Development, Demonstration, and Analysis of an Integrated Iodine Hall Thruster Feed System

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The design of an in-space iodine-vapor-fed Hall effect thruster propellant management system is described. The solid-iodine propellant tank has unique issues associated with the microgravity environment, requiring a solution where the iodine is maintained in intimate thermal contact with the heated tank walls. The flow control valves required alterations from earlier iterations to survive for extended periods of time in the corrosive iodine-vapor environment. Materials have been selected for the entire feed system that can chemically resist the iodine vapor, with the design now featuring Hastelloy or Inconel for almost all the wetted components. An integrated iodine feed system/Hall thruster demonstration unit was fabricated and tested, with all control being handled by an onboard electronics card specifically designed to operate the feed system. Structural analysis shows that the feed system can survive launch loads after the implementation of some minor reinforcement. Flow modeling, while still requiring significant additional validation, is presented to show its potential in capturing the behavior of components in this low-flow, low-pressure system.

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 and a mass of 1.33 kg (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 is capable of executing high Δv maneuvers. This makes it difficult to use CubeSats on missions requiring certain types of maneuvers (i.e. formation flying, spacecraft rendezvous).

Recently, work has been performed investigating the use of iodine as a propellant for Hall-effect thrusters (HETs) [2] that could subsequently be used to provide a high specific impulse path to CubeSat propulsion.[3–5] Iodine stores as a dense solid at very low pressures, making it acceptable as a propellant on a secondary payload. It has exceptionally high $\rho I_{\rm sp}$ (density times specific impulse), making it an 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 also be thermally regulated, subliming at relatively low temperature (< 100 °C) to yield I_2 vapor at or below 50 torr. 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 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. In addition, the temperature doesn't have to be extremely cold to maintain a low vapor pressure in the vacuum chamber (it is 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 low temperature gaseous helium cryopanels.

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An iodine-based system is not without its challenges. The primary challenge is that the entire feed system must be maintained at an elevated temperature to prevent the iodine from depositing (transitioning from the gas phase back into the solid phase), which will block the propellant feed lines. Furthermore, deposition will occur if the temperature in the lines is not greater than the temperature of the propellant reservoir.

In the present paper, we describe the development, laboratory demonstration, and analysis that has been performed on an integrated iodine Hall thruster feed system design. A separate paper describing the iSAT program status can be found in Ref. [6]. In Sect. II we describe the present feed system design, discussing in-depth components that have received considerable attention during the design and development process. The fabrication and operation of an integrated feed system-thruster unit are described in Sect. III. This system forms the core of the iSAT program's laboratory-model integrated feed system-thruster-cathode test, which will be performed after publication of the present paper. A structural analysis of the feed system design was performed and is presented in Sect. IV, with results from this analysis being used to inform design decisions to ensure the feed system will survive launch loads. Finally, a flow modeling effort has been started to better understand how the iodine can be best regulated to feed both the cathode and thruster from a single, low-pressure reservoir where the rate of iodine vapor production is sublimation-dependent.

II. Baseline Propulsion System

It is worth reviewing the present iSAT iodine propellant feed system design since there have been changes since Ref. [4]. Renderings showing the front and back views of the iSAT propulsion system are presented in Fig. 1. The iodine propellant feed system that we are primarily concerned with in this paper consists of several components. 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 propellant tank is also fabricated from Hastelloy and is sealed with an o-ring at the cap. There are two VACCO proportional flow control valves (PFCVs), providing control of the flow to the cathode (PFCV-C) and the thruster (PFCV-A, anode). There are two fittings in the rendering, installed to permit a gas purge of the tank and iodine-exposed line once iodine is loaded into the system. An Inconel bellows is used to allow the lateral removal of the tank lid so that iodine can be loaded into the system after it is completely assembled.

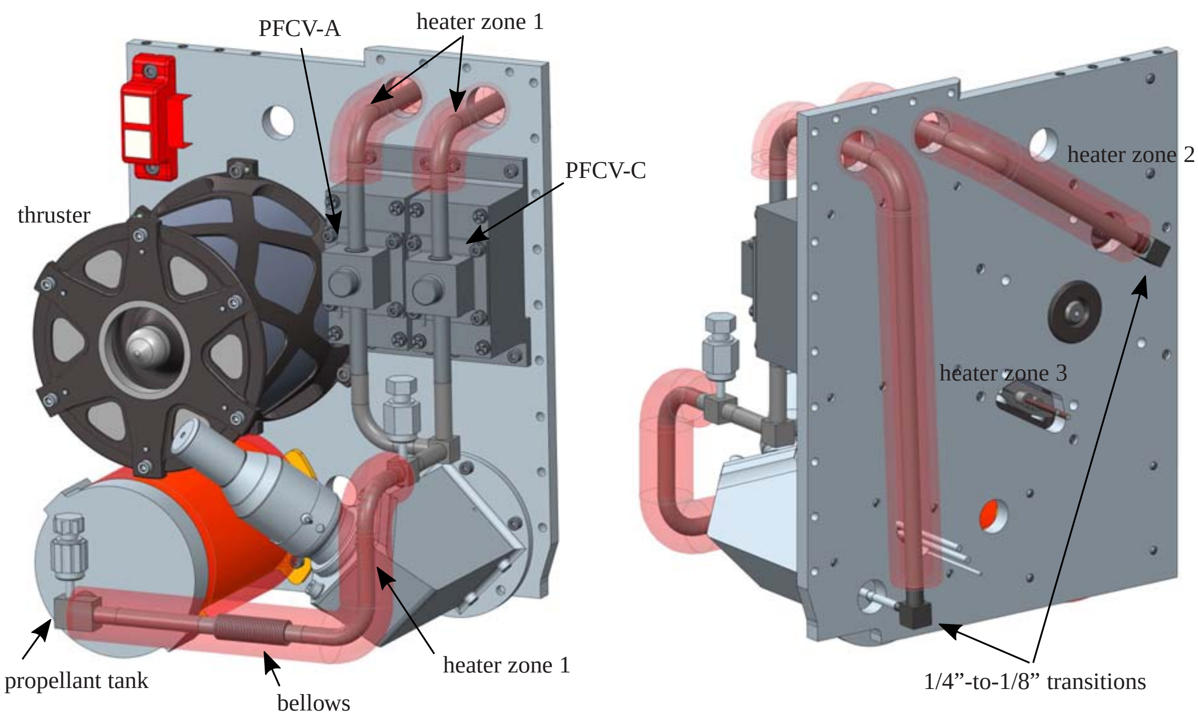

Figure 1. Renderings showing the front and back views of the iSAT propulsion system.

There are six separately heated 'zones' for the system. Each is independently controlled and monitored with an RTD. The propellant tank and each of the PFCVs comprise three of the zones. The other three consist of all the tubing on the thruster-side of the plate (zone 1), the portion of the tubing on the back side of the plate going to the thruster (zone 2), and the portion of the tubing on the back side of the plate going to the cathode (zone 3). The reason why the tubing downstream of the valves going to the thruster and the cathode (located spatially above the valves in Fig. 1) are included in zone 1 is that all the tubing on that side of the plate faces the space environment while the tubing on the other side of the plate faces the interior of the spacecraft. As a consequence, they are in different radiative heat transfer environments and will have different insulation commensurate with the zone needs.

The PFCVs have internally-embedded heaters so sublimed iodine vapor does not redeposit in the interior of the valves. The tank and lines have Tayco flexible polyimide (Kapton) heaters. These heaters are custom-designed for an input voltage of 28 VDC and will fully cover the areas of the feed system requiring heating. The heaters are required to elevate the temperature of tank to 90 deg C and the lines to 125-130 deg C in an amount of time commensurate with the spacecraft ConOps. The heaters all have two independent resistive circuits, allowing for redundancy in case a fault develops in one of the heaters. The thruster PPU has the functionality to operate the primary heater circuits, and the auxiliary control board included as part of the spacecraft avionics card stack has the capability to operate the secondary heater circuits for the tank and zones 1, 2, and 3 if required.

On the space-facing side of the propulsion plate, the thermal insulation is double aluminized Kapton (perforated, 1% open area, 2-mil thick, 0.059-in (1.5 mm) hole dia.). Two layers are loosely wrapped over all exposed surfaces (propellant tank, zone 1 lines, PFCVs, serving to reflect heat back into the system. Aluminized Kapton tape is used on the seams to secure the insulation in place. On the interior-facing side of the propulsion plate, custom-multi-layer insulation (MLI) is wrapped around the entirety of the tubing for zones 2 and 3. The MLI consists of 10 layers of double aluminized Mylar (perforated, 1% open area, 0.25-mil thick, 0.059-in (1.5 mm) hole dia.) with layers of B2A Dacron netting between the Mylar layers. Aluminized Kapton tape is again used on the seams to secure the layers.

The propellant tank and PFCVs have received special attention during the design and development process, and it is worth discussing these components in more detail before proceeding.

A. Propellant Tank

The design of the iodine propellant tank has several challenges. The primary one is that for the best heat transfer rates the solid iodine should be in contact with the externally-heated tank walls (conduction). Past testing has been performed on the ground, with gravity alone holding the iodine against the tank walls. However, in the microgravity environment of space the iodine can potentially float away from the tank walls.

Thermal modeling was performed to determine if solid iodine propellant floating in the tank would be able to reach the temperature required to sublimate enough propellant for the iSAT mission (approx. 90 deg C). [4] It was found that conduction or convection of the heat through the gaseous iodine material was insufficient to raise the temperature in a reasonable amount of time ($\gg 3$ orbits). In the case of radiation, the time required could be reduced only by assuming that the gaseous iodine was fully transparent, which is most certainly not the case. It was concluded that the design could not rely solely on radiative heat transfer, so a method was devised to maintain the solid iodine in direct thermal contact with the walls of the propellant tank.

The present tank design, shown in Fig. 2, uses a spring-loaded plate to push the iodine against the tank walls, keeping it from floating away from the surface. Multiple holes in the plate allow for the sublimed vapor to pass through the plate into an evacuated space on the other side of the tank. The gas flows to the thruster through the pressure gradient that arises owing to the higher pressure of the sublimed iodine in the tank. The plate rides on a centrally-mounted rod with a compressed spring applying force to the plate. As the iodine sublimes, the plate advances under the force of the decompressing spring. The design as-shown is the laboratory model demonstration design, fabricated from Hastelloy and using an Inconel spring to apply a force to the plate.

The tank was tested in various orientations to simulate a microgravity environment and validate the spring-loaded plate design. Specifically, the tank was heated to 90 deg C while being oriented in the ‘normal’ right-side-up direction (iodine held in place by both gravity and the plate) and in the inverted up-side-down direction (iodine held in place only by the spring-loaded plate, which was fighting gravity). An additional right-side-up direction case was tested with no plate in the tank to determine if the holes in the plate were adequately sized for the passage of iodine from the side containing the propellant mass to the evacuated space on the other side of the tank. The mass flow rate in each instance was measured using an MKS1152 vapor flowmeter. A visual inspection of the tank was made after each test to determine if there was a build-up of redeposited iodine on the wrong side of the plate. Only minimal deposition was observed during these inspections. No special preparation of the iodine, such as crushing it to increase the packing fraction in the propellant tank, was performed. The tank and iodine were always cleaned/purged with a neutral gas using the purge procedure in Ref. [4].

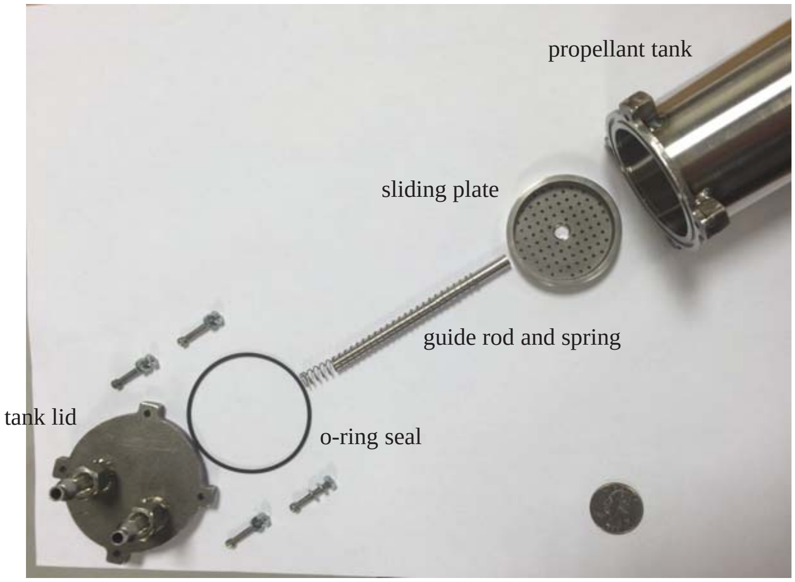

Figure 2. Exploded view of the laboratory model propellant tank.

Table 1. Average propellant flow rates from the propellant tank situated in different orientations.

Normal orientation	3.89 mg/s
Normal orientation (no plate)	2.83 mg/s
Inverted orientation	3.29 mg/s

The average flowrates measured during this testing are given in Table 1. In all cases, the tank was heated to 90 deg C with the only flow resistance in the line between the tank and vacuum being the MKS flowmeter. It is interesting that the flow rate was lowest with no plate installed in the tank. We can speculate that the presence of the plate in the normal orientation served to push the iodine into more intimate thermal contact with the tank walls, improving the heat transfer to the propellant. It also appears that the presence of the plate significantly aided the sublimation process in the inverted orientation relatice to the normal orientation where there was no plate used. Testing was conducted until the tank was emptied. A visual inspection showed that the tank had exhausted all the solid iodine apart from a few trace residual pieces.

B. Proportional Flow Control Valves

The valves described in Refs. [4, 5] encountered problems after prolonged exposure to iodine, necessitating some changes to the design. It was found that large pieces of debris were making their way into the valves, cluttering the sealing surface so a solid leak-tight seal could not be achieved. As a consequence, the valves will have Inconel 625 mesh filters (nominal 25 micron pore size) incorporated into the inlets. The valves will also have weld tube stubs instead of fitting ports, allowing for integration with the rest of the system through orbital welding. The iodine-wetted surfaces in the valves and in earlier propellant reservoirs used in this work were fabricated from anodized aluminum. However, it was found that the aluminum started to wear and pit quickly once the anodized layer was scratched to expose the aluminum underneath. For this reason, the wetted surfaces in the valves (and elsewhere in the feed system) are now almost exclusively Hastelloy, with Inconel used in a few of the non-Hastelloy locations. The original valve design used titanium springs, but it was found that the springs were decomposing (likely into TiI_4 gas) through exposure to the iodine vapor. To alleviate this issue, the new valves will use an Inconel spring, which is far more robust in the presence of iodine vapor.

III. Feed System Demonstration Unit

As part of the iSAT project,[6] the entire integrated propulsion system (thruster, cathode, and feed system) must demonstrate operation as one single package. A test unit was assembled for this purpose, using the laboratory-model spring-loaded plate propellant tank, the previous-generation PFCVs described in Ref. [4,5], and the BHT-200-I iodine-vapor Hall effect thruster (HET). The assembled unit is shown in Fig. 3 and was assembled to be a close approximation to the schematic shown in Fig. 1. We added stainless steel Swagelok 40 micron filters upstream of the PFCVs since this valve design does not have filters in the valves. The unti uses off-the-shelf Minco heaters that are similarly-sized (physically) relative to the flight heaters but that are not properly sized to yield the flight heater power density or overall heater power drop per zone. The temperature for the propellant tank and zones 1, 2, and 3 were measured using RTDs while these PFCVs have embedded thermistors for temperature measurement. The insulation is very much like the flight configuration and Hastelloy tubing was used as much as practical. The fittings are stainless steel except for the two purge port fittings, which are Hastelloy torque-elimination metal face seal fittings from Omnisafe (using Hastelloy gaskets).

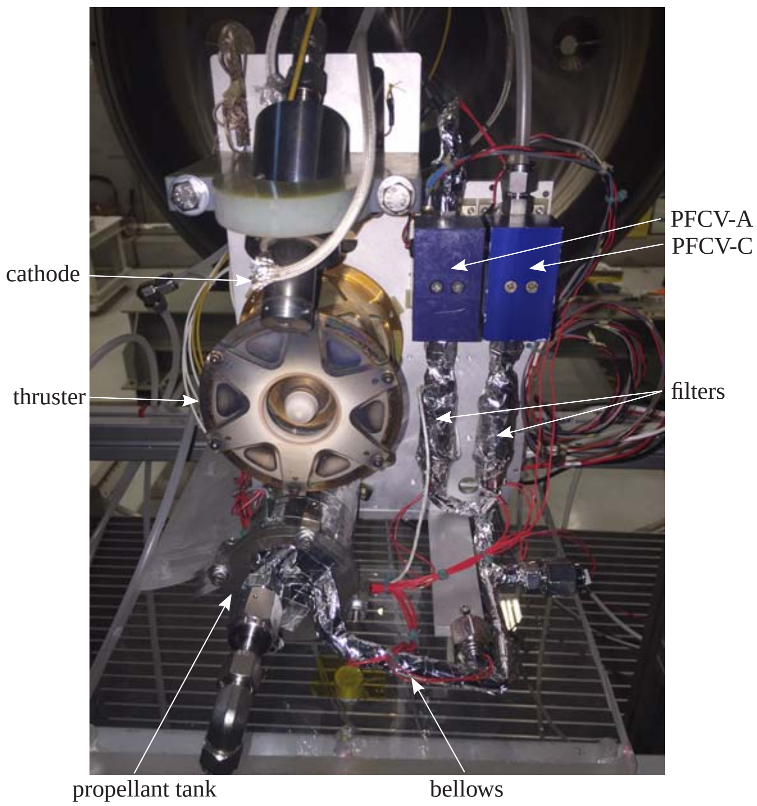

Figure 3. iSAT integrated feed system-thruster test setup (with Xe-fed cathode).

An auxiliary control board and auxiliary power distribution card (shown schematically in Fig. 4) were discussed previously in Ref. [4] and have been 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. In the iSAT flight unit, this functionality will nominally be in the PPU, but for this test the auxiliary boards are used to completely operate the feed system in a self-contained manner. The 'spare' serial connection was used to interface the control board to an external computer running LabView. There is no latch valve in this setup, so that connection is unused. However, spare analog voltage channels on board were used to perform real-time measurements of the thruster discharge voltage (through a 100:1 voltage divider) and current (through a shunt resistor). The discharge current and voltage data were measured using a pair of Wilkerson Electronics DR4380A field rangeable isolated amplifiers.

In this testing, xenon was supplied to the cathode since it was not iodine-compatible. Operation was demonstrated at 200 W (250 V, 0.8 A) on both xenon (Fig. 5A) and iodine (Fig. 5B). In the former case, the flow of xenon to both the thruster and cathode was controlled by the propellant feed system, while in the latter case it was only iodine flow to thruster that was controlled by the feed system. The temperatures were monitored and the LabView PID controller was

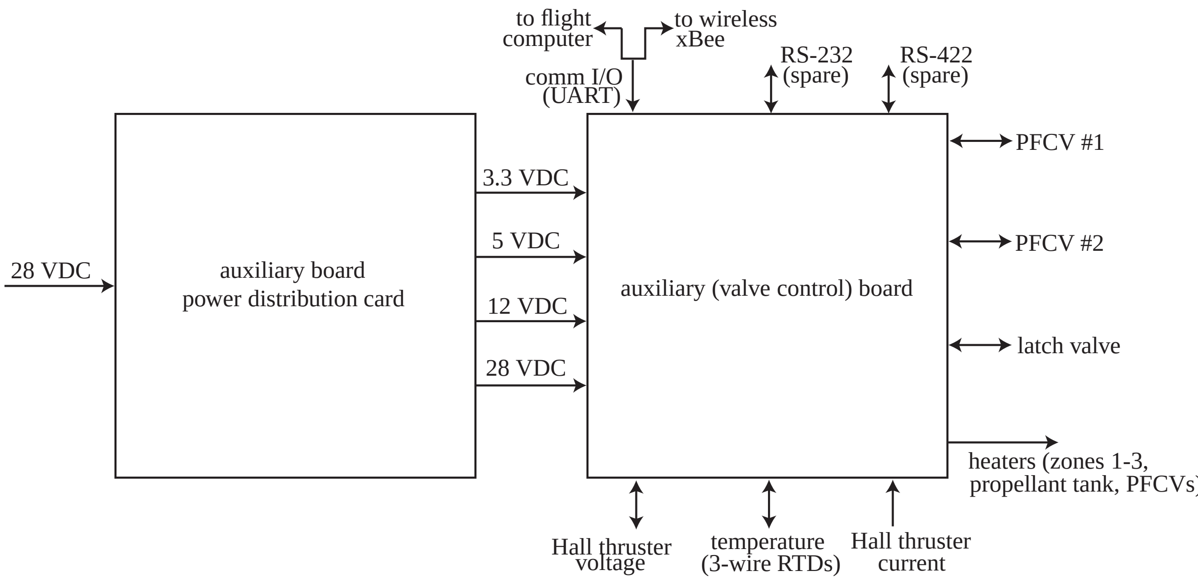

Figure 4. Schematic representation of the auxiliary valve control and power distribution boards.

used to adjust/maintain setpoint valves for all the heated components. The PFCV openings were manually adjusted in this test until the anode discharge current reached 0.8 A. While we incorporated the capability to adjust PFCV-A using a feedback measurement of the discharge current, this option was not used in our testing.

A) 

B) 

Figure 5. iSAT integrated feed system-thruster test setup operating on A) xenon and B) iodine propellant.

One issue encountered was loss of communication via RS-422 to the auxiliary board. This was caused by EMI produced from thruster ignition. As a consequence, the entire electronics system was more-heavily shielded in anticipation of the fully-integrated testing to occur with an iodine-compatible cathode at NASA-GRC.

IV. Structural Analysis

A structural analysis of the propulsion plate was performed to predict the dynamic response of the iSAT feed system when undergoing qualification random vibration testing. The current qualification environments are obtained from GSFC-STD-7000A, Table. 2.4-3 (General Environmental Verification Standard or GEVS). These environments are shown in the Table 2 and are used in lieu of launch vehicle specific random vibration environments as those environments are not yet known.

A finite element model was used to predict the dynamic response of the feed system. This model included a

Table 2. **Generalized Environmental Verification Standard summary.**

Frequency (Hz)	22.7 kg (50 lb) or less Qualification (g^2/Hz)	Acceptance (g^2/Hz)
20	0.026	0.013
50	0.16	0.08
800	0.16	0.08
2000	0.026	0.013
G_{RMS}	14.1	10.0

detailed representation of the iodine propellant tank and feed lines. All other components were modeled as point masses with rigid attachments to the support plate. The model assumed that the propulsion plate was hard mounted at its boundary to a vibration test fixture with infinite stiffness. To best match the flight configuration, a free edge was retained to capture relevant dynamic effects. Figure 6 shows the finite element model viewed from both the front and back of the propulsion plate. Random frequency response analysis was conducted using this finite element model. A flat damping schedule of 1% for every mode was assumed as no finite element model correlation for the feed system has occurred to date. This damping assumption was used for all response analysis.

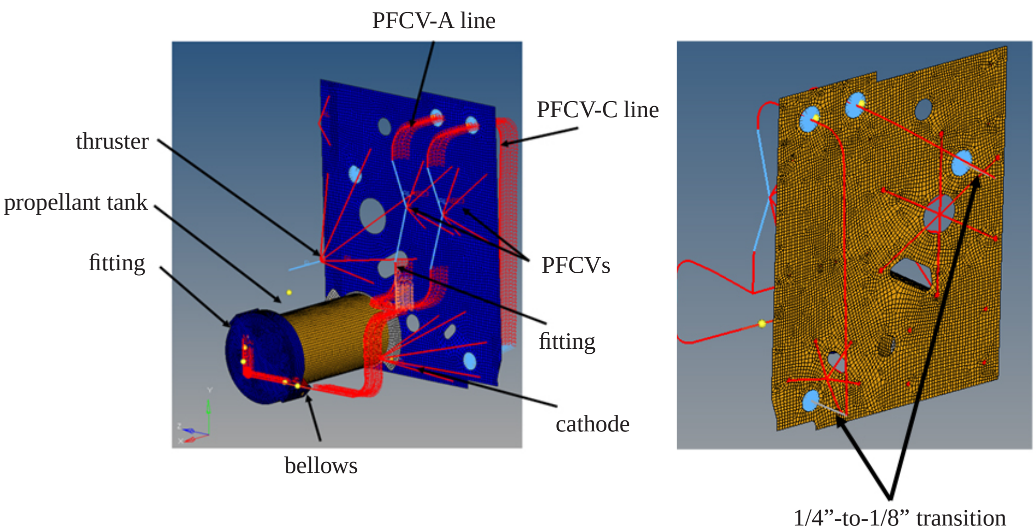

Figure 6. Finite element model for structural analysis of the iodine propellant feed system.

One major impact of the results of this analysis is a modification to the feed system lines and fittings. The original configuration contained two cantilevered fittings (the feed system purge ports) as shown in Figure 6. A frequency response assessment showed that these fittings would see extreme g-loadings that would result in negative margins of safety. This result was confirmed by using MSC PATRAN to obtain 3-σ von Mises stress results in the areas of concern. It has been recommended based on this analysis that an approach be developed that will permit removal of the fittings from the design.

Results from this analysis also helped to determine the most effective way to constrain the feed lines to the propulsion plate. The critically stressed areas of the feed lines were observed using a contour plot of the 3-σ von Mises stresses for each beam element in the feed line. Once the critical area was determined, plots of the cumulative RMS von Mises stress and von Mises stress power spectral density (PSD) were generated to ascertain which mode shape and natural frequency produced the worst case stress. This information was used to determine the most effective way to support the feed system. As can be seen from the data in Fig. 7, the mode causing the most damage occurs around 750Hz. The corresponding modes shape at 735 Hz revealed that the 1/4”-to-1/8” tube transition locations were not adequately constrained. Therefore a recommendation was made to constrain these areas. A trade study was performed using rigid elements to enforce this notional constraint and confirm that this would yield positive margins of safety for the feed lines.

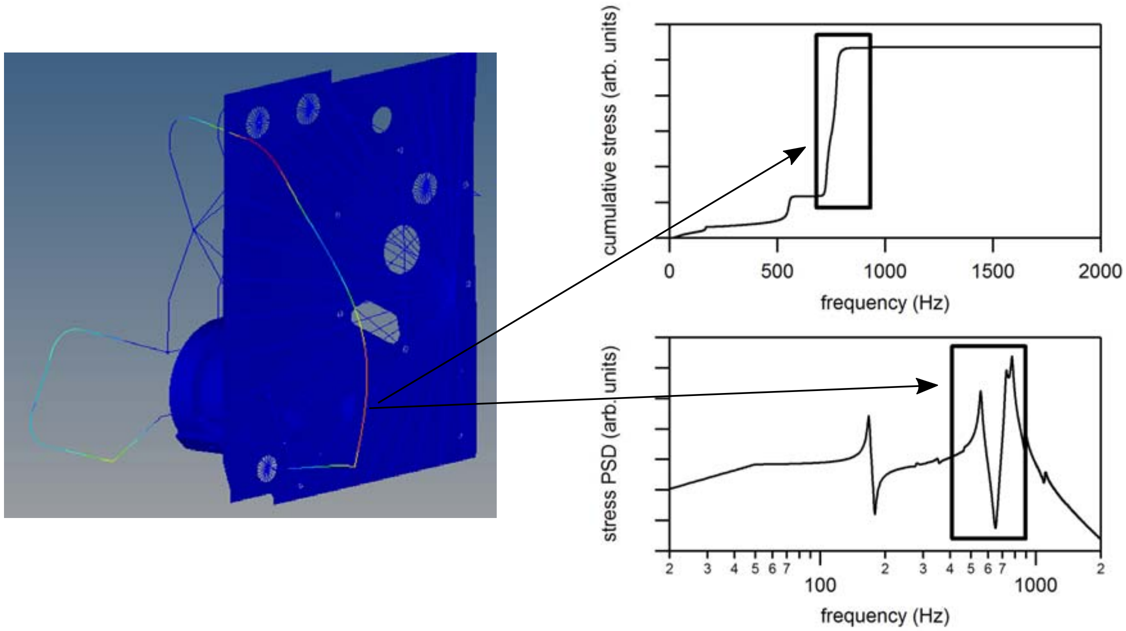

Figure 7. (left) Modal analysis results for 735 Hz and (right) cumulative RMS stress and stress power spectral density as a function of frequency.

V. Flow Modeling

A time-dependent model of the iSAT propellant feed-system has been developed using the Generalized Fluid System Simulation Program (GFSSP). GFSSP[7] is a general purpose simulation tool for modeling complex flow networks; both steady-state and unsteady fluid behavior may be treated, as well as conjugate heat-transfer, and fluid and phase mixtures. The model, shown in Fig. 8, treats the tank ullage volume as a fluid node (Node 1). The solid iodine reservoir, tank wall, and tank lid are treated as solid nodes (numbered 51, 52, and 53, respectively).

Heat is applied to the tank from an ambient node which is in close thermal contact with the tank and held at a prescribed temperature; this effectively holds the temperature of the tank at a constant value. A consideration of the thermal resistances for the system indicates that heat flows from the tank wall primarily into the solid iodine, rather than into the iodine vapor in the ullage space. It will also, to a lesser extent, flow along the walls of the tank into the tank lid. These heat fluxes are modeled in GFSSP with solid-solid heat conductors. The flow of heat from the solid iodine and from the tank lid into the ullage space is modeled with solid-fluid convective elements; the heat transfer coefficients are chosen to be sufficiently large so that the ullage vapor is in close thermal contact with both the lid and the solid iodine.

The heat-transfer assumptions were checked by comparing the results of a simplified model, consisting of just the tank components (including the ullage space) to experimental data. In the experiment, the tank was loaded with 228 g of solid iodine, with an experimentally determined packing fraction of 0.56. It was instrumented with thermocouples (including one inserted directly into the solid iodine) and insulated with MLI, and then heated in a vacuum chamber with a heating power of 8 W. In the GFSSP model, the masses of the tank and the iodine were specified, as well as the heat transfer areas and the ullage volume, based on the dimensions of the tank and the effective density of the iodine. The calculated temperatures of the propellant tank and solid iodine are shown in Fig. 9. These

The standard fluids available for use in GFSSP do not include iodine, so its properties had to be defined with the user-defined fluid option. Fluid property files for gaseous I_2 were created, containing the specific heat at constant pressure (C_p), standard enthalpy (H), standard entropy (S), ratio of specific heats (γ), thermal conductivity (κ), viscosity (μ), and density (ρ), over a range of pressures and temperatures. Data on these properties were collected from research articles, data handbooks, and the NIST website.

The sublimation of solid iodine into vapor was also included in the model. The quasi-steady sublimation of a solid can be calculated with an equation first proposed by Langmuir,[8,9] in which the rate of mass evolution is given by:

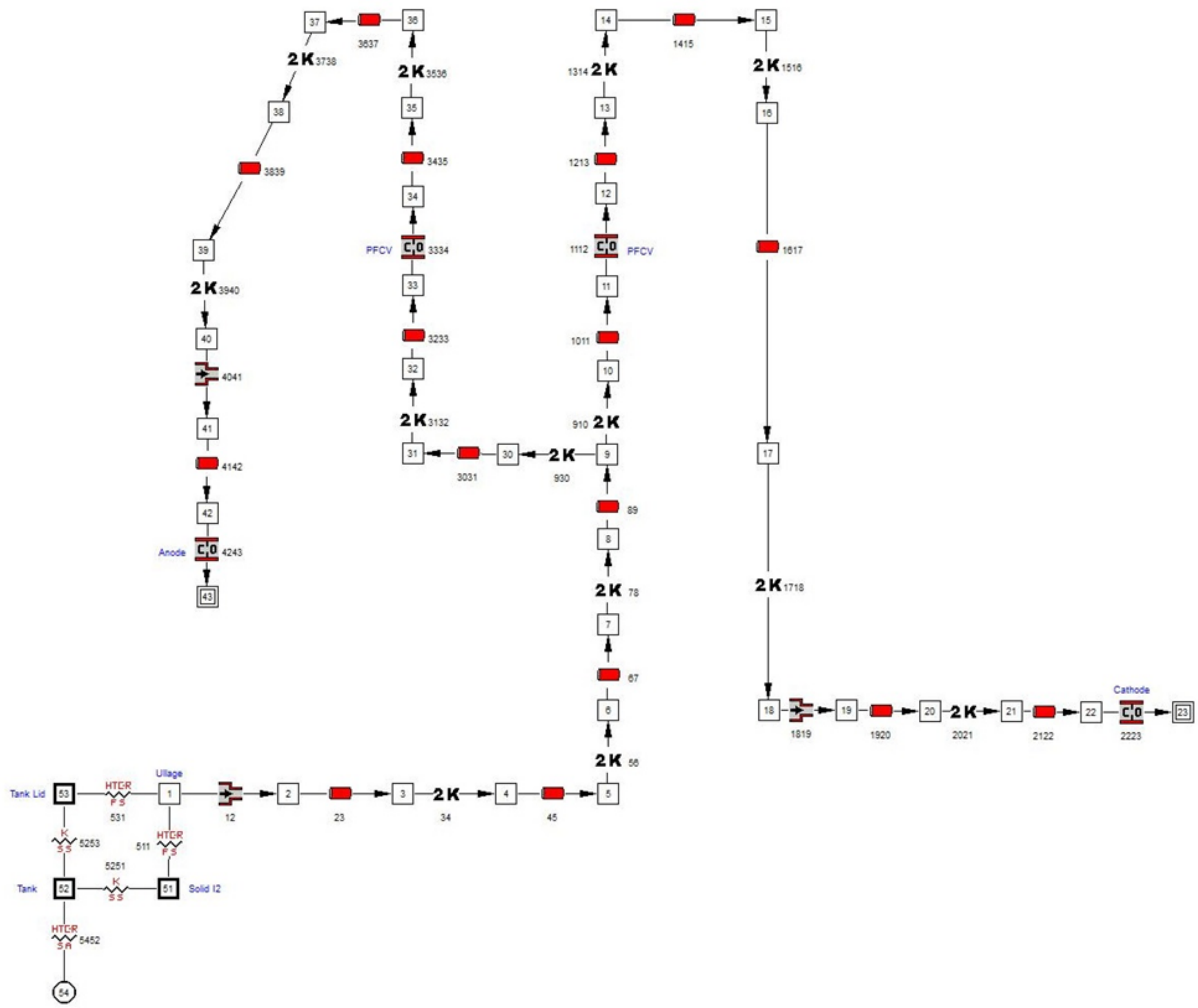

Figure 8. Time-dependent GFSSP model of the iSAT propellant feed system.

$$\frac{dm}{dt} = \alpha A \sqrt{\frac{M}{2\pi RT}}\left(P_{vap} - P\right) \tag{1}$$

where α is a sticking coefficient (usually assumed to be 1), A is the exposed surface area, M is the molar mass of the solid material, R is the universal gas constant, P and T are respectively the ambient pressure and temperature of the overlying gas, and P_{vap} is the vapor pressure at the temperature of the solid. This equation assumes that the solid and the overlying gas are in approximate equilibrium.

The sublimation of mass into the tank was implemented in the model by including a mass source term that is governed by Eq. (1) in a GFSSP user sub-routine (BNDUSER). The rate of mass evolution in the tank node is calculated at every time-step using the updated fluid and solid node variables. A back-relaxation scheme was used to make the calculation numerically stable.

A wide variety of components can be modeled in GFSPP and are available as standard options, assuming the flow coefficient, C_f, is well known. This is the case for standard flow system elements, such as straight sections of tubing, elbows, and tees, and for commercially available valves, characterized for and used within their nominal operating regime, but is not the case for two of the custom components in the iSAT propellant feed system: the PFCVs and the thruster anode. In the low Reynolds number regime of the feed system, the behavior of the valves will be dominated by the viscous flow in the boundary layer and this will be highly dependent on the specific geometry of the component. Consequently, the flow coefficient, C_f, for each component should be measured under likely operating conditions.

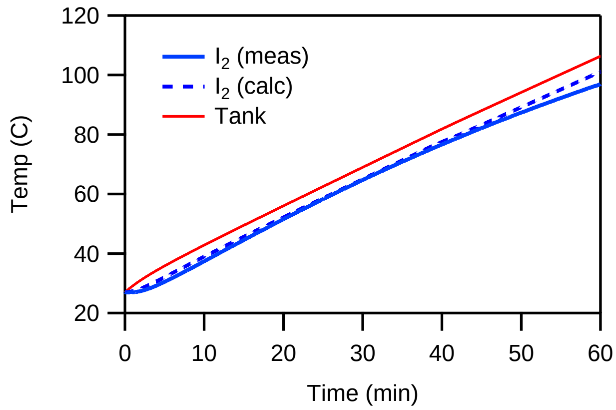

Figure 9. Measured and calculated temperatures for a propelnat tank loaded with solid iodine at a packing fraction of 0.56.

Tests of the latch valve (since removed from the design) and the anode were made with N_2 as the working fluid, under the assumption that it is a suitable simulant for I_2. The measured flow rates and pressure drops were used as inputs into a simple GFSSP calculation in which the device under test was modeled as a compressible orifice. The flow coefficient in the model was varied until the calculated flow-rate matched the measured one. Plotting C_f as a function of Reynolds number (obtained from the GFSSP model) showed that a variety of curves with different test conditions all essentially collapsed to one curve. The curve obtained from test data for the anode from the 600 W Busek Hall thruster is shown in Fig. 10. It was also found, both for the latch valve and the anode, that $C_f(Re)$ could be fit with a function of the form:

$$C_f = a\, Re^n \tag{2}$$

for the anode, the fitting parameters were $a = 0.0036 \pm 0.0002$ and $n = 0.59 \pm 0.02$.

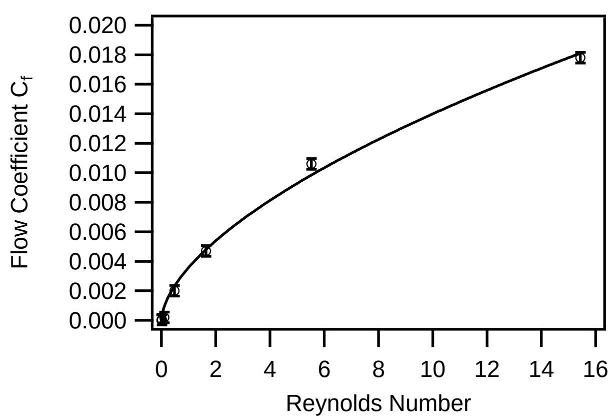

Figure 10. Flow coefficient as a function of Reynolds number for the 600 W anode, as deduced with GFSSP. The error bar for C_f is ± 0.00036. The solid curve is a fit to the data using Eq. (2).

Time-dependent calculations were performed using the full propellant feed system model (Fig. 8). The Reynolds number dependent flow coefficients described above were not included in the model at this time, as the actual components used have not been characterized yet. Instead, representative values, based on previous experience, were used. The initial temperature of the entire system is 90 deg C, and the initial pressure is 0.524 psia, the vapor pressure of I_2 at that temperature. In the actual system, everything downstream of the tank would have to be hotter than the tank to prevent redeposition of the iodine on the walls. However, in the GFSSP model this is not necessary; no provision was made for phase-changes in the I_2 vapor, and once it is liberated by sublimation it stays in the gas phase, no matter what the temperature. The effective areas for the PFCVs were chosen so as to yield a maximum flowrate of 3 mg/s, with 80% of that going to the anode and 20% to the cathode. The opening time of the valves is assumed to be 2 seconds with a smooth, sinusoidal opening profile, $A(t)$.

Figure 11 shows the results for a case in which the cathode PFCV is opened at $t = 10$s. As the valve opens, the pressure immediately upstream drops sharply. After a short delay, the pressure in the tank dips, and then increases as mass is sublimed into the tank. Eventually, after about 45 seconds, the tank pressure returns to the equilibrium value. The pressure downstream of the PFCV reaches an equilibrium value of about 0.2 psi. The mass flow through the cathode-leg spikes briefly, and then settles down to a steady rate of 0.5 mg/s, as the sublimed mass from the tank continuously feeds the line.

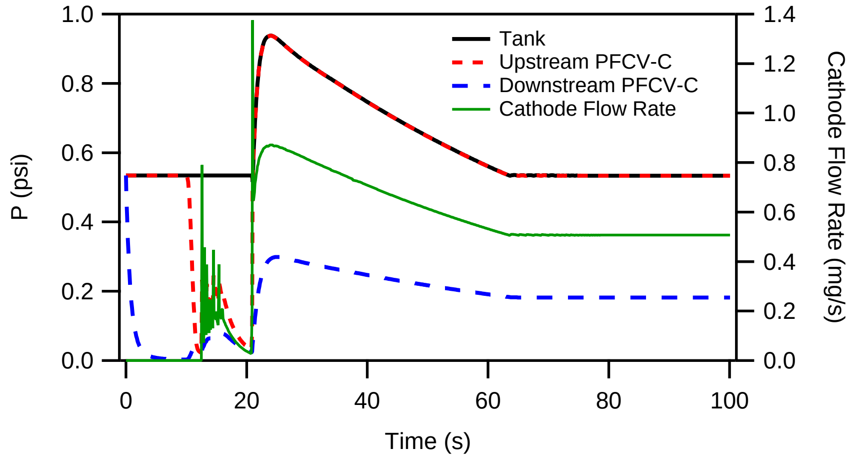

Figure 11. Simulation of the cathode PFCV opening: tank pressure, up-stream and down-stream PFCV pressures, and cathode flowrate. The cathode-leg PFCV opens at $t = 10$s.

In figure 12, the cathode PFCV is again opened at $t = 10$s, and after a short delay, when the cathode pressure reaches a maximum at about $t = 25$s, the external pressure at the cathode is quickly raised to 0.2 psi ($\sim$10 torr) to simulate the pressure increase expected at cathode ignition. The equilibrium pressure downstream of the PFCV is higher than in the case previously considered, yet still extracts the same mass flow from the tank and provides the necessary pressure drop to drive that mass flow through the cathode leg.

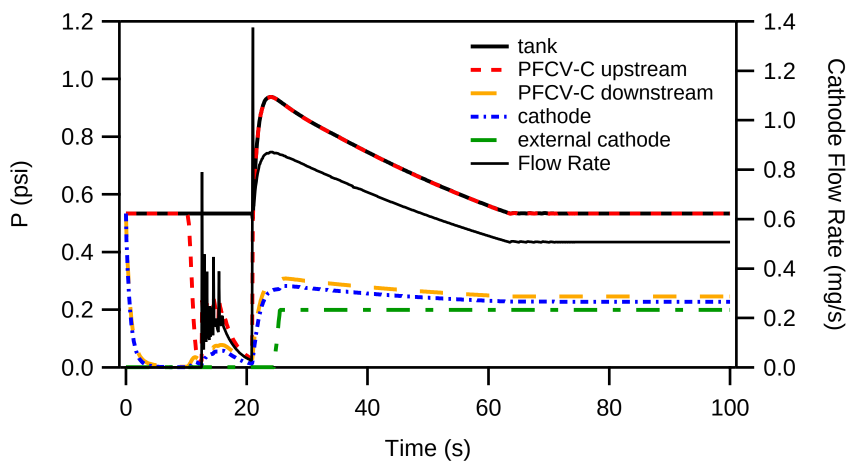

Figure 12. Simulation of the cathode PFCV opening and subsequent cathode ignition: tank pressure, upstream and downstream PFCV pressures, cathode pressure, external pressure, and cathode flowrate. The cathode-leg PFCV opens at $t = 10$s; the cathode ignition is assumed to occur at $t = 25$s.

VI. Conclusions

We have presented a feed system design to support operation of a 200-W iodine-fed Hall effect thruster. This type of thruster operating on iodine offers certain advantages over xenon because iodine stores as a dense solid and can be sublimed to a low-pressure gas through the application of heat, obviating the need for high-pressure in the propulsion system. The feed system features a propellant tank specially designed for operation in the microgravity environment and two proportional flow control valves to regulate flow to the thruster and cathode. The tank must be heated to produce iodine vapor through sublimation while maintaining any other wetted surfaces at further-elevated temperatures to keep iodine from redepositing back into solid form. Materials have been selected to make the entire system as resistant as possible to the corrosive iodine vapor, with Hastelloy and Inconel being use extensively in the feed system. A full demonstration-model feed system has been fabricated and successfully used to operate an iodine-fed Hall thruster. Analysis of the feed system structure has indicated some areas where the present design is prone to vibrational failure under launch loads, prompting minor future design changes. Modeling of the flow is ongoing, and while significant further validation is still required it does show the potential to capture the performance of various components within the system.

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