The development and testing of a 200-W iodine-fed Hall thruster propulsion system that will be flown on a 12-U CubeSat is described. The switch in propellant from more traditional xenon gas to solid iodine yields the advantage of high density, low pressure propellant storage but introduces new requirements that must be addressed in the design and operation of the propulsion system. The thruster materials have been modified from a previously-flown xenon Hall thruster to make it compatible with iodine vapor. The cathode incorporated into this design additionally requires little or no heating to initiate the discharge, reducing the power needed to start the thruster. The feed system produces iodine vapor in the propellant reservoir through sublimation and then controls the flow to the anode and cathode of the thruster using a pair of proportional flow control valves. The propellant feeding process is controlled by the power processing unit, with feedback control on the anode flow rate provided through a measure of the thruster discharge current. Thermal modeling indicates that it may be difficult to sufficiently heat the iodine if it loses contact with the propellant reservoir walls, serving to motivate future testing of that scenario to**

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**verify the modeling result and develop potential mitigation strategies. Preliminary, short-duration materials testing has thus-far indicated that several materials may be acceptable for prolonged contact with iodine vapor, motivating longer-duration testing. A propellant loading procedure is presented that aims to minimize the contaminants in the feed system and propellant reservoir. Finally, an 80-hour duration test being performed to gain experience operating the thruster over long durations and multiple restarts is discussed.**

## Nomenclature

| | |
|---|---|
| $\mathbf{B}$ | = magnetic induction (T) |
| $C$ | = capacitance (F) |
| $\mathbf{E}$ | = electric field (V/m) |
| $I_{\text{sp}}$ | = specific impulse (s) |
| $L$ | = inductance (H) |
| $R$ | = resistance ($\Omega$) |
| $V_d$ | = thruster discharge voltage (V) |
| $\Delta v$ | = velocity increment for performing a given mission (m/s) |
| $\rho$ | = density (kg/m$^3$) |

## I. Introduction

CubeSats are relatively new spacecraft platforms that are typically deployed from a launch vehicle as a secondary payload,[1] providing low-cost access to space for a wide range of end users. These satellites are comprised of building blocks having dimensions of 10x10x10 cm$^3$ (a 1-U size). While providing low-cost access to space, a major operational limitation is the lack of a propulsion system that can fit within a CubeSat and that is capable of executing high $\Delta v$ maneuvers. This makes it difficult to use CubeSats on missions requiring certain types of maneuvers (i.e. formation flying, spacecraft rendezvous).

While electric thrusters typically provide high specific impulse, there are several challenges associated with integrating into a CubeSat platform an electric propulsion system with enough propulsive utility to enable various missions of interest. The power requirements of small or scaled-down electric thrusters are often still greater than the steady-state power levels a CubeSat can provide. Packaging of an electric thruster is also difficult owing to the occupied volume and inherent mass of the thruster system [thruster, tankage and valves, power processing unit (PPU)]. Thermal issues can arise as the thruster dissipates power during operation, potentially radiating that power as heat to other, more temperature-sensitive systems in the spacecraft. Finally, while many electric thrusters operate on gaseous propellants stored in tanks at high pressure, CubeSats are often launched as secondary payloads where high pressure systems are typically not permitted by the primary payload launch customer.

As an alternative to the storage of a high-pressure gaseous propellant, recent work has been performed investigating the use of iodine as a propellant for Hall-effect thrusters (HETs).[2] The iodine satellite (iSAT) mission (see spacecraft view in Fig. 1), is being assembled as a flight test demonstration of an iodine-fed Hall thruster. Iodine stores as a dense solid at low pressure making it acceptable as a secondary payload thruster propellant. It has exceptionally high $\rho I_{\text{sp}}$ (density times specific impulse) making it a densely-packaged enabling technology for small satellite near-term applications and providing the potential for systems-level advantages over mid-term high-power electric propulsion options. Iodine flow can be thermally regulated, subliming at relatively low temperature ($< 100$ °C) to yield $I_2$ vapor at or below 50 torr (see Fig. 2).[3,4] At low power, the measured performance of an iodine-fed HET is very similar to that of a state-of-the-art xenon-fed thruster. Just as importantly, the current-voltage discharge characteristics of low power iodine-fed and xenon-fed Hall thrusters are remarkably similar, potentially reducing development and qualifications costs by making it possible to use an already-qualified xenon-HET PPU in an iodine-fed system. Finally, a cold surface can be installed in a vacuum test chamber on which expended iodine propellant can deposit. Referring to Fig. 2, the temperature doesn't have to be extremely cold to maintain a low vapor pressure in the vacuum chamber (under $10^{-6}$ torr at $-75$ °C), making it possible to 'cryopump' the propellant with lower-cost recirculating refrigerant-based systems as opposed to using liquid nitrogen or very low temperature gaseous helium cryopanels.

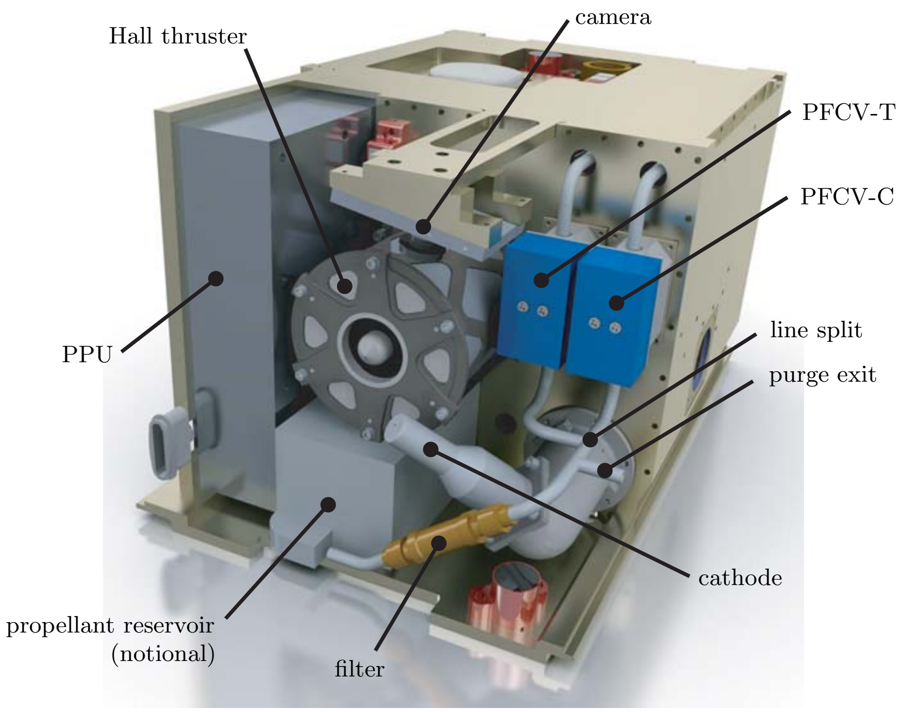



**Figure 1. Aft view of the iSAT spacecraft (shown without solar arrays).**

An iodine-based system is not without its challenges. One such challenge is that the entire feed system must be maintained at an elevated temperature to prevent iodine vapor from redepositing (transitioning from the gas phase back into the solid phase), a process that results in a blocked propellant feed line. Furthermore, deposition will occur if the temperature anywhere within the lines is less than the temperature of the propellant reservoir.

The iSAT flight-demonstration mission aims to fly a 200-W iodine-fed Hall thruster in space. The iSAT spacecraft consists of a 12-U CubeSat that will be launched as a secondary payload. In this paper, we describe the various propulsion system components that will be assembled to form the complete iSAT propulsion system and the work performed to understand how the system will react in the relevant environment. Emphasis is placed on the design constraints imposed by the CubeSat platform (e.g. size, power) and the challenges introduced by the use of iodine as a propellant. In Section II the various components that comprise the propulsion system will be described. Results of thermal modeling of the present propellant tank design are presented in Section III. Data on iodine compatibility with other materials are presented in Section IV. Finally, in Section V we discuss how the iodine propellant tank will be loaded and the near-term test plans for the propulsion system.

## II. iSAT Propulsion System Overview

The primary components of the iodine Hall thruster propulsion system are labeled in Fig. 1. Most of the propulsion system components are mounted to a plate and face the aft-end of the spacecraft, external to an enclosure containing the remaining spacecraft components. This has been done to protect the spacecraft hardware from the heat of the propulsion system and to exclude iodine vapor from the spacecraft interior. The propellant and power feeds and part of the power processing unit (PPU) must penetrate this bulkhead as shown in Fig. 3 to allow for connections to the thruster and cathode. The overall size of the PPU also necessitates its penetration through the bulkhead.

During operation, the propellant tank and lines are heated to their respective operating temperatures. Iodine is sublimed in the propellant tank and passes through a filter before reaching a split in the feed line. This allows for a common propellant tank to feed gaseous iodine to both the cathode and anode. The flow in each branch is controlled using a proportional flow control valve (PFCV). Power for operation of the thruster

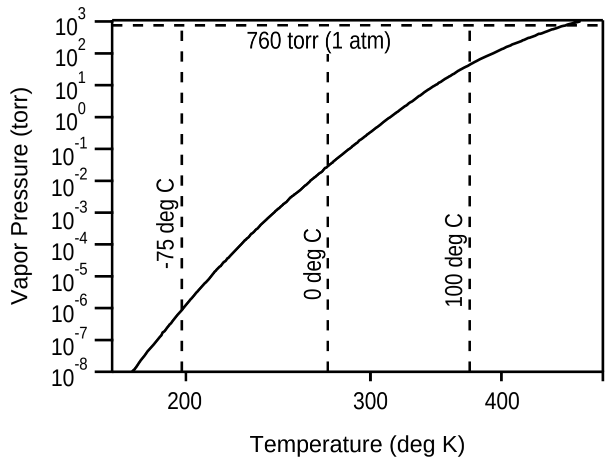



**Figure 2. Vapor pressure curve for molecular iodine ($I_2$). After Refs. [3, 4].**

and cathode, as well as feed system control functionality, are provided by the PPU. In the remainder of this section, the components that are assembled to yield the complete propulsion system are described in more detail.

## A. Thruster

The thruster for the iSAT mission is a version of the xenon-fed Busek BHT-200 HET that has been modified for compatibility with iodine propellant (the BHT-200-I, shown with a cathode in Fig. 4a). The xenon-fed BHT-200 became the first American HET to fly in space when it was launched in 2006 as part of the US Air Force TacSat-2 satellite.[5]

A HET uses crossed electric and magnetic fields to generate and accelerate ions. The overall structure of the BHT-200 is defined by a magnetic circuit that produces a steady magnetic field, $\mathbf{B}$ , that is nominally directed radially across an annular channel. Neutral propellant is introduced to the gas distributor at the base of the channel. The downstream portion of the channel is formed from a dielectric material, between which the bulk of the plasma discharge occurs. A potential difference $V_d$ is applied between the anode and a hollow cathode located outside the channel. The resulting electric field $\mathbf{E}$ is predominantly axial and is concentrated near the channel exit by the interaction of the applied magnetic field and the plasma. In ground testing, the cathode potential is typicaly permitted to float with respect to facility ground.

In the discharge channel, electrons are strongly magnetized and their transport is predominantly azimuthal due to the Hall effect. The extended electron path enables an efficient, impact-driven ionization cascade. Ions are weakly magnetized and most are accelerated directly out of the channel by the electric field, producing a collimated ion beam. The iodine plume from an experimental version of the BHT-200 is shown in Fig. 4b.

Laboratory testing conducted with the BHT-200 and other even higher power thrusters has shown that at the same discharge potential and power the thruster efficiency is almost identical between xenon and iodine propellants.[2,6,7] Beam ion current measurements have demonstrated a lower plume divergence angle for iodine relative to xenon.[2,7] Other measurements have shown that the iodine ion velocity distribution and composition by species vary with proximity to the beam centroid and thruster exit.[8] Iodine deposition upon spacecraft surfaces is not expected owing to the high vapor pressure of $I_2$ at the expected spacecraft temperatures.[7,9]

## B. Cathode

The cathode in a HET performs two separate functions. Some of the cathode-produced electrons follow a path into the discharge channel, initially forming and then sustaining the plasma. However, most cathode-produced electrons perform the equally important task of following the ions accelerated out of the thruster, serving to neutralize the exhaust.

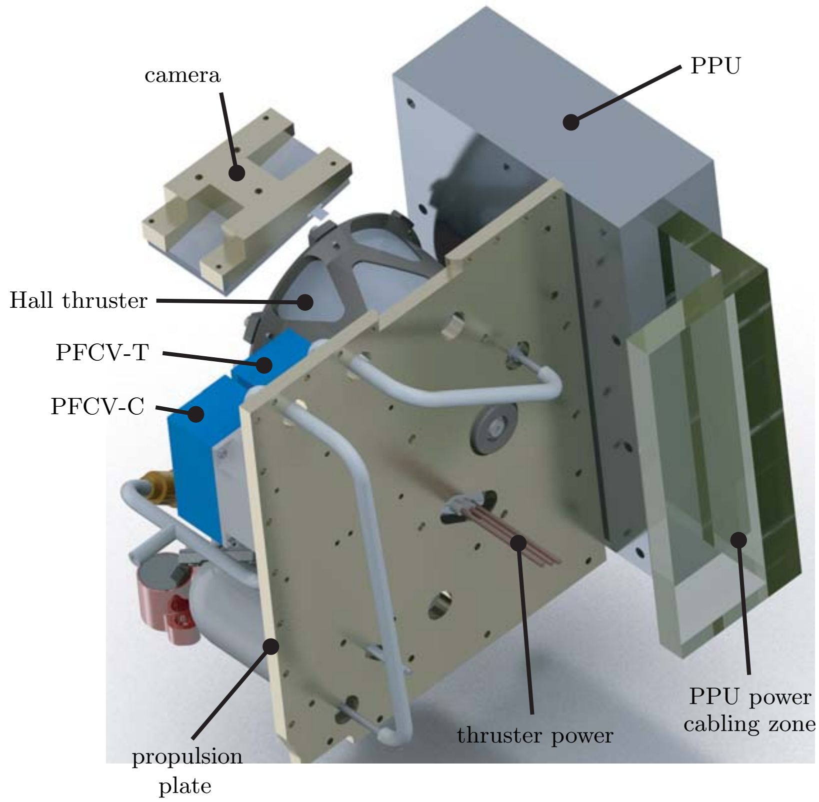



**Figure 3. Cutaway view of the iSAT spacecraft showing the feed system tubing as it penetrates the thruster plate bulkhead.**

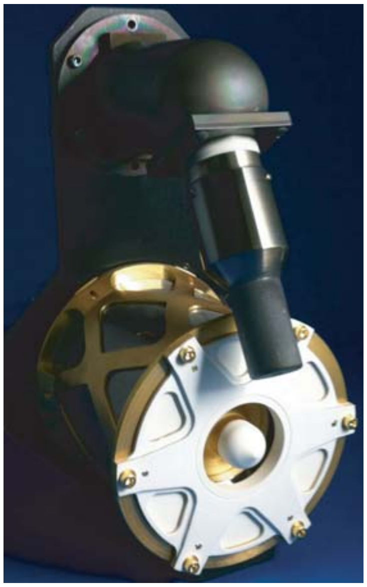
For the xenon-fed BHT-200 flight model thruster there was a xenon-fed hollow cathode with a BaO-W emitter. However, as this emitter material is incompatible with iodine, other alternatives have been explored for the iSAT mission. The baseline plan for the BHT-200-I is for neutralization to be accomplished using an iodine-fed hollow cathode that has a $12CaO\text{-}7Al_2O_3$ electride emitter.[10] The systems-level advantage of this particular emitter is that the cathode discharge can be initiated with little or no heating, yielding a power savings over more standard Hall thruster cathodes that employ a BaO-W or $LaB_6$ emitter material. In terms of materials compatibility, $LaB_6$ has also been successfully operated on iodine vapor, so it could be used as a cathode on future iodine-fed missions, but at the price of requiring more power to initiate a discharge.

## C. Power Processing Unit

The power processing unit (PPU) will not only provide power to the thruster and cathode, but it is also planned that it will power the feed system heaters and operate the valves to control the flowrate. In addition, it will be capable of monitoring the propulsion system and providing data to the flight computer that can be transmitted back to the ground for additional post-processing.

The requirements on the PPU concerning the operation of the thruster are as follows.

- Provide power for the main discharge, the magnet circuit, and cathode operation.
- Accept input power at a voltage of 28 $(+6/-4)$ VDC.
- Have a peak total efficiency objective of $> 90\%$ for 200W thruster operation.
- Include the capability to change polarity on the magnet circuit.
- Have the capability to ignite an electride cathode with an objective to achieve cathode ignition without heater power.



a)

b)

**Figure 4. a) Iodine-fed BHT-200-I. b) Iodine plasma plume from 200 V discharge.**

- Include the capability to provide heater power to condition and start a cathode.

To support laboratory testing, control and monitoring of the propellant feed system has been accomplished using a separate auxiliary control board, which is discussed in this paper in Sect. II.D.2 and has previously been described in Ref. [11]. In the actual spacecraft, it is planned for these functions to be incorporated within the PPU, allowing for the PPU to control the feed system just as it does in a xenon-fed Hall thruster. The feed system control and monitoring functions the PPU will perform are:

- Operating at least one Vacco latch valve and at least two piezoelectric PFCVs, including providing power for the internal valve heaters and monitoring the thermistors within the valves.
- Providing the functionality to perform closed-loop control of flow, adjusting the piezoelectric PFCVs based on a measure of the discharge current.
- Monitoring at least four (4) temperature sensors, with a goal of monitoring ten (10).
- Monitoring at least one (1) pressure transducer, with a goal of monitoring three (3).
- Possessing a heater control unit that can operate four (4) independent heater 'zones', providing heat to the propellant tank and feed system lines.

We note that the iSAT design presently contains no latch valve or pressure transducers. However, in the future a 200-W iodine-fed HET on a different spacecraft may require these capabilities, so they are being included in the PPU to make the design and functionality extensible to other spacecraft and missions.

### D. Feed System

The propellant feed system for the iSAT iodine-fed HET consists of several components, as illustrated schematically in Fig. 5. The tubing consists of 6.35 mm (quarter-inch) diameter Hastelloy c276 and is welded throughout. Hastelloy has been selected owing to its high corrosion resistance when exposed to iodine vapor. The filter is a Swagelok model HC-4F2-40 fabricated from Hastelloy with a 40 micron pore size. There are two Vacco PFCVs, providing control of the flow to the cathode and the anode. The propellant tank is an in-house design containing approximately 0.7 kg of iodine (roughly equal to the amount required to provide 1 km/s $\Delta v$ to the spacecraft) with a starting ullage volume consisting of 20% of the reservoir.

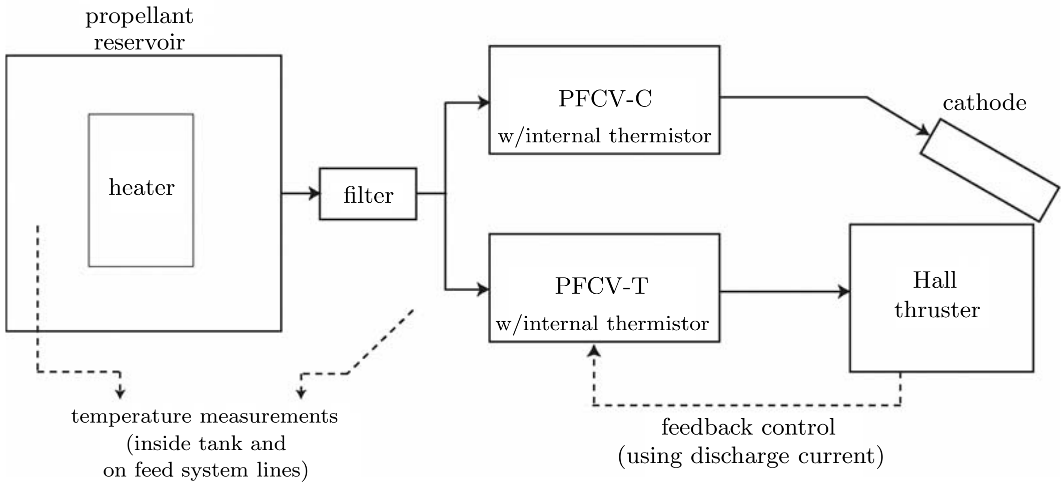



**Figure 5. Schematic illustration of the components comprising the iSAT propellant feed system.**

### *1. Valves*

The PFCVs are included in the system to provide rapid adjustment and control of the propellant flow rate to both the anode and cathode. The flow rate can be controlled by adjusting the heating applied to the reservoir, but as with any thermal control system this process exhibits a relatively slow response to changes in the heating rate.[11] The PFCVs adjust the flow rate very quickly, permitting dynamic control of the propellant flow rate without having to constantly adjust the temperature of the propellant reservoir. The PFCV is internally heated to maintain the wetted surfaces at a temperature greater than the deposition temperature of the gas and they are equipped with tube stubs of Hastelloy c276, permitting them to be welded to the propellant feed lines. It is planned that these valves will provide the means to isolate the propellant reservoir from the thruster and cathode prior to in-space operation. While not presently in the baseline iSAT design, an option under consideration is to include 40 micron filters within the PFCVs, obviating the need to have a large filter in the line upstream of the PFCVs. The specifications for the PFCV are given in Table 1.

**Table 1. Specifications for the proportional flow control valve.**

| | |
|---|---|
| Mass | $< 250$ g |
| Volume | $< 100$ cm$^3$ |
| Voltage | 0-130 VDC (adjustable) |
| Power | 5.2 $\mu$W at 22 deg C |
| Proof Pressure | 35 psig GHe, 5 mins |
| External Leakage | 20 psig GHe, 6 mins, $6.8\times10^{-9}$ sccm |
| Internal Leakage | 20 psig GHe, 6 mins |
| | none indicated at 22 and 150 deg C |
| Flow Capacity | 20 psid GHe, 130 VDC applied |
| | 27,448 sccm at 22 deg C |
| | 19,664 sccm at 150 deg C |

### *2. Feed System Control Electronics*

An auxiliary control board and auxiliary power distribution card (shown schematically in Fig. 6) were designed and fabricated to support development of the feed system and to test the control circuitry that would be needed to control and monitor all the items that comprise the feed system. As mentioned in Sect. II.C, it is anticipated that most if not all of these functions will be integrated into the flight PPU. The functionality of this design has been demonstrated in vacuum and in the presence of an operating thruster. We provide in this section a brief description of that functionality.

The auxiliary control board has previously been described in Ref. [11]. It has been developed to operate a Vacco latch valve, up to two (2) PFCVs, and heaters for the reservoir, feed lines and valves. It also is used to measure feed system pressures, temperatures, and the actual applied voltage to the PFCVs. An onboard field-programmable gate array (FPGA) provides a serial link to accept commands and handle all lower level input/output functions.

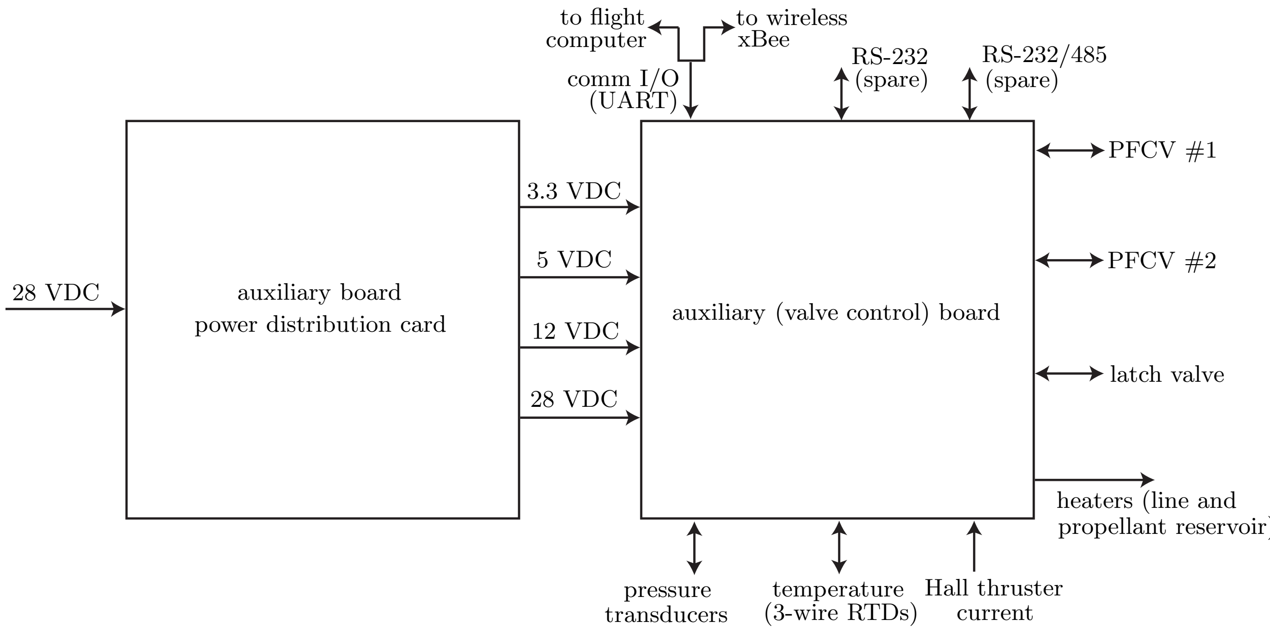



**Figure 6. Schematic representation of the auxiliary valve control and power distribution boards.**

The auxiliary power distribution card accepts an input of 28 VDC from the spacecraft and converts that into outputs of 3.3, 5, 12, and 28 VDC with a ripple voltage of less than 3%. These are the voltage levels required for operation of the auxiliary control board. The voltage conversion is accomplished using VPT DC/DC converters. The triple output converter containing the 3.3, 5, and 12 VDC buses was found to have an output ripple higher than 3%, so an $LCR$ filter was incorporated into the 3.3 and 5 VDC outputs to dampen this effect. While in laboratory experiments the ripple could be dampened using only an output capacitor, a full $LCR$ filter was implemented in case more robust filtering was required once the system was integrated with the thruster. As this card was only required to support development testing, no communication protocols were implemented in the design.

## III. Thermal Modeling

Thermal modeling of the propellant reservoir was performed to determine how long it would take for iodine to be heated to operating temperature (the temperature required to produce enough vapor pressure to operate the thruster). This modeling was performed for the worst case scenario where solid iodine had detached from the sides of the reservoir and was floating in the middle of the cylindrical reservoir, having no contact with the walls. The geometry of the propellant reservoir is that of a cylinder with a height of 85.5 mm, an outer radius of 31.75 mm, and a wall thickness of 0.7874 mm. A solid cylinder consisting of 100 g of iodine is assumed to be floating in the center of the reservoir, equidistant from all sides of the container. The insulation is modeled as a single layer that adheres perfectly to the reservoir and has a thickness of 1 mm. The material properties used to model the propellant reservoir, iodine propellant, and insulation are found in Table 2

The model is created in Thermal Desktop 5.6 and analyzed using SINDA/FLUINT 5.5 (both by C&R Technologies, Inc., Boulder, CO). The reservoir is assumed to be a closed cylinder with negligible heat loss to the feed system lines and the iSAT spacecraft enclosure. The heaters are modeled as two separate strip

Table 2. **Material properties for the thermal model of the reservoir.**

| component | material | thermal conductivity (W/(m-°C)) | density (kg/m$^3$) | specific heat (J/(kg-°C)) | IR emissivity |
|---|---|---|---|---|---|
| propellant reservoir | titanium | 7.1 @ 25°C | 4428.8 | 539.6 @ 25°C | 0.2 |
| propellant (solid) | iodine | 0.449 | 4940 | 429 | 0.8 |
| propellant (gaseous) | titanium | 0.004351 | 4930 | 217.6 | – |
| insulation | aluminized black kapton | 0.1557 @ 25°C | 1449.6 | 1001.5 @ 25°C | 0.03<br>**Solar Absorptivity** 0.12 |

heaters, located on the top and bottom of the reservoir. They provide a maximum of 2.88 W of power, cycling on when the temperature is below 90°C and off when the temperature is at or above 100°C. The coldest point on the reservoir is used for the determination on heater cycling.

Two separate cases were modeled for this problem. The first was the case where heat transfer to the iodine was dictated by radiation-only (iodine fully transparent) while the second is where heat is only conducted through the iodine vapor (iodine fully opaque). These two cases should serve to bound the answer to the question of whether sufficient heat can be transferred to a floating iodine block to raise its temperature to the point where the iodine will sublime at the rate required to support feed system operation. For the first case (iodine fully transparent) it requires roughly 1.5 orbits to heat the iodine cylinder to 100°C, which potentially manageable for the mission. However, in the second case (iodine fully opaque) it is estimated that the iodine will only reach operational temperature after roughly 9 orbits (estimated based upon heating rate after 3 orbits). Unlike the first case, this is completely untenable for the iSAT mission. Experimental testing is presently being performed to validate these modeling results and provide data to support an operational mission strategy for heating the reservoir.

## IV. Materials Compatibility and Testing

Work has been undertaken as part of the iSAT project to determine the effects of iodine exposure on materials used in the construction of the spacecraft, including the thruster and propellant feed system. A literature search resulted in the compilation of qualitative and, in some instances, quantitative data documenting the resistance of various materials to exposure to iodine vapor. These data are presented in Table 3. Iodine typically affects materials by forming surface iodide or iodate compounds. Details on the formation of these compounds are presented in Table 4.

Table 3. **Compilation of literature data on iodine material interaction and compatibility, from Refs. [12-16].**

| Systems | Metal or Alloy | Base Elements | Dry Iodine Vapor @ 25°C | Dry Iodine Vapor @ 100°C | Dry Iodine Vapor @ 300°C, 0.53 atm (Corrosion Rate mm/year) | Dry Iodine Vapor @ 450°C, 0.53 atm (Corrosion Rate mm/year) |
|---|---|---|---|---|---|---|
| **Nickel Alloys** | Pure Nickel | Ni | Resistant | Resistant | 0.27 | 1.2 |
| | Inconel 600 | Ni-Cr-Fe | Resistant | Resistant | 0.107 | 0.54 |
| | Inconel 625 | Ni-Cr-Mo | Resistant | Resistant | 0.057 | No Data |
| | Hastelloy B | Ni-Mo | Resistant | Resistant | No Data | 0.464 |
| | Hastelloy C | Ni-Cr-Mo | Resistant | Resistant | 0.056 | No Data |
| **Noble Metals** | Pure Platinum | Rt | Resistant | Resistant | 0 | 0.006 |
| | Pure Gold | Au | Resistant | Resistant | 0 | 0.024 |
| **Refractory Metals** | Pure Tungsten | W | Resistant | Resistant | 0 | 0.008 |
| | Pure Molybdenum | Mo | Resistant | Resistant | 0.003 | 0.033 |
| | Pure Tantalum | Ta | Resistant | Resistant | 0.005 | 0.88 |
| **Aluminum** | Pure Aluminum | Al | Unusable | Unusable | Unusable | Unusable |
| **Copper Alloys** | Pure Copper | Cu | Resistant | Unusable | Unusable | Unusable |
| | Brass | Cu-Zn | Resistant | Unusable | Unusable | Unusable |
| **Iron Alloys** | Iron, Cast Iron, Steel | Fe | Resistant | Unusable | Unusable | Unusable |
| | 316 Stainless Steel | Fe-Cr-Ni | Resistant | Resistant | 0.4 (Estimated*) | 2.1 |
| | 304 Stainless Steel | Fe-Cr-Ni | Resistant | Resistant | 0.6 (Estimated*) | 3.2 |

* Estimated corrosion rate at 300°C based upon extrapolation from 450°C data.

**Table 4. Compilation of literature data on metal iodide and iodate oxide formations and their melting and decomposition temperatures, from Ref. [17].**

| Element | Primary Iodide Form | Primary Iodide Melting Point (°C) | Metal Iodate Oxide Form | Metal Iodate Oxide Form Melting Point (°C) |
|---|---|---|---|---|
| **Copper** | $Cu_2I_2$ | 605 | $Cu(IO_3)_2$ | decomposes 290 |
| **Zinc** | $ZnI_4$ | 499 | | |
| **Aluminum** | $AlI_3$ | 191 | $AlI_3 \cdot 6H_2O$ | decomposes 185 |
| **Chromium** | $CrI_2$ | sublimate 800 in vacuum | $(Cr(H_2O)_6)I_3 \cdot 3H_2O$ | 41 |
| | $CrI_3$ | sublimate 350 in vacuum | | |
| **Iodine** | N/A | N/A | $IO_2$ | decompose 75-130 |
| | | | $I_2O_5$ | decompose 300-350 |
| **Iron** | $FeI_2$ | 587 | $Fe(IO_3)_3$ | decompose 130 |
| | | | $FeI_2 \cdot 4H_2O$ | decompose 90-98 |
| **Molybdenum** | $MoI_3$ | decompose 927 | | |
| | $MoI_4$ | decompose 100 | | |
| **Nickel** | $NiI_2$ | 797 | $Ni(IO_3)_2$ | |
| | | | $Ni(IO_3)_2 \cdot 4H_2O$ | decompose 100 |
| **Gold** | $AuI$ | decompose 120 | | |
| | $AuI_3$ | | | |
| **Platinum** | $PtI_2$ | decompose 360 | | |
| | $PtI_3$ | decompose 270 | | |
| | $PtI_4$ | decompose 130 | | |

Unfortunately, most of what is known about materials interaction with iodine has been learned from testing under conditions that are far from those that will be encountered in the space environment. Materials testing has been undertaken as part of this project to quantify the effects of iodine vapor on the iSAT spacecraft materials. Two separate types of material tests are being performed.

One test involves active iodine flow, where the materials under test are sealed in a vacuum furnace maintained at elevated temperature (approx. 200°C). In this test, low pressure argon gas is first passed over solid iodine at 80°C. At this temperature, the vapor pressure of iodine is 16 torr. The mixture of argon and iodine at a total combined pressure of 75 torr (about 10% of atmospheric pressure, where roughly 20% of the gas is iodine vapor) is then passed over the test sample before being actively drawn through the system by a vacuum pump. When volatile iodide compounds are formed, surface erosion is maximized by minimizing the partial pressure of the iodine vapor in the vacuum chamber. Of the two types of tests performed the active flow test best simulates space exposure of iSAT materials to iodine vapor from the thruster plume.

The second test uses a static bath where the materials are enclosed in a sealed container and 'soaked' in an iodine vapor at elevated temperature. This will yield the worst case saturated exposure testing as it maximizes the surface interaction with the iodine vapor. The only components that will experience anything like these conditions are the propellant tank and feed system, where iodine vapor is contained and flows only very slowly. In this testing where a sealed container is used, partial pressure saturation effects limit surface erosion to a level where the volatile iodide compounds reach an equilibrium partial pressure.

To date we have performed iodine vapor flow testing on aluminum alloys, copper alloys, titanium alloys, nickel alloys, polymers, and carbon fiber composite material over testing periods lasting one week and one month. The one week iodine flow testing resulted in little reaction with any of the materials except copper and brass (see a partial list of the results in Table 5). The most surprising result was the lack of reaction between aluminum and iodine in the flow testing. Literature research indicated that aluminum would fare just as poorly as copper, but it was pretty resilient in the flow testing. Presently, we are preparing to start the static iodine bath tests.

## V. Iodine Loading and Long-Duration Thruster Testing

As a reactive propellant that can also be corrosive to the thruster and propellant feed system components, it is important to ensure a level of cleanliness of the components with which iodine will come into contact and that these components can survive prolonged contact with the iodine propellant. In this section we describe the procedure presently employed to load iodine into the propellant feed system and outline an 80-hour test

**Table 5. Summary of qualitative results for testing of various alloys in the one week active iodine flow exposure test apparatus.**

| Material Category | Material Identification | 1 Week Surface Condition | 1 Week Thickness Change |
|---|---|---|---|
| Steel Alloys | 304 Stainless Steel | Minor Darkening | None |
| | 316 Stainless Steel | Minor Darkening | None |
| | 4130 Alloy Steel | Minor Darkening | None |
| Aluminum Alloys | 6061 Aluminum | Minor Darkening | None |
| | 7075 Aluminum | Minor Darkening | None |
| | 7075 Aluminum, Anodized | Minor Darkening | None |
| Copper Alloys | 110 Copper | White Layer | Swelled |
| | Brass | Blackened | None |
| Titanium Alloys | Titanium 6-Al-4V | Minor Darkening | None |
| | Commercially Pure Ti | Minor Darkening | None |

that aims to demonstrate the overall throughput expected for the iSAT mission.

## A. Loading Procedure

Ideally, there will be incorporated into the feed system tubing a way to introduce a gas flow into the propellant reservoir and have it exit the feed system at some point downstream. These separate inlet and exit ports would be closed during testing and/or flight, being used only to introduce a purge gas into the feed system during the iodine loading process. The loading process aims to drive out of the system as much of the oxygen and water vapor as possible, minimizing the chance for reactions and the formation of the corrosive compounds mentioned in Section IV. In what follows, we outline the present process for loading the iodine propellant reservoir.

1. Vacuum bake out the reservoir, propellant lines, and valves for several hours, preferably with the entire assembly in and exposed to vacuum. The minimum bake out time for removing adsorbed water vapor is typically 12 hours.

2. Load iodine into the reservoir (this could be done in a glovebox, but it is not necessary since the iodine 'as shipped' is already exposed to the ambient environment). The iodine may be pre-ground into finer particles to permit more-dense packing, though they should still be coarse enough so that the minimum particle size is greater than the filter size. Load quickly to minimize the time that the vacuum-baked feed system is exposed to the ambient environment.

3. After loading, install the feed system in a vacuum chamber and purge the tank with a continuous flow of a non-reactive cover gas (e.g. argon). Place a needle valve on the gas exit to limit the outflow (or alternately use the PFCV if the exit during purging is through the valve and thruster). Purge for at least 2 hours with the gas pressure within the feed system at roughly 100 torr (2 psi). Perform the purge for up to up to 12 hours if a prolonged exposure occurred or if the air was humid. Adjust the needle valve (or alternately the PFCV) to maintain the pressure during this process.

4. While purging the tank, bake out the valve and lines downstream of the valve to drive off any gases adsorbed as the tank was being loaded. The bake out should continue for up to 12 hours if the lines were exposed for a long time or if the air was humid.

5. Once the purge and bake out are completed, seal the purge inlet first, then the exit. At this point, iodine feed system and thruster operations may commence.

6. Complete the following before the vacuum chamber is vented and/or the reservoir and propellant feed lines are exposed to atmosphere (for example, at the end of test or if more propellant must be added). After iodine feed system and thruster operations are halted, turn off the tank heaters and let the tank return to near ambient temperatures. Continue heating the valve and lines downstream of the valve (i.e. the parts still exposed to vacuum when the feed system valves are closed) for at least 12 hours to drive off any volatile iodine compounds in that part of the system.

7. While baking out the lines and valve, reopen the exit and inlet purge valves and for two hours continuously apply the purge in the same manner as step 3, exhausting to vacuum.

8. If testing is to be continued after the feed system is exposed to the ambient environment (e.g. if more iodine was to be loaded in the tank), minimize the amount of time that the feed system and remaining iodine are exposed to atmosphere. After the system is reassembled, proceed back to step 3 to prepare the system for continued testing.

### B. Long-Duration Testing

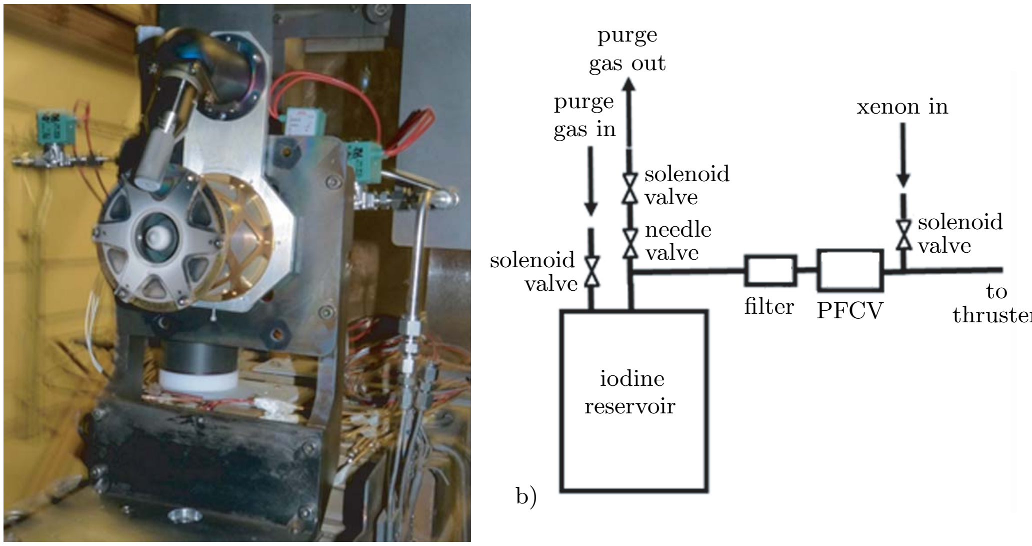
An 80 hour duration test of the Busek BHT-200-I engineering model (EM) Hall thruster with iodine propellant is being conducted at NASA Glenn Research Center (GRC) to support the development of the iSAT flight-model thruster. While this test is not yet complete, we describe herein the test objectives and basic setup.

The objectives of this duration test are:

- Map the performance of the BHT-200-I EM thruster with xenon and iodine propellants over the entire thruster throttling range.
- Operate the thruster for over 80 hours to confirm the sustained performance of the thruster operating on iodine propellant and to confirm the integrity of the coatings applied to the various thruster wetted surfaces.
- Map the plume of the thruster throughout the duration of the test to confirm that no change in the beam profile occurs.
- Measure and record the temperature of selected thruster components to confirm the thermal operation of the thruster and to obtain data that will be used to validate the thruster thermal model.
- Demonstrate the operation of the iodine feedystem.
- Test the operation of the MSFC-developed iodine feedsystem auxiliary board that will used to control the PFCV and to monitor and control the temperature of the various iodine feed system heaters.
- Evaluate the impact of iodine on various material specimens that will be exposed to the iodine thruster plume.
- Evaluate the impact of iodine on the vacuum facility walls and pumping train.

A photograph of the thruster installed on an inverted pendulum thrust stand is shown in Fig. 7a while a schematic of the iodine feedsystem is shown in Fig. 7b. The laboratory iodine feed system enables thruster operation with both xenon and iodine propellants. In this test the thruster cathode is fed only with xenon propellant. The iodine tank will be loaded with 270 g of iodine. Initial thruster tests will be performed with xenon to measure a baseline thruster performance. Testing will then be conducted with iodine propellant at a variety of throttle points. After this initial performance evaluation is complete, the 80 hour duration test will commence. The thruster operating condition for the 80 hour duration test will be finalized after completing the preliminary thruster performance evaluation, but it is expected that this testing will be conducted at a discharge voltage of approximately 250 V and a power level of 200 W.

During the testing, a Faraday probe and a Langmuir probe installed on a linear stage will be used to map the exhaust plume of the thruster. A CCD camera will also be installed on the linear stage and will periodically obtain close-up images of the thruster at prescribed intervals to document the status of the thruster and its coatings. The BHT-200-I EM thruster test will be performed in NASA GRC vacuum facility 7 (VF7). Vacuum facility 7 is an oil diffusion pump-evacuated facility that has roughly a 3-m (10-ft) diameter and is 4.6-m (15-ft) long. The facility has been modified for compatibility with iodine propellant. Liquid nitrogen-cooled chevrons are used to condense and sequester the iodine propellant while the thruster is operating. After the testing is completed, the chevrons will be heated, resubliming the sequestered iodine propellant, which will then be removed through a dedicated iodine vent line.




a) b)

**Figure 7. a) Photograph of the BHT-200-I on a thrust stand and b) schematic of the iodine feed system for the long-duration testing.**

## VI. Conclusion

A flight demonstration mission using a 12-U CubeSat aims to demonstrate a propulsion system based upon a 200-W iodine-fed Hall-effect thruster. A thruster operating on this type of propellant offers advantages as a secondary payload propulsion system because iodine stores as a dense, well-packaged solid that can be sublimed to a low-pressure gas through the application of heat, obviating the need for high-pressure in the propulsion system. The low pressure of an iodine-fed system makes it possible to launch a spacecraft with high $\Delta v$ capability as a secondary payload. The 200-W BHT-200 thruster that has previously been flown is modified to withstand contact with hot iodine vapor. The cathode is also changed to an electride cathode, which is both iodine-compatible and requires little to no heating to start, saving on the overall propulsion system power draw. The propellant feed system must be heated to support sublimation of the iodine propellant, with a pair of proportional flow control valves incorporated into the iSAT propulsion system to permit rapid adjustment of the flow rates to the anode and cathode. While a separate electronics boards has been used for laboratory testing of the feed system, in the flight uint this functionality will be folded into the PPU, allowing for centrally-controlled and monitored operation of all thruster system components. Thermal modeling indicates that the propellant can be brought to temperature even in the worst-case scenario, but operationally this may take too long for the iSAT mission and require additional attention. The iodine-wetted components must be capable of withstanding prolonged exposure to iodine vapor. Limited literature data and the experimental testing performed to date as part of the iSAT project indicate that several materials may be able to survive iodine exposure for long periods of time. Propellant loading aims to minimize the time that impurities can form in the iodine propellant reservoir and other wetted surfaces, with a process in place to purge the system after loading to drive off any remaining impurities. An 80-hour duration test with multiple restarts and a throughput level close to what is required for the iSAT mission is presently in-progress. This testing will demonstrate the feed system, thruster, and iodine loading procedure to determine if the procedures and hardware in place are sufficient to support the iSAT mission profile.

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