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Development of a Magnesium and Zinc Hall-Effect Thruster

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This paper describes the first demonstrations of a Hall-effect thruster operating on zinc propellant as well as experiments using magnesium propellant. Pathfinding experiments were performed using consumable anodes that were machined from solid magnesium and zinc, which sublimated under the heat load from the discharge plasma and delivered propellant gas to the thruster. The magnesium and zinc anodes served as the acceleration electrode and as the propellant supply. A retarding potential analyzer was used to obtain plume diagnostics during early operation of the experiments, showing acceleration of the propellant ions. A new porous anode with internal propellant reservoir was designed and built to be capable of being refilled with either propellant. A scheme developed earlier for bismuth-fueled Hall-effect thrusters was employed wherein shim anodes were implemented to shift discharge current to and from the main anode to control the main anode temperature and hence the metal propellant sublimation rate. Results are reported showing stable operation of a thruster using a porous anode with magnesium propellant. The magnesium-fueled thruster could be operated for approximately 100 min durations, which was governed by the propellant supply. Also demonstrated was the ability of the shim anode scheme to actively control the propellant mass flow rate from the porous anode.

Nomenclature

I_D	=	discharge current
I_M	=	magnet current
I_{Main}	=	main anode current
I_{Probe}	=	probe current
I_{Shim}	=	shim anode current
I_{Total}	=	main anode current + shim anode current
T_{Anode}	=	main anode temperature
T_{CP}	=	center pole temperature
V_D	=	discharge voltage
V_{Main}	=	main anode discharge voltage
V_{Shim}	=	shim anode discharge voltage

I. Introduction

STARTING in 2004 the Ion Space Propulsion Lab at Michigan Technological University (MTU) has worked to develop Hall thrusters and hollow cathodes that can operate using bismuth as a propellant [1–5]. Bismuth was chosen for a number of reasons, including its vapor pressure, atomic weight, and ionization potential. Some of the more general reasons for using metal propellants are that they typically have lower ionization potentials and they cost less than traditional propellants such as xenon [6]. Also, ground testing of metal propellants is significantly less expensive due to the metals of interest being solid at room temperature. Hall-effect thrusters that use inert gaseous propellants require expensive cryogenic pumping systems, whereas operating a thruster using a metal propellant only requires a pumping system that is capable of keeping up with the cathode mass flow (assuming the cathode is operated using an inert gas).

In the method used by Massey et al. [1] to operate a bismuth Hall thruster, bismuth was stored in a hollow anode that served as a reservoir within the thruster discharge channel. The anode had a porous vapor diffuser that kept the heated liquid bismuth reservoir inside the hollow anode. Naturally occurring waste heat from the thruster discharge was used to drive direct evaporation from the anode/reservoir into the discharge channel where the bismuth vapor could be ionized and accelerated away from the anode. The evaporation rate of the bismuth is governed by the reservoir temperature and the vapor escape area. Since it was not feasible to mechanically vary the vapor escape area through the reservoir, the mass flow rate was to be controlled by varying the reservoir temperature within the thruster. The evaporation rate, then, is governed by the vapor pressure of the liquid metal and the goal was to maintain the proper reservoir temperature that, when combined with the vapor escape area, yielded the desired mass flow rate [2].

The concept employed by Massey et al. [1] used a segmented anode design to achieve closed-loop control of the bismuth reservoir temperature. The thermal control mechanism employed three separate anodes: the traditional main anode in the back of the discharge channel and two *shim* anodes that are electrically and thermally isolated from the main anode near the exit plane. A cutaway view of the anode locations is shown in Fig. 1.

The main anode served three purposes: as a propellant diffuser, as an acceleration electrode, and as a reservoir of liquid bismuth. Electron current from the discharge plasma that naturally attaches to the anode was then used to heat the anode/reservoir at a rate of approximately 10% of the total thruster power, driving the direct evaporation of propellant into the chamber. Main anode temperature could then be controlled by sharing the plasma discharge current with the shim anodes on the inner and outer wall. By varying the shim voltage with respect to the main anode, the plasma current and, hence, the thermal load could be shared between the shims and main anode, thus controlling the main anode temperature and the evaporation rate [2].

Unfortunately bismuth thruster development posed numerous problems that require technical advancements in material properties in order to have dependable thruster operation. Because of these problems bismuth thruster operation was limited to numerous tests of approximately 10–30 min duration. During these short tests the shim

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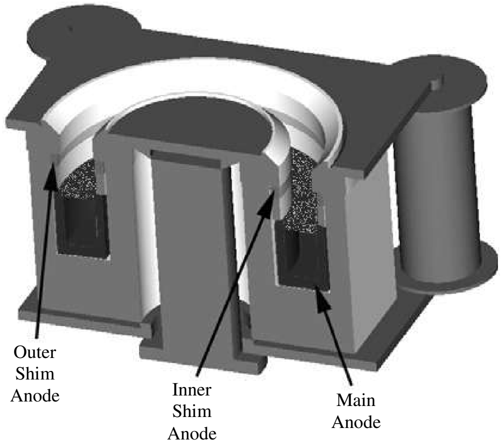


Fig. 1 Cutaway view of a modified BPT-2000 Hall-effect thruster, showing the location of the shim anodes and main anode. The cavity within the main anode is filled with metal propellant feedstock, with the porous face allowing metal vapors to diffuse into the discharge chamber [1].

anode concept for propellant flow control was never conclusively demonstrated. However, the principle of using the shim/main anode scheme to control main anode temperature was proven in separate tests using xenon as propellant so that the anode temperature, and hence mass flow rate, could be controlled independently of discharge current. Kieckhafer recorded plume diagnostics and thrust measurements of a BPT-2000 thruster modified to contain separate shim and main anodes and found little change in thruster performance when shifting the discharge current between the main anode and the shim anodes [7,8].

While bismuth was the focus for early work on condensable propellant thrusters at MTU, researchers soon identified other metals that provided different advantages for certain missions. In particular, the light metals zinc and magnesium were suitable candidates for use as Hall-effect thruster propellants. After publishing their initial magnesium and zinc results in 2009 [9], the MTU researchers learned of concurrent Busek work [10] and earlier Soviet work [11] with implementing magnesium as a thruster propellant.

Magnesium and zinc have a number of physical advantages as well as low ionization energies, which make them desirable for use as a propellant, while also possessing thermal properties that can avoid many of the materials issues encountered with bismuth thrusters. A comparison of traditional propellants, krypton and xenon, as well as the metal propellants of interest is shown in Table 1.

The light metals can be used to achieve higher specific impulse than xenon at an equivalent discharge voltage. By operating at similar discharge voltage to modern thrusters, little would have to be changed to existing power processing units, voltage isolators, and other subsystems to realize a higher specific impulse thruster than one operated using xenon. Assuming an acceleration potential of 300 V and given the physical attributes of magnesium and zinc, magnesium would be ideal for missions requiring a specific impulse of approximately 4000 s whereas zinc suits missions near 2400 s. As an added benefit, Martian and lunar studies have shown that magnesium is found in Martian and lunar regolith [12,13], allowing for the possibility of refueling an exhausted propellant supply in space. While high specific impulse operation of magnesium and zinc thrusters may be attractive for deep space missions, the light metals could also be used to achieve moderate specific impulse of 1500–2000 s using a low-voltage direct-drive scheme that could significantly reduce thruster system mass for earth orbital missions.

The main challenge in using any condensable propellant is design of the feed system. While gaseous propellants such as xenon and krypton can easily be transported through plumbing and metered using well established technology, a condensable supply system requires power to drive the phase change from solid-to-vapor and some method for controlling the rate of delivery of evolved propellant vapors. Furthermore, because of the metallic nature of candidate condensable propellants, the entire feed system must be at high temperature and any wetted components will likely be electrically connected to the anode and, hence, at high potential. For early work with bismuth these cumulative challenges complicated the MTU development effort for two reasons:

1) Many components of the bismuth feed system needed to be maintained at temperatures over 800°C and, at these temperatures, material failure was an ever present issue most notably at junctions of dissimilar materials.

2) Because the feed system contained bismuth in the liquid state the material failures led to destructive propellant leaks, a difficulty compounded by bismuth's expansion upon freezing.

Magnesium and zinc have thermal properties that should avoid the main difficulties encountered with bismuth.

For an evaporative feed system, the propellant supply rate is governed by the feedstock vapor pressure and the surface area of evaporation. Fixing the surface area to be commensurate with the anode dimensions of a 2-kW Hall thruster, Fig. 2 shows the evaporation rate and, hence the propellant feed rate of bismuth, magnesium, and zinc as a function of temperature. Immediately apparent is the fact that magnesium and zinc have vapor pressures (and thus evaporation rates) that are some three to 4 orders of magnitude greater than bismuth. This means that the feed system components for a magnesium or zinc supply system can be considerably cooler than that of a bismuth system. The horizontal dashed line of Fig. 2 indicates a mass flow rate of 1 mg/s, which is approximately equal to what is required of a 2-kW-class Hall thruster. To supply 1 mg/s bismuth must be maintained at approximately 600°C, while magnesium and zinc require only 400 and 300°C, respectively. Another key factor making magnesium and zinc easier to use than bismuth is evident when considering the melting temperature of the solid metal as shown in Fig. 2. Since bismuth melts at 271°C the propellant feedstock will be in the liquid phase when evolving vapors at 600°C to produce 1 mg/s. However, both magnesium and zinc have melting temperatures significantly higher than the temperature required to evaporate 1 mg/s. Thus, a magnesium or zinc feed system need not handle any liquid metal: the vapors will sublimate directly from the solid at a rate sufficient to operate the thruster.

Table 1 Propellant comparison between the metals of interest, as well as common propellants [6]

Element	Atomic mass	Melting temperature, °C	First ionization potential, eV
Magnesium	24.3	650.0	7.646
Zinc	65.39	419.53	9.394
Bismuth	208.98	271.4	7.2856
Krypton	83.8	−157.38	13.9996
Xenon	131.3	−111.79	12.1298

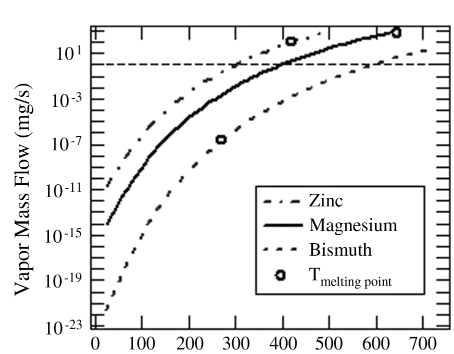


Fig. 2 Mass flow [6] as a function of temperature for bismuth, magnesium, and zinc with the horizontal dashed line indicating the temperature that each propellant must be to evaporate at 1 mg/s.

II. Goal of Study

The goal of the research reported here was to demonstrate the ability to operate a Hall-effect thruster with magnesium and zinc by directly sublimating propellant from the solid state. Preliminary findings will be presented from pathfinding experiments that were performed with consumable anodes. Following the initial results, data are presented from a hollow/porous anode design while implementing shim anodes in the discharge channel to control the propellant temperature.

III. Description of Apparatus

The thruster used for the experiments reported here was a modified Aerojet BPT-2000 Hall-effect thruster [8,14]. While the overall geometry and magnetic circuitry of the BPT-2000 was preserved, the interior boron nitride (BN) body and anode structure were modified to accommodate the inner and outer shim anodes as well as the new magnesium, zinc, and porous anodes [3]. The main thruster components and anodes are shown in Fig. 1.

Although functioning magnesium and zinc cathodes have been demonstrated at MTU [9], the tests reported in this paper utilized a standard LaB_6 gas-fed cathode built in-house. The cathode body was made of titanium and measures approximately 25 mm in diameter by 100 mm long. The cathode orifice was 4 mm in diameter and the propellant used was argon. A tungsten keeper electrode was placed approximately 3.5 mm from the cathode face and was referenced to ground potential.

Pathfinding experiments were conducted to demonstrate the ability to directly sublime magnesium and zinc from solid metal surfaces within a Hall thruster for use as a propellant supply. The objective of those experiments was merely to sublime a sufficient mass flow of metal vapor to sustain the plasma discharge, hence no mechanism was incorporated to control the supply rate. The first anode that was used in the thruster was made from magnesium and was machined from solid magnesium plate as shown in Fig. 3a. Tabs were included on the anodes for mechanical and electrical connection. For the target flow rates, each magnesium anode had enough propellant to operate the thruster for approximately 1 h. In subsequent tests, anodes were made by sandwiching multiple magnesium plates together for extended operation. The magnesium anode location within the thruster is shown in Fig. 3b.

In addition to the consumable anodes, another anode, similar in design to that shown schematically in Fig. 1, was manufactured with a porous diffuser and the capability to be refilled. The porous anode was utilized in combination with shim anodes in experiments to control the evaporation rate. Since the mass flow of metal propellants is a function of two controllable parameters, the open surface area and propellant temperature, the porous anode was designed so that the open area of the pores when combined with the anode temperatures reported by Kieckhafer [8] would produce the target mass flow rates. Because of propellant availability at the time of testing the porous anode was tested only with magnesium.

All of the reported testing was performed in a 2-m-diam by 4-m-long vacuum chamber. The chamber was evacuated using three magnetically levitated turbomolecular pumps capable of pumping at 2000 L/s each and backed by a mechanical pump with a pumping capacity of 400 ft^3/min. An operating pressure of 1×10^{-5} Torr or better was maintained while testing the condensable propellant thrusters.

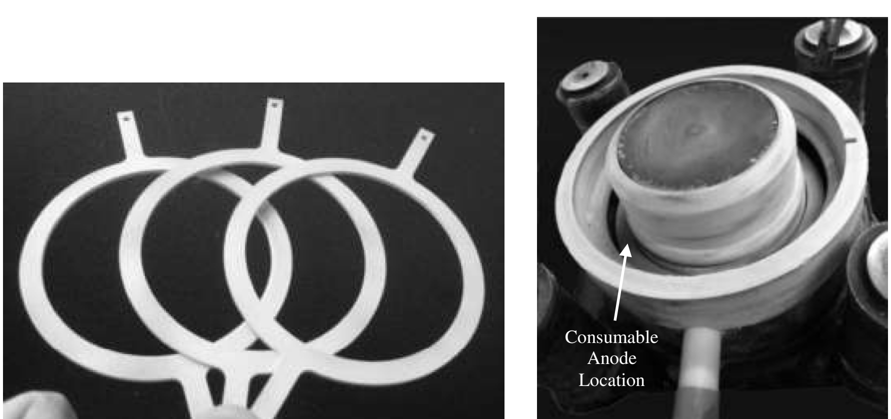
IV. Experimental Results and Discussion

A. Thruster Operation Using Magnesium Plate Anodes

To operate the thruster using consumable magnesium plate anodes the anode was first heated with approximately 650 W using two sets of resistive heaters. The resistive body heater was wrapped around the BN body and made up 290 W of the total heater power required. The anode heater was in a BN housing behind the anode and made up the remaining 360 W of heater power. The heater locations, thermocouple location, and consumable anode location are shown in the schematic in Fig. 4. The thermocouple was placed on the thruster's center axis in the middle of the center pole.

The anode was heated for 60 min while at a 100 V potential with respect to cathode, which was grounded. Applying 100 V of anode potential allowed for electron current to supply additional heat to the anode. Then the anode voltage was increased to 150 V to light the thruster. Once a plume was established, both resistive heaters were turned off. The anode power supply was then current-limited rather than voltage-limited as is customary for gas-fed thrusters. The current-limited mode was used to prevent thermal runaway of the discharge: as the consumable anode became overly hot and the evaporation rate increased, the current-limited mode would cause the thruster discharge voltage to decrease and hence would reduce the thermal power to the consumable anode. In voltage-limited operation an overly hot anode would cause greater mass flow and, hence greater current. Increased current at constant voltage would increase the thermal power input to the anode and further increase the mass flow causing runaway. For most of the experiment the anode current was held at 4 or 5 A while the magnet current was constantly adjusted to maintain thruster operation. Because the voltages and currents were adjusted manually, these values varied throughout the experiment as investigators explored the criteria necessary to maintain a discharge sustained only by plasma heating. Despite open loop operation and lack of anode temperature control, it proved surprisingly easy to maintain thruster operation for more than 60 min, as shown in Fig. 5.

Since the propellant mass flow is directly coupled with the anode temperature and no attempts were made to control the anode temperature, the magnesium mass flow varied greatly, causing the discharge voltage of the thruster to vary between about 100 and 300 V during each experiment. Also, the geometry of the anodes



a) b)

Fig. 3 Images of a) three consumable magnesium anodes and b) a single magnesium anode inside the discharge channel of the thruster with the front plate and BN ring removed.

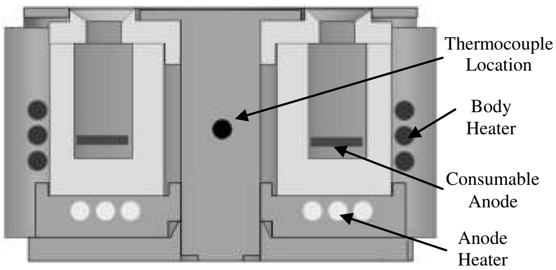


Fig. 4 Thruster cross section showing the anode, thermocouple, and resistive heater locations.

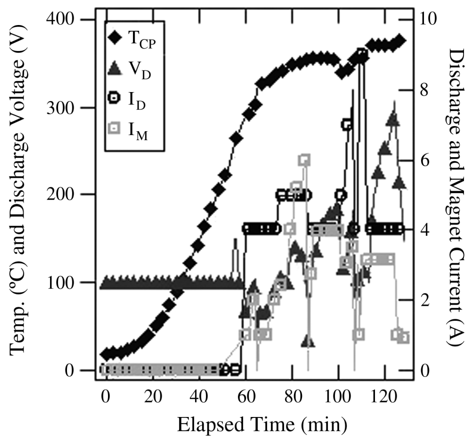


Fig. 5 Magnesium thruster data while operating using two consumable anodes. The data includes center pole temperature (T_{CP}), discharge voltage (V_D), discharge current (I_D), and magnet current (I_M). The uncertainty of the temperature data is ±2°C and the discharge current and voltage measurements are ±1% of the reported value.

limited the propellant supply of the thruster. Each anode could supply about 2 mg/s for approximately 30 min and a maximum of three magnesium anodes could be stacked within the discharge channel. Post-test inspection showed that the anode sublimed nearly uniformly around the circumference, with a wear-through point causing eventual mechanical failure. A picture of the thruster operating using magnesium is shown in Fig. 6. As is apparent in the image, using the consumable magnesium anodes it was possible to maintain a plasma discharge; however, no plume structure was discernible, likely due to the variability of the mass flow rate of propellant for the preliminary magnesium experiments since no attempts were made to control the mass flow rate for the preliminary experiments.

Fig. 6 Preliminary experiment showing a Hall-effect thruster operating using magnesium propellant and an argon cathode, with no attempt made to control the anode temperature and, hence, the mass flow rate.

B. Thruster Operation Using Zinc Anode

Since the demonstration of a Hall-effect thruster operating using magnesium proved to be a surprisingly successful task when compared with using bismuth, other metals were investigated as potential propellants. One of the few nontoxic metals that possessed a desirable vapor pressure was zinc. A consumable zinc anode that was machined from cylindrical stock is shown in Fig. 7.

To operate the zinc thruster a single resistive heater around the outside of the thruster body was used to heat the entire thruster with 370 W of power for 60 min. After the 60 min warm-up period the anode voltage was increased to 400 V while current-limiting the anode power supply at 3 A. After a few minutes the thruster lit at an anode voltage of 120 V and a current of 3 A. The resistive heater was then turned off and the magnet current was increased to about 4.5 A to keep the thruster operating. Over the course of the 30 min that each zinc experiment was performed the anode voltage increased from about 100 to 300 V, as shown in Fig. 8. It is reasonable to assume that increasing anode voltage at constant current corresponds to decreasing propellant mass flow.

A retarding potential analyzer (RPA) was used to determine the ion energy during each thruster experiment with shim anodes. The probe that was implemented was a four-grid RPA, as shown in the schematic of Fig. 9.

The first grid in the RPA, at the probe entrance, was electrically floating. The second grid was biased negatively with respect to plasma potential to ensure that only ions are allowed to enter the probe. The third grid is the ion repeller. The grid was biased from 0 to 300 V with respect to ground to filter the ions that can enter the probe.

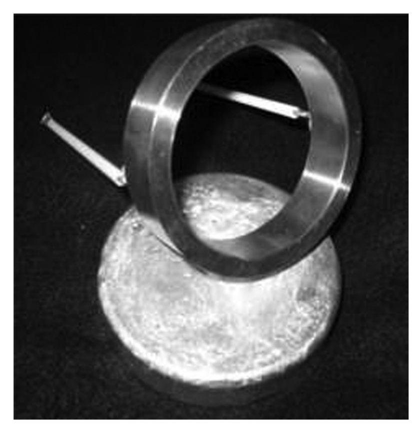


Fig. 7 Image of a consumable zinc anode before and after being machined.

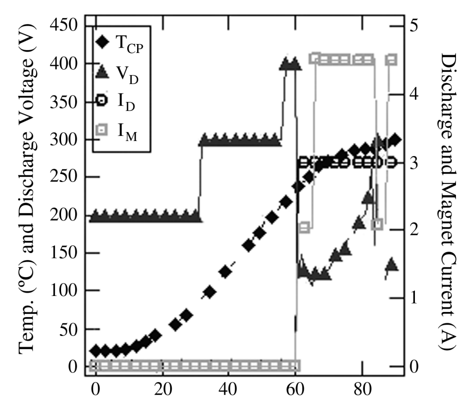


Fig. 8 Zinc thruster data while operating using a consumable anode. The data includes center pole temperature (T_{CP}), discharge voltage (V_D), discharge current (I_D), and magnet current (I_M). The uncertainty of the temperature data is ±2°C and the discharge current and voltage measurements are ±1% of the reported value.

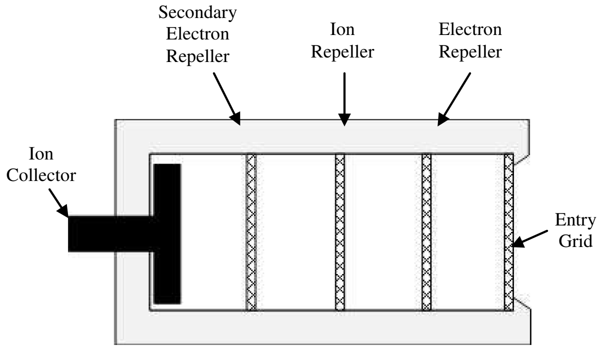


Fig. 9 Diagram of a four-gridded RPA showing the approximate grid locations and each grid's function.

Fig. 11 Hall-effect thruster operating with a well-structured plume at 3 A of anode current and 260 V using zinc propellant with an argon cathode.

As the grid potential is increased, only ions with a sufficient amount of energy can pass through. The fourth grid is biased with a negative potential to prevent any secondary electrons from escaping from the collector when it is struck with the high energy ions.

The four-grid RPA was placed 1 m downstream of the thruster on the thruster axis. RPA data were acquired at an operating condition of 220 V and 3 A on the main anode while the thruster was running. A smoothing spline was applied to the data and the RPA plot is shown in Fig. 10. The RPA data from the zinc thruster shows the peak ion energy at 189 ± 15 V.

As expected, the anode temperature increased due to direct anode heating from the discharge power and caused the zinc anode to melt in nearly every zinc thruster experiment. However, in the series of 30 min zinc experiments that were performed the ions in the plume had ion energies that corresponded well with the discharge voltage of the thruster. A picture of the zinc thruster operating at an anode voltage of 260 V at 3 A with a well-structured plume is shown in Fig. 11, however, it should be noted that throughout the duration of the experiment the structure of the plume varied greatly as discharge power levels, and hence propellant mass flow rates, changed.

C. Thruster Operation Using Porous Anode

After the pathfinding studies using consumable anodes demonstrated the ability to sublime sufficient propellant vapor to sustain a Hall thruster discharge, a hollow/porous anode was implemented so that investigators could perform repeated tests to explore the ability to control propellant mass flow using shim anodes. Along with the porous anode, the shims were introduced into the discharge channel to control the anode temperature, and subsequently the evaporation rate of propellant. A cross-section schematic of the thruster is shown in Fig. 12.

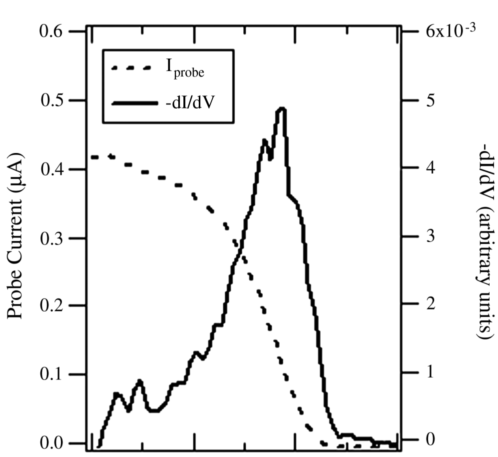


Fig. 10 Retarding potential analyzer I-V sweep and derivative of probe current with respect to repeller voltage with 220 V and 3 A on the anode and 4.5 A of magnet current during zinc operation. The probe current was smoothed by applying a smoothing spline and then differentiated to obtain $-\mathrm{d}I/\mathrm{d}V$. The maximum peak is 189 ± 15 V.

The goals of the experiment using the porous main anode and shim anodes were to 1) demonstrate the ability to stabilize the main anode temperature and thus the propellant supply rate and 2) increase/decrease the main anode temperature and propellant supply rate in a controlled manner. To accomplish these goals the thruster was preheated using the external body heater until the main anode temperature was approximately 450°C, whereupon the body heater was turned off and remained off for the duration of the test. The thruster discharge was initiated by setting both the main anode power supply and the shim power supply to current-limited mode with an initial start-up voltage of 300 V on both main and shim. The current limit on the main anode was 3 A and the shim anode was 1 A. The discharge initiated with the main anode voltage dropping to approximately 60 V and the shim voltage to approximately 40 V. The magnet current was set to 0.6 A and was not changed during the experiment. The temporal history of discharge parameters is indicated in Fig. 13. Over the next few minutes both the main and shim anode voltages were seen to drop, which indicated the mass flow was increasing. To remedy the increased mass flow, current, and thus heat, was removed from the main anode by reducing the main anode current limit while current was added to the shim anodes by increasing their current limit. Reduction of main anode current continued until 20 min into the test when the main anode current was brought to zero and the shim current was set to 5.0 A. This operating condition represented a stable point for the mass flow control system: the thruster ran steadily with 125 V on the main anode and 145 V on the shims with no change of parameters for more than 10 min.

The stability of the mass flow control system was surprising. As seen in Fig. 13 and 14 the main and shim anode voltages varied by only a couple of volts from 22 to 35 min and the main anode temperature varied by less than 2°C. The heat deposited into the shims and conducted through the body of the thruster to the main anode was apparently sufficient to provide a constant mass flow. Operating the electrodes in current-limited mode likely provided some form of stabilization: slight increases in main anode temperature would produce more flow which would, in turn, cause a decrease in voltage at constant current. Thus the net power into the thruster would be reduced in effect cooling the main anode and restoring equilibrium. This same effect would be reversed wherein

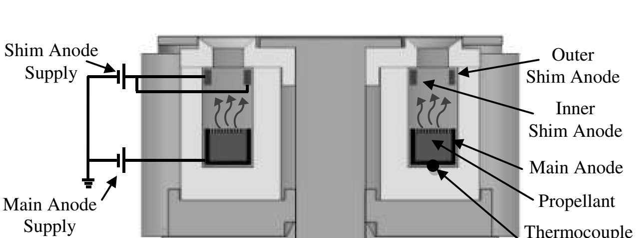


Fig. 12 Cross-section schematic of the condensable propellant thruster showing the main anode and shim anode locations.

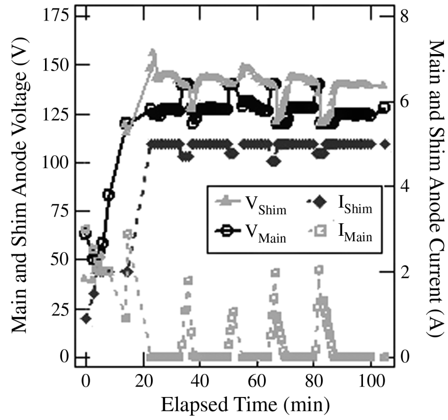


Fig. 13 ***I-V*** **plot for the shim anode and main anode for the 105 min porous anode experiment using magnesium propellant. The data includes shim anode voltage (V_{Shim}), shim anode current (I_{Shim}), main anode voltage (V_{Main}), and main anode current (I_{Main}). The uncertainty of the discharge current and voltage measurements are ±1% of the reported value.**

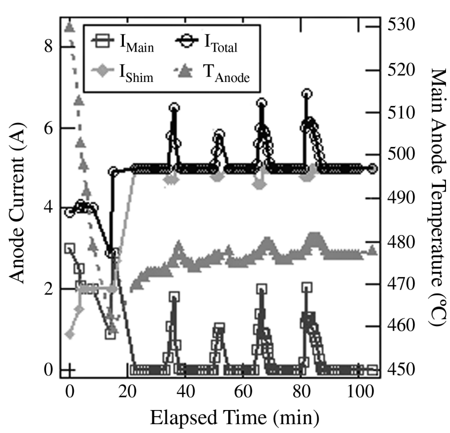


Fig. 14 Plot showing main anode current (I_{Main}), shim anode current (I_{Shim}), total anode current (I_{Total}), and the anode temperature (T_{Anode}) as current is shared between the main anode and shim anodes. The uncertainty of the discharge current measurements are ±1% of the reported value.

cooling of the main anode would result in increased voltage and power.

With stable operation established investigators addressed the second objective, which was to alter the mass flow in a controlled manner. The goal was to intentionally increase the main anode temperature, causing an increase in mass flow and hence total thruster current, then decrease the temperature and attempt to reacquire the stable operating point. To accomplish this, the main anode was changed from current-limited mode to voltage-limited mode. At the stable point (from 22 to 35 min) the main anode was at 0 A and 125 V. At 35 min the main anode power supply was set to 140 V in voltage-limited mode. This initially caused a very slight current of about 0.2 A on the main anode, increasing the power deposition into the propellant reservoir. Simultaneously the shim anode current limit was reduced by 0.2 to 4.8 A so that the total current remained at 5.0 A. Over the next three minutes, 1) the main anode current increased from 0.2 to 2.0 A, 2) the main anode temperature increased from 470 to 480°C, and 3) the total current (shim plus main) increased from 5.0 to 6.5 A. All of these factors indicate that the propellant supply rate was increased due to the increased thermal input to the main anode propellant reservoir.

At 38 min investigators attempted to reduce the propellant supply rate and return the thruster to the previously stable condition. The main anode was switched back to current-limited mode at 0.0 A and the shim anode current was set back to 5.0 A. Within two minutes the main anode cooled and the thruster discharge stabilized to its initial equilibrium point, where it remained without input from investigators. Such controlled excursions from equilibrium were repeated three more times and, each time, the results were the same and the thruster returned back to a stable operating point with constant mass flow. The overall test lasted for 105 min before being voluntarily terminated.

The temperature data that are reported in Fig. 14 are from a thermocouple that was spot-welded to the back of the anode, as shown in Fig. 12. As expected, the anode temperature increased each time current was shifted from the shim anode to the main anode, supporting the theory that the main anode temperature was driving an increase in propellant mass flow. Although the thermal peaks were slightly offset from the main anode current peaks and there is a gradual increase in anode temperature over 80 min, the delay in peaks and gradual temperature increase are attributed to the thermocouple location on the back of the anode. The actual plasma heating, which drove evaporation, was delivered to the downstream face of the anode, thus changes in anode thermal power very rapidly caused a change in evaporation rate even though the thermocouple on the back of the anode responded with some delay. A picture of the thruster operating at 4 A and 250 V with the magnesium-filled porous anode is shown in Fig. 15.

An RPA probe current vs repeller voltage sweep and the derivative of the sweep during magnesium thruster operation is shown in Fig. 16. A smoothing spline was applied to the raw data so that the data could be differentiated to obtain a typical RPA plot of $-\mathrm{d}I/\mathrm{d}V$.

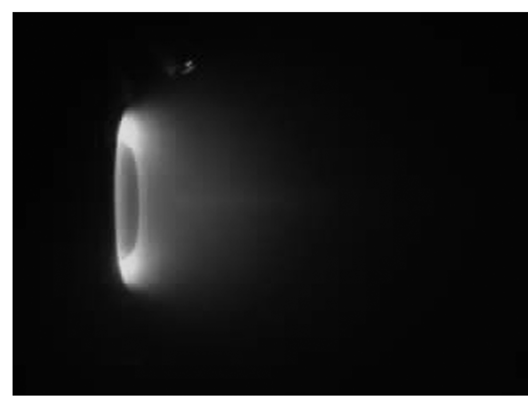


Fig. 15 Hall-effect thruster operating at 4 A of anode current and 250 V using magnesium propellant with an argon cathode.

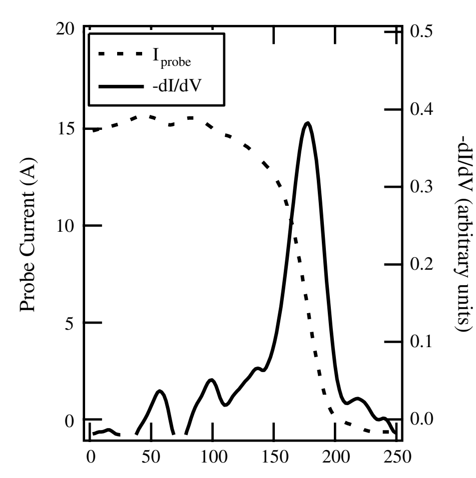


Fig. 16 Retarding potential analyzer ***I-V*** **sweep and derivative of probe current with respect to repeller voltage with 192 V and 4 A on the main anode, 187 V and 2 A on the shim anodes, and 3 A of magnet current during magnesium operation. The probe current was smoothed by applying a smoothing spline and then differentiated to obtain $-\mathrm{d}I/\mathrm{d}V$. The maximum peak is at 177 ± 15 V.**

When the RPA data were taken, the thruster was operating with 4 A and 192 V on the main anode and 2 A and 187 V on the shims. The RPA data show a peak ion energy at 177 ± 15 V.

V. Conclusions

This paper includes the first reported results of a Hall-effect thruster operating on zinc. Crude but successful pathfinding tests with consumable anodes showed that direct sublimation of magnesium and zinc propellant vapors from solid anodes using discharge plasma waste heat was surprisingly easy. The thermal properties of conventionally designed Hall thrusters are compatible with evaporation of propellant and no elevated temperatures or heaters are required beyond start-up.

The ability to control the propellant supply rate in an active manner utilizing separate evaporative and no-evaporative anodes to share plasma discharge current was demonstrated. Thermal control of the propellant reservoir and evaporator was demonstrated by operating the thruster using a porous hollow anode with inert shim electrodes intercepting a large fraction of the discharge current. This configuration proved stable using a combination of current- and voltage-limited supplies to maintain equilibrium. The equilibrium could be disturbed by directing a small amount of current and, hence, thermal power into the main anode. When shifting current to the main anode, the anode temperature would increase and hence increase the propellant mass flow. Shifting all of the main anode current back to the shim anodes cooled the main anode and enabled the thruster to return to the passively stable operating condition. Shifting the thruster discharge current between the main anode and shim anodes was repeated four times with consistent results [3].

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