

Performance Characteristics of a Magnesium Hall-effect Thruster

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The direct-evaporation magnesium Hall thruster exhibits thermal runaway when operated in voltage-limited mode. This paper reports on a method of controlling runaway mass flow by manipulating the pre-set current and voltage limits of the anode power supply. By choosing proper voltage and current limits, voltage-limited operation was achieved for periods of greater than 9 minutes without any active control scheme. Natural cyclic transitions into and out of voltage-limited mode with a period of a few minutes were observed and are attributed to a time delay between onset of power increase and temperature rise in the propellant. By adjusting the current and voltage limits, both the amplitude and the frequency of the cyclic oscillations were reduced such that the thruster was semi-stable. From this semi-stable operating point minor adjustments in the current to the electromagnets allowed true stabilization of the thruster discharge. Using this control scheme voltage-limited operation at 225 V and 5 A was sustained for more than two hours. Thrust data showed a peak thrust of 33 mN with a peak specific impulse of 2760 seconds, with a nominal efficiency of 31%. Relatively low efficiency is attributed non-optimum magnetic field and low flow rates.

Nomenclature

A_{open}	=	open area of anode face
I_d	=	discharge current
M	=	atomic mass
\dot{m}	=	mass flow rate
P_d	=	discharge power
$P_v(T)$	=	temperature dependent vapor pressure
T	=	temperature
V_d	=	discharge voltage

I. Introduction

XENON is the most widely used propellant for state-of-the-art Hall thrusters since it has the highest demonstrated efficiency of all atomic species that are gaseous at near-ambient operating conditions. Because it is gaseous in both storage and delivery, xenon is also a convenient propellant that can be integrated with spacecraft using well established gas feed system technology. However, if convenience is traded for performance then there are

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a number of atomic species other than xenon that may enhance or enable certain missions. Bismuth, for example, is a good alternative to xenon propellant for several reasons: bismuth has the highest molecular mass of all non-radioactive elements, it has a lower ionization potential than xenon, and it has a favorable vapor pressure. Bismuth is also solid at room temperature. This is a major benefit for ground testing, since the propellant exhausted from the thruster will condense on the room temperature walls of the vacuum facility, such that the vacuum chamber itself effectively pumps the propellant, greatly reducing the required pumping speeds of the vacuum system. Because of the reduction in required pumping speeds, a condensable propellant, such as bismuth, is ideal for use in high power thrusters. The potential for the use of bismuth as a propellant for Hall-effect thrusters was investigated in the Ion Space Propulsion (Isp) lab at Michigan Technological University from 2004-2008.^{1,2,3,4,5} In experiments performed by Massey et al,¹⁻³ a hollow anode with a porous face was developed to store liquid bismuth and deliver bismuth vapor into the discharge chamber. This method of direct evaporation utilized the waste heat from the plasma discharge to heat the bismuth propellant and produce the vapors necessary for operation.

Unfortunately there were several difficulties prohibiting the use of bismuth as a propellant. The anode temperatures required for operation, which were as high as 800 °C, caused many material failures, including catastrophic failure of several anodes.³ For this reason, other condensable propellants were explored. In 2009 experiments were performed in the Isp lab that demonstrated the use of zinc ($M = 65$ amu) and magnesium ($M = 24$ amu) as Hall thruster propellants.⁶ Zinc and magnesium both have desirable traits that make them good candidates for use as propellants. They have lower ionization potentials than xenon, allowing for increased operating efficiencies; they have lower molecular masses, increasing the attainable specific impulses at lower voltages; and like bismuth, they are both solid at room temperature – they are condensable propellants.

Magnesium in particular is very desirable as a Hall thruster propellant. Because of its low molecular mass, a thruster operating on magnesium at 300 volts could achieve a specific impulse on the order of 4000 seconds. Magnesium has also been found in both Martian and lunar regolith, which may allow for in-situ refueling.^{7,8} Magnesium also shows benefits over other condensable propellants such as zinc and bismuth; it has both a high melting point, 650 °C, and a high vapor pressure which allows for direct sublimation of propellant vapors from solid feedstock so that no liquid metal need be present anywhere in the propellant storage and delivery system. Magnesium was first explored as a potential Hall thruster propellant by Soviet researchers in the 1970s.⁹ Later experiments performed by Makela et al⁶ and Busek Co.¹⁰ in 2009 further demonstrated the potential of magnesium as a Hall thruster propellant.

The obvious fundamental difference between a gaseous Hall thruster and one employing condensable propellants is the need to somehow heat the condensable propellant to evolve sufficient vapors for discharge operation. Moreover, once the propellant is vaporized it must be metered and delivered to the thruster via a suitably hot supply system such that the propellant does not re-condense. One approach that has been used in the development of both bismuth¹¹ and magnesium Hall thrusters¹⁰ is to heat the solid propellant in a dedicated vaporizer located external to the thruster head and then pass these vapors to the anode, in a manner similar to that used for xenon thrusters, using heated supply lines. Work reported in this paper takes a different approach: the solid propellant is housed within the thruster head inside a hollow anode and this propellant is directly heated and vaporized by waste heat from the plasma discharge. The intended benefits of this approach are twofold: (1) there is no need for an external heater which would reduce the overall system efficiency, and (2) there is no need for heated propellant supply lines since solid feedstock can be delivered to the thruster head. This so-called direct evaporation approach was demonstrated in experiments performed by Makela et al,⁶ and Hopkins et al.¹² The hollow anode was designed with a porous front face to produce magnesium vapor and feed it into the discharge chamber without external heating. During operation, the refillable anode acted as the propellant reservoir, gas distributor and ion accelerator.

While using the direct evaporation approach eliminates the need for external heating, it also directly couples the mass flow rate with the thruster discharge conditions. Mass flow from the anode is determined by the temperature-dependent vapor pressure, $P_v(T)$, and the open area of the anode, A_{open} , as shown in equation (1).

$$\dot{m} = \frac{P_v(T)}{\sqrt{\frac{2\pi k_B T}{M}}} A_{open} \quad (1)$$

According to equation (1) for an anode with a particular open area, mass flow is dictated only by anode temperature. Therefore if the discharge power of the thruster increases, then so too will the amount of power deposited into the anode. Because the anode power deposition increases the temperature and mass flow rate also increase. Conversely, if the discharge power of the thruster decreases, then the temperature and mass flow decrease. Because of the direct coupling between discharge power and mass flow rate, the traditional method of operating the thruster – operation using voltage-limited power supplies – creates a scenario in which passively stable operation is not possible. With voltage-limited supplies, if the propellant temperature increases, mass flow increases, current increases, and discharge power increases, causing a further unsteady increase in temperature. If the propellant temperature decreases, mass flow decreases, current decreases, and discharge power decreases, which causes the temperature to decrease again. Thus, a voltage-limited thruster running in direct evaporation mode is inherently unstable and has been shown to exhibit runaway that either extinguishes the discharge or causes unacceptable heating. In an attempt to passively stabilize the thruster, the researchers at Michigan Tech operated a direct-evaporation magnesium Hall thruster using power supplies in current-limited mode rather than voltage-limited mode.^{6,12} Flow diagrams of voltage-limited and current-limited operation of a direct-evaporation metal propellant thruster are shown below in Figure 1.

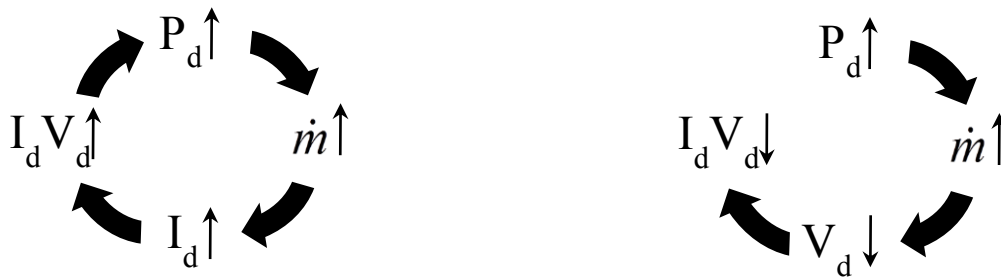


Figure 1. Left: Voltage-limited operation resulting in run-away current. Right: Current-limited operation arrests runaway mass flow.

Current-limited operation of a thruster is very different than voltage-limited operation. When operating in current-limited mode, the discharge voltage is determined by the plasma impedance which is largely affected by the mass flow rate of the propellant. If there is a disturbance from a stable point of operation such that the anode temperature and, with it, the mass flow increase, then the discharge voltage will decrease and, since the current is constant, the power will decrease, causing the temperature to decrease, correcting for the disturbance. If the disturbance is instead such that the temperature and mass flow decrease, then the discharge voltage and power will increase, causing the temperature to increase, again, compensating for the disturbance. The behavior of a thruster in either voltage-limited mode or current limited-mode can be qualitatively described using notional I-V characteristics of Hall thrusters like those shown in Figure 2.

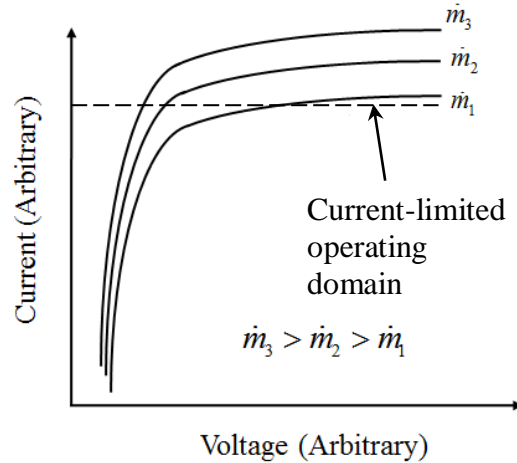


Figure 2. Using typical I-V characteristics of Hall thrusters, the behavior of a thruster operating in current-limited mode can be predicted and understood. The dashed line is indicative of current-limited operation.

Figure 2 shows the operation domain of a current-limited Hall thruster operating with the direct evaporation method. If the thruster is in current-limited mode with mass flow rate \dot{m}_2 and there is a small increase in propellant temperature, then the mass flow rate must increase to \dot{m}_3 . An increase in mass flow while current-limited must be accompanied by a corresponding decrease in discharge voltage, and therefore discharge power. With less discharge power, less heat is deposited onto the anode, causing a subsequent drop in propellant temperature, forcing the mass flow rate back towards \dot{m}_2 . Conversely if there is a small decrease in temperature while current-limited, then the mass flow rate of the thruster must decrease to \dot{m}_1 . A decrease in mass flow while current-limited must cause an increase in discharge voltage and therefore power. An increase in discharge power will deposit more heat on the anode and increase the temperature of the propellant, forcing the mass flow rate back towards \dot{m}_2 .

Hopkins et al¹² performed experiments to find passively stable operating points at voltages greater than 200 volts while operating the thruster in current-limited mode. Hopkins' investigation did produce some positive results, but also brought to light several difficulties associated with current-limited thruster operation. While current-limited operation tends toward stability, the control logic is that of the power supplies, which are not specifically tuned to stabilize temperature excursions in a Hall thruster. Because of the untuned nature of the control logic, the experiments did yield multiple current-limited operating points with voltages larger than 200 volts, but these operating points were only semi-stable and the thruster discharge always extinguished within ten minutes. Additionally, because discharge voltage is determined by passive operation parameters, the specific impulse (discharge voltage) of a thruster operating current-limited is not easily controlled. Finally, it is not known how to find the optimum magnetic field strength of a current-limited thruster, because traditionally the magnetic field of a thruster operating voltage limited is tuned to minimize the discharge current.

II. Goal of Study

Past research performed by Makela et al⁶ and Hopkins et al¹², demonstrated the feasibility of quasi-stable Mg Hall thruster discharge using current-limited operation. However, early work uncovered significant difficulty in choosing discharge conditions (current, voltage, and mass flow) a priori and, instead, the thruster settled into quasi-stable points that were unpredictable and not repeatable. The goal of the research reported here was to explore the capability of operating a direct-evaporation Mg Hall thruster in voltage-limited mode by arresting the thermal runaway through limits placed on the allowable discharge current. This paper expands on a recent conference paper¹³ by adding preliminary performance data.

III. Description of Apparatus/Experimental Design

The thruster used in the experiments reported here is a modified Aerojet BPT-2000 with a refillable porous anode. The anode used was the same refillable anode used by Makela et al,⁶ and was Anode 1 in Hopkins et al;¹² it has an open area (front face area through which vapors may pass) of $7.13 \times 10^{-4} \text{ m}^2$. In order to record anode temperature, a thermocouple was welded to the back of the anode. The cathode was a laboratory LaB₆ hollow cathode operating on argon. Thrust data was taken using a NASA-Glenn style inverted-pendulum null-displacement thrust stand.

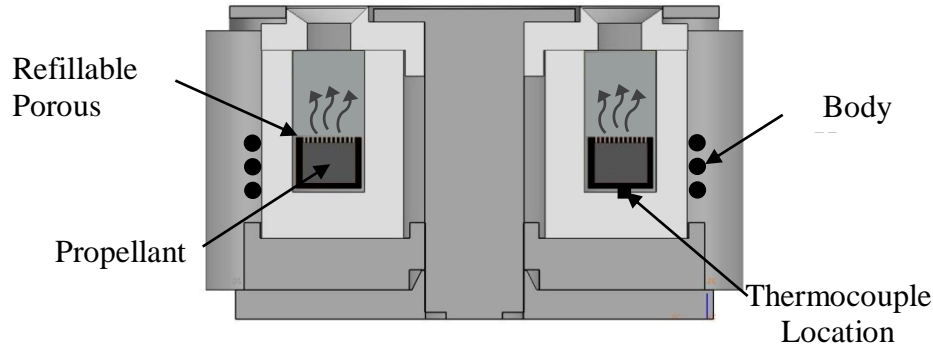


Figure 3. Section view of the magnesium Hall thruster showing the refillable porous anode, body heater, and thermocouple location.

To start the discharge a resistive heater wrapped around the body of the thruster is used to heat the anode and ignite the discharge. The heater provides approximately 450 watts of power and is used to heat the anode to a temperature of $\sim 450 \text{ }^\circ\text{C}$. Once discharge is established, the body heater is no longer used; all subsequent anode heating occurs from the discharge.

IV. Experimental Results/Discussion

For all of the experiments in Sections A and B the thruster was operated with a constant magnet current of 2 Amps, corresponding to a maximum radial magnetic field near the thruster exit of 140 Gauss. Magnet current was only adjusted to reignite the discharge in the case of interruption. If the thruster went out for periods longer than about 3 minutes the body heater was used to reheat the anode and re-start the thruster. Thruster telemetry including discharge voltage, discharge current, cathode coupling voltage, and magnet current was recorded electronically with a sample rate of 1 Hz, with the exception of anode temperature, which, due to electrical isolation issues, was recorded by hand.

A. Using the Current Limit to Arrest Runaway Mass Flow

For the first experiment, the hypothesis was that by operating the thruster voltage-limited to 400 volts runaway discharge heating could be arrested by setting the current limit to 6 amps. The results of the experiment agreed with the hypothesis; the current limit was successful in arresting the runaway discharge heating. From minute 0 to minute 1 the discharge power was heating the anode and increasing mass flow, as indicated by the steady growth of the discharge current. Between minute 1 and 1.2, the discharge current approached the current limit and the thruster transitioned from voltage-limited operation to current-limited operation, ending the runaway discharge heating, but leaving the thruster in an undesired low-voltage operating point. Figure 4 shows the experimental results.

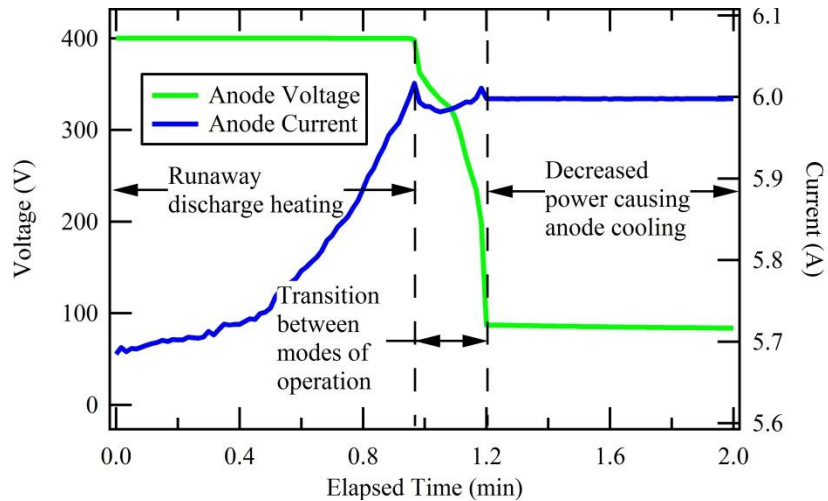


Figure 4. Results of voltage-limited operation using a current limit of 6 amps. The experiment shows that the current limit can successfully be used to arrest runaway discharge heating.

During the transition between voltage-limited and current-limited operation, the discharge power of the thruster dropped from a maximum power of 2.4 kW to less than 600 W. Because of the large drop in discharge power, the investigators hypothesized that the anode would begin to cool over time, which in turn would cause a decrease in the mass flow rate. Given that the thruster was operating in current-limited mode, a decrease in mass flow would directly correlate to an increase in discharge voltage. If the anode temperature and subsequently the mass flow rate decreased enough, the discharge voltage could possibly increase until reaching the voltage limit again, allowing for another period of voltage-limited operation. It was because of this possibility of a second period of voltage limited operation that the thruster was allowed to continue operation current-limited. It was hypothesized that after a period of cooling the voltage may rise again, and re-enter voltage-limited mode. The results are shown in Figure 5.

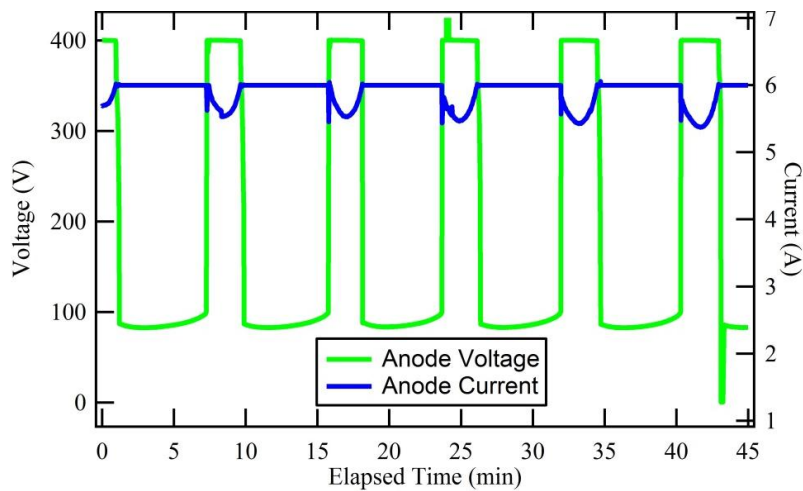


Figure 5. Operation of the magnesium thruster using the current limit to correct for runaway voltage. Each time the thruster operates in constant voltage, the propellant heats, mass flow increases, and current starts to run away. The current limit forces the voltage and discharge power down, arresting the runaway current. It was found that the power deposited on the anode face during the period of current-limited operation was low enough that the anode cooled, and mass flow decreased until the thruster transition from current-limited to voltage-limited operation once more.

As Figure 5 shows, when the thruster operated voltage-limited and current ran away, the current-limit forced the discharge power down, allowing the anode to cool and the mass flow rate to decrease. When the mass flow rate decreases, the discharge voltage begins to increase again and eventually the thruster re-enters voltage-limited mode. The result is a series of cyclic transitions between voltage-limited and current-limited operation, which will be referred to as discharge cycles. A more detailed examination of a single cycle is shown in Figure 6, where discharge voltage, discharge current, magnet current, and cathode coupling voltage for one complete oscillation are all plotted versus time.

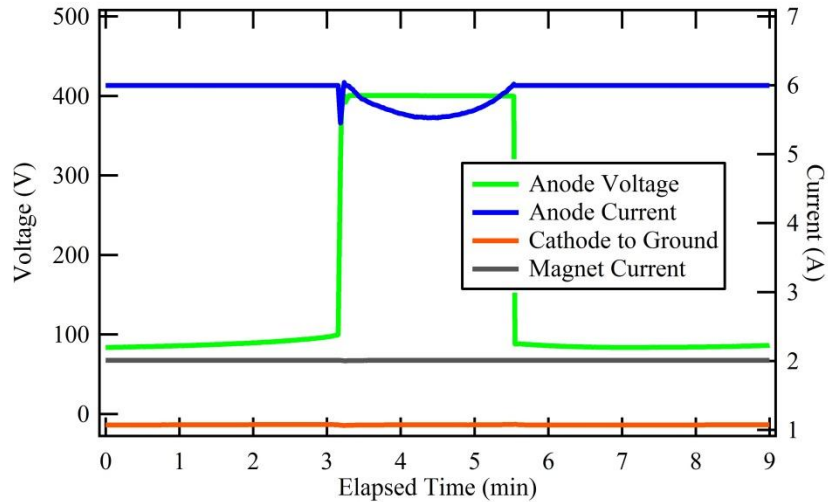


Figure 6. One complete discharge cycle showing discharge voltage, discharge current, magnet current, and cathode coupling voltage. From minute 0 to minute 3 the anode is cooling. From minute 3 to 5.5 the anode is being heated due to the increased discharge power. From minute 5.5 to minute 9 the anode is cooling again.

As is shown in Figure 6, at minute 0 the thruster has just transitioned from voltage-limited mode to current-limited mode, and therefore had a mass flow rate that was too large for operation in voltage-limited mode. The anode was then cooling from 0 until about 3 minutes, due to the low discharge power, which caused the voltage to slowly rise over this time period. However, until about 3 minutes the voltage (power) increased very slowly and, though this increase in power counteracted the cooling by slowing the rate of temperature decrease, the anode temperature continued to drop. Eventually the voltage made a sharp increase as the anode cooled to the point where the thruster operating conditions reached the intersection of the constant current line and the ‘knee’ in the I-V distribution as shown in Figure 2. Since the voltage limit on the power supply was set to 400 V, the thruster was forced to operate at this level. At this point the discharge current was mass-flow limited. This jump in voltage then caused a jump in discharge power, which would cause the anode to start re-heating, increasing the mass flow and in turn allowing the voltage to come down. However, there appears to be a time lag between when the power deposited into the anode front face increases and when the propellant, which is inside the anode, actually starts to increase in temperature. According to Figure 6 this time lag appears to be about 1.5 minutes; at the 4.5 minute mark the increase in discharge power that occurred at 3 minutes finally starts to affect the propellant temperature causing the mass flow to increase, the discharge current to increase, and eventually the thruster falls out of voltage-limited mode back to current-limited mode at about 5.5 minutes. This cycle was then seen to repeat as shown in Figure 5.

Taking the heat conduction through the stainless steel anode into account, it is important to examine the temporal differences in changes to discharge power, propellant temperature, and the temperature measured at the back of the anode. The examination of Figure 6 revealed what appears to be a 1.5 minute time lag between an increase in discharge power, and the apparent propellant temperature increase and corresponding rise in mass flow rate. To better examine the relationship between discharge power, propellant temperature, and the temperature at the back of the anode, discharge power (as calculated from Figure 6) was plotted with anode temperature in Figure 7. The anode and propellant started at ~ 450 °C in current-limited mode. The thruster had recently transitioned from voltage-

limited to current-limited operation, resulting in a low discharge power (~500 W). Because of the low discharge power, the temperature of both the anode and propellant were decreasing from minute 0 to minute 3. At minute 3 the voltage rose dramatically and the thruster transitioned into voltage-limited mode due to the decreasing propellant temperature and decreasing mass flow rate. Even with the substantial increase in discharge power, the anode and propellant temperatures continued to fall from minute 3 to minute 4.5. At minute 4.5 the heat deposited on the face of the anode by the increased discharge power reached the propellant, as indicated by the increasing discharge power in voltage-limited mode. From minute 4.5 to 6 the temperature at the back of the anode continued to fall. The heat from the increase in discharge power finally reached the back of the anode at minute 6, when the measured temperature finally increased. The total time between the increased discharge power, and the measured temperature change at the back of the anode was 2.5 minutes, which is consistent with the apparent lag between increased discharge power and the increase in mass flow rate.

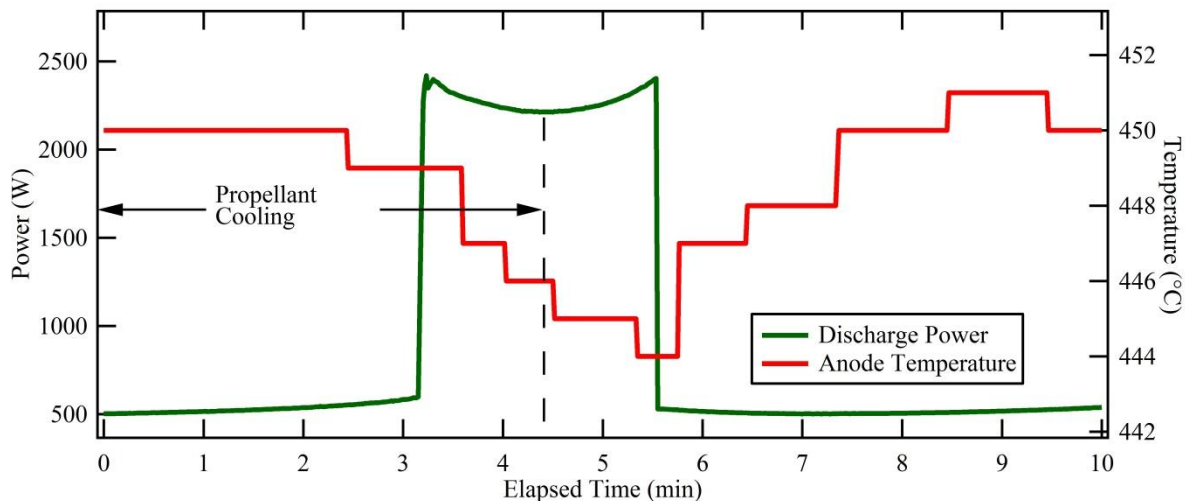


Figure 7. One full discharge cycle showing discharge power at the anode face and temperature at the back of the anode. While the input power sharply increases at 3, the temperature does not start increasing until minute 6. This is due to the conduction time from the front of the anode, where heat is deposited from the discharge, to the back of the anode, where the thermocouple is located. This is the same discharge cycle as that shown in Figure 6.

B. Voltage and Current Limits

It is also important to isolate and understand the effects of the voltage and current limits chosen for thruster operation. During the current-limited portions of the discharge cycle, the power is lower than when in the voltage-limited mode and thus the propellant is cooling, as was shown in Section A. It was hypothesized that by increasing or decreasing the power supply pre-set current limit, the amount of power deposited on the anode during the current-limited portion of the discharge cycle could be increased or decreased. By increasing the power deposited on the anode during current-limited operation, it was expected that the thruster would cool more slowly during the current-limited portion of the discharge cycle and the thruster would remain current-limited longer. Conversely by decreasing the current limit, the amount of power deposited on the anode during the current-limited phase of the discharge cycle would decrease, causing the thruster to transition to voltage limited mode faster. Figure 8 shows two different discharge cycles with different current limits.

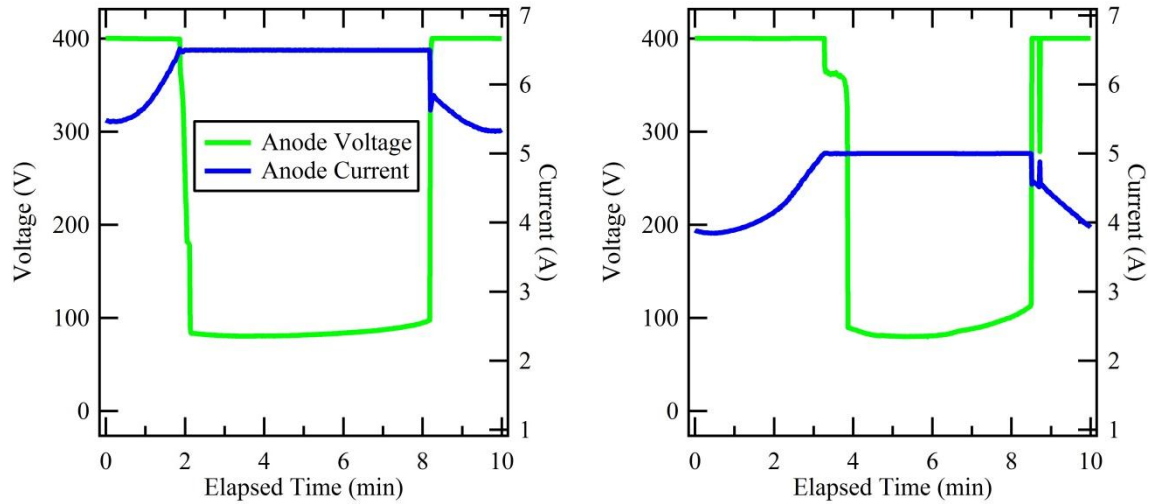


Figure 8. Cooling portions of two discharge cycles with different current limits. Left: discharge cycle current-limited to 6.5 amps with a minimum power of 523 W. Right: discharge cycle current limited to 5 amps with a minimum power of 400 W.

The result of varying the current limit did reveal a correlation between the lengths of time spent current-limited in the discharge cycle and the current limit. The time spent current-limited for a pre-set maximum of 6.5 A was 6 minutes with a minimum discharge power of 523 W, while the time current-limited for the discharge cycle with a 5 A current limit was only 4.5 minutes with a minimum power of 400 W.

Just as the current limit dictated the amount of time the thruster spent in the current-limited (cooling) portion of the discharge cycle, so too should the voltage limit dictate the amount of time spent in the voltage-limited (heating) portion of the discharge cycle. The effect of the voltage limit on the discharge cycle was measured and the results are shown in Figure 9.

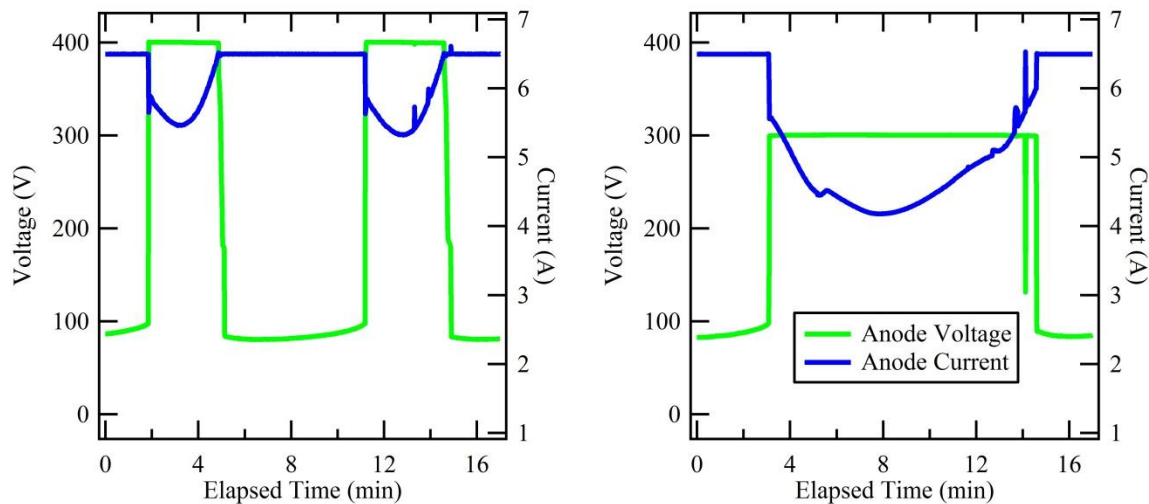


Figure 9. The heating portion of two different discharge cycles with a current limit of 6.5 amps. Left: Discharge cycle with a 400 volt voltage limit. Right: Discharge cycle with 300 volt voltage limit.

By lowering the pre-set maximum voltage limit of the discharge power supply, the amount of time the thruster is able to operate voltage-limited can be increased. When limited to 400 volts the step change from current-limited-mode into voltage-limited-mode is accompanied by a step change in discharge power of 1.95 kW. This large power

increase quickly heats the thruster into runaway, which is arrested by a transition back into current-limited mode. When the voltage limit was decreased to 300 V the step change in power is only 1.3 kW and thus the heating happens more slowly. As shown in the plots the thruster operated in voltage-limited mode for ~4.5 min per cycle when the pre-set maximum was 400 V; when limited to 300 volts the thruster was voltage-limited for ~9.5 min per cycle.

The sudden transition into and out of voltage-limited mode happens because of the intersection of the constant current line with the knee of an I-V trace associated with a particular mass flow (for instance, as the thruster cools from \dot{m}_2 to \dot{m}_1 along the constant current line in Figure 2). Since the I-V curve is relatively flat to the right of the knee small changes in temperature (mass flow) cause large changes in voltage. For instance as the thruster is cooling such that the progression is from larger to smaller mass flow the thruster suddenly jumps from 100 V – which must be the knee in the I-V trace – to the pre-set voltage limit of 400 V. This sudden and large increase in power reverses the cooling trend and transitions the thruster back into current-limited operation. By decreasing the pre-set max voltage below 400 V the effect is to limit how far to the right of the knee the thruster can jump and, also, how much additional power is associated with the transition into voltage-limited mode. Thus, reducing the pre-set maximum voltage decreases the amount of power increase to the anode and extends the amount of time that the thruster spends in voltage-limited mode before heating itself back into current-limited mode.

C. Active Stabilization in Voltage-limited Operation

Figure 8 and Figure 9 showed the ability to make the thruster more stable, that is, to reduce both the amplitude of the voltage oscillations as well as the frequency, by adjusting the pre-set values at which the power supply transitioned from constant-current to constant-voltage. While it is tempting to expect a stable point where the pre-sets are adjusted such that the excursions are vanishingly small in amplitude and the period very long, the existence of such a point would be fortuitous. The amplitude of the oscillation is dictated by the shape of the I-V curve in the vicinity of the knee and this shape is an inherent characteristic of the thruster that is not necessarily ideal for thermal control. However, if the pre-sets can be chosen such that the voltage excursions are ‘small enough’ and the period ‘long enough’ then it may be possible to incorporate some additional power control mechanisms that can be used exclusively to stabilize the discharge by inducing only small changes to the anode temperature.

It is well known that the discharge current in a Hall thruster operating in constant-voltage (mass-flow-limited) mode can be directly controlled by varying the current through the electromagnets, so work reported here attempted to use the magnet current to control the power input to the anode and, thus, the propellant temperature to stabilize the thruster thermal excursions. Furthermore, if the power supply pre-sets were chosen such that the thruster was in a semi-stable mode, meaning the oscillation amplitude and frequency were suitably small, then only small changes in magnet current would be necessary to maintain thruster operation in voltage-limited mode and prevent over-heating into current-limited mode.

A set of experiments were designed to determine if it was possible to use small variations in magnet current to stabilize a direct-evaporation Hall thruster in voltage-limited mode by starting from a semi-stable operating point. The semi-stable point was chosen by analyzing the total average power required to produce sustained evaporation of propellant. A plot of discharge power vs. time as calculated from Figure 5 is plotted in Figure 10 for many discharge cycles. While the power oscillates and the oscillation amplitude and frequency vary depending on the chosen pre-set voltage limit it is interesting that the time-average power draw of the thruster is about 1 kW. It was reasoned that 1 kW of discharge power corresponded to a mass-flow rate that might yield a semi-stable operating point.

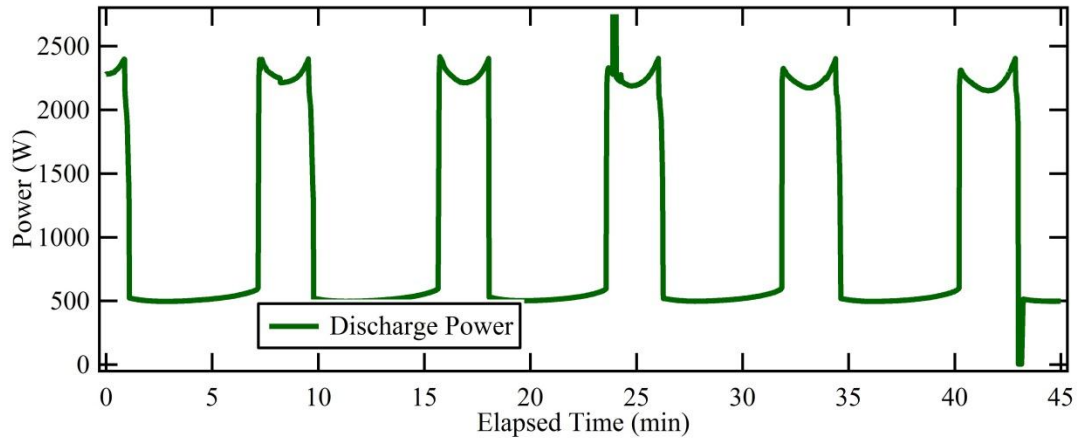


Figure 10. 45 minutes of discharge power cycles.

The pre-set voltage limit was set to 225 volts so that operation was relevant to a reasonable specific impulse that might be used in an application. To operate the thruster at a discharge power of 1 kW at 225 volts the discharge current would need to be kept to ~4.5 amps. The discharge current was controlled through small manual adjustments to the magnet current made from the magnet power supply front panel; if the discharge current started to climb, the magnet current was increased, if the discharge current started to fall the magnet current was decreased. The results of the constant voltage experiment are shown below in Figure 11.

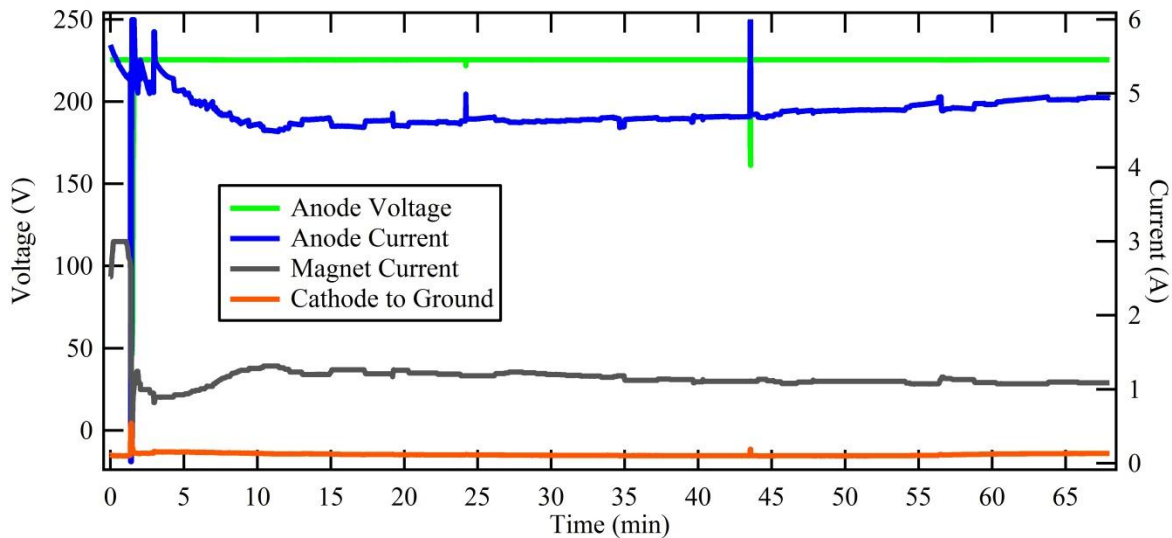


Figure 11. Constant voltage operation of the magnesium Hall thruster was achieved for more than an hour. Mass flow was controlled by manually adjusting the magnet current to increase or decrease discharge power.

As Figure 11 shows, constant voltage operation of the magnesium Hall thruster was achieved for 69 minutes until the experiment was voluntarily terminated. Stability of the discharge current was maintained manually by adjusting the magnet current. If the discharge current was rising, then the magnet current was increased, forcing a decrease in the discharge current and power, cooling the anode and decreasing the mass flow. If the discharge current was falling, then the magnet current was decreased, allowing an increase in the discharge current and power, heating the anode and increasing mass flow. Figure 12 shows the correlation between magnet current and discharge current showing that the magnet current can be used to provide an almost instantaneous control of the discharge

current and hence power deposited into the anode. The magnetic field varied only by $\sim 20\%$ over the course of the steady run, indicating that only slight changes in the magnetic field are necessary to stabilize the thruster; these magnetic field variations should have little measurable effect on thruster performance. Furthermore the size of the magnet current adjustment increments was chosen arbitrarily by the user and did not incorporate any control theory that might enable greater stability.

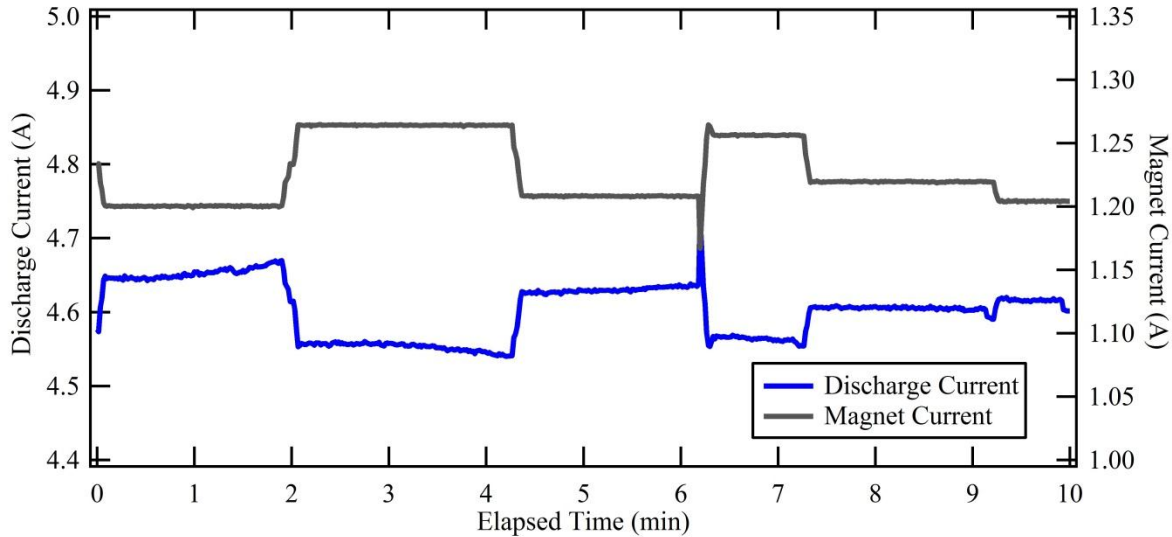


Figure 12. The discharge current of the thruster was controlled by minor adjustments in the current through the electro magnets. If the discharge current was falling, magnet current was decreased to raise the discharge current, heat the propellant and increase mass flow. If the discharge current was rising, magnet current was increased to decrease the discharge current, cool the propellant and decrease mass flow.

D. Performance Data

Thrust data were taken using a NASA-Glenn style, inverted-pendulum, null-displacement thrust stand. The thruster was operated in constant-voltage mode at 225 volts and approximately 5 amps for more than 2 hours. The results of the test are shown in Figure 13. In order to calculate the mass flow rate of the thruster, the anode was loaded with propellant and the pre-test mass was recorded before assembling the thruster. Immediately after the experiment, when the thruster had cooled to ambient temperature, the thruster was disassembled and the post-test mass of the anode was recorded. The difference in the pre- and post-test measurements was the total propellant used during the thruster test. As shown in Figure 13, after approximately 128 minutes of operation, the thruster was allowed to cool until the discharge extinguished; the point at which the thruster extinguished indicated the point at which the mass flow rate had dropped significantly from normal operation and served as the stop time for the mass flow calculation. Dividing the total propellant used by the run time, that is, the total amount of time the thruster was on (from minute 0 to minute 136.1 in Figure 13) yields a mass flow rate of 1.35 mg/s. Because a significant amount of propellant was evaporated while the thruster was initially heated before the discharge was started, as well as after the thruster was turned off and cooling down, this 1.35 mg/s flow rate was considered the worst case mass flow rate and used as the upper bound on the mass flow rate. Based on recorded anode temperatures from previous tests, it was known that the mass flow rate of the thruster during the current-limited portion of operation was much greater than the mass flow rate during the voltage-limited operation. To compensate for the heat-up and cool-down losses and the higher flow rates while the thruster was current limited (from minute 0 to minute 10.77), the mass flow rate was assumed to be two times greater during current-limited operation than during the time voltage-limited operation (minute 10.77 to minute 136.1). This adjustment yielded a nominal mass flow rate of 1.25 mg/s during voltage-limited operation (minute 10.77 to minute 136.1). A lower bound on the mass flow rate was determined by assuming the flow rate was four times greater during current-limited operation than during voltage-limited operation. The error in thrust was calculated by adding the root-mean-squared-error of the calibration curve and two standard deviations of the noise in the measured thrust. The peak thrust measured was ~ 32.75 mN correlating to a peak specific impulse of ~ 2670 seconds. On average, the thruster operated at ~ 30.5 mN with a specific impulse of ~ 2500

seconds. Using these results the average efficiency of the thruster was found to be ~31% with a peak of ~35%. All of these values are calculated using the nominal mass flow rate of 1.25 mg/s along with the actual instantaneously measured thrust and power.

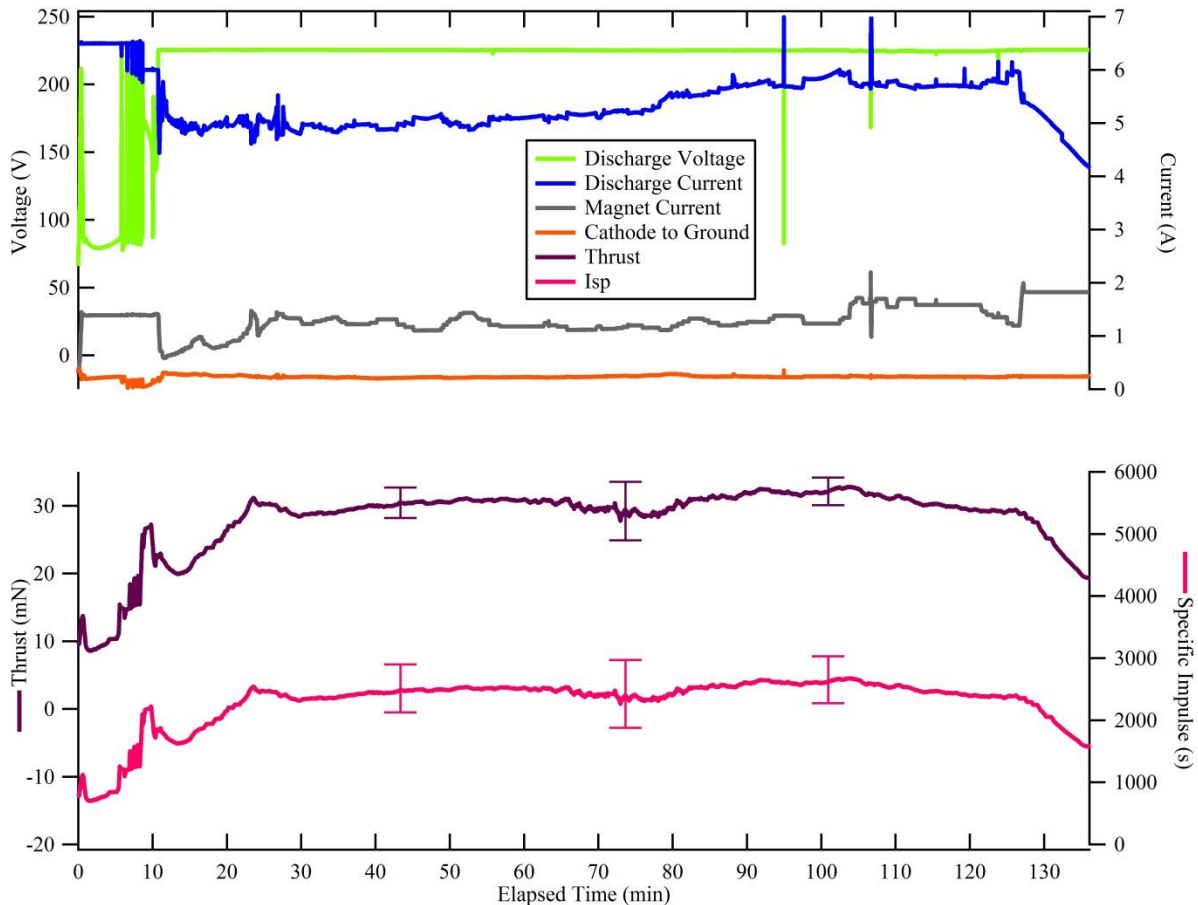


Figure 13. Results of performance testing on the magnesium Hall-effect thruster are displayed. Constant-voltage operation was achieved for more than two hours, allowing for a reliable time-averaged mass flow rate to be calculated. The highest measured thrust was ~32.75 mN correlating to a peak specific impulse of ~2670 seconds. Representative error bars for thrust and specific impulse are displayed.

There are several likely causes of the low efficiency exhibited by the thruster. First, it is possible that the loss in propellant mass during the initial heat-up, current-limited operation, and final cool-down was much more significant than was assumed previously. If the mass flow rate during the current-limited portion of the test was 8 times higher than the mass flow rate during the voltage-limited portion of the test, then the peak specific impulse would be 3750 seconds, an increase of 40% from the reported value of 2670 seconds. Since the evaporation rate is exponentially dependent on the anode temperature it is not unreasonable to assume that the mass flow rate during heat-up was ~8x or more than the nominal time-averaged rate.

The second major cause of error was operating the thruster without optimizing the magnetic field strength. Traditionally the optimum magnetic field strength is that which minimizes the discharge current of the thruster while operating in constant voltage mode. For the direct evaporation magnesium thruster, this method was complicated due to the direct coupling of mass flow rate and discharge current. In order to determine the optimum magnetic field strength, the magnet current was rapidly swept and the discharge current recorded. By performing a rapid sweep in magnet current, the thermal response of the anode was too slow to affect the mass flow rate. The results of this experiment can be seen in the graph in Figure 14. As shown by the graph, the discharge current was minimized at a magnet current of 1.84 Amps. After re-examining Figure 13 it is apparent that the thruster was not operated at the optimum magnet current.

The third major source of inefficiency may be from a low electron impact ionization frequency. A xenon thruster operated using a molar flow rate similar to that which is reported here for the magnesium thruster, would undoubtedly have a much higher overall efficiency. However, taking into account the reduction in molecular weight from xenon to magnesium along with their respective ionization cross sections, there is a 30% drop in the ionization collision frequency.

V. Conclusion

It was found that a magnesium Hall-effect thruster operating using the direct evaporation method can function in voltage-limited mode for minutes at a time by using the current limit of the power supply to arrest runaway current. Transitions into and out of voltage-limited mode were repeatable such that the thruster operated in a discharge cycle with a period on the order of minutes. By intelligently selecting the current and voltage pre-sets for transition into and out of voltage limited mode both the amplitude and the frequency of the discharge cycle oscillations were reduced such that the thruster was nearly stable. True stability was then achieved by using small adjustments in thruster magnet current to finely control the anode power deposition, enabling steady constant-voltage operation for more than two hours, during which a thrust of 32.5 mN and a specific impulse of 2760 seconds were measured with a total efficiency of 31%.

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References

- ¹ Massey, D., A. Kieckhafer, J. Sommerville and L. B. King, "Development of a Vaporizing Liquid Bismuth Anode for Hall Thrusters", *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA-2004-3768, Fort Lauderdale, Florida, 2004.
- ² Massey, D. R., L. B. King and J. M. Makela, "Progress on the Development of a Direct Evaporation Bismuth Hall Thruster", *International Electric Propulsion Conference*, IEPC-2005-256, Princeton, NJ, 2005.
- ³ Massey, D. R., "Development of a Direct Evaporation Bismuth Hall Thruster", *Doctoral Dissertation*, Michigan Technological University, 2008.
- ⁴ Makela, J. M., L. B. King, D. R. Massey and E. C. Fossum, "Development and Testing of a Prototype Bismuth Cathode for Hall Thrusters", *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA-2005-4236, Tucson, Arizona, 2005.
- ⁵ Makela, J. M., D. R. Massey and L. B. King, "Bismuth Hollow Cathode for Hall Thrusters", *Journal of Propulsion and Power*, 24, 1, 142-146, 2008.
- ⁶ Makela, J. M., R. L. Washeleski, D. R. Massey, L. B. King, M. A. Hopkins, "Development of a Magnesium and Zinc Hall-effect Thruster", *International Electric Propulsion Conference*, IEPC-2009-107, Ann Arbor, MI, 2009.
- ⁷ Landis, G. A., "Materials refining on the Moon", *Acta Astronautica*, 60, 10-11, 906-915, 2007.
- ⁸ Banin, A. and R. L. Mancinelli, "Life on Mars? I. The Chemical Environment", *Adv. Space Res.*, 15, 3, 163-170, 1995.
- ⁹ Gnedenko, V. G., V. A. Petrosov and A. V. Trofimov, "Prospects for using metals as propellant in stationary plasma engines of Hall-type", *International Electric Propulsion Conference*, IEPC-95-54, Moscow, Russia, 1995.
- ¹⁰ Szabo, J., M. Robin, J. Duggan and R. Hofer, "Light Metal Propellant Hall Thrusters", *31st International Electric Propulsion Conference*, IEPC-2009-138, Ann Arbor, MI, 2009.

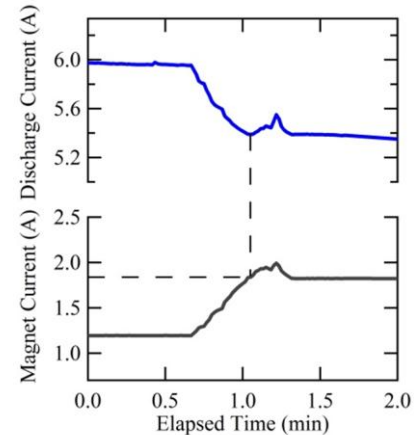


Figure 14. A graph of magnet current and discharge current showing the optimum magnet current is 1.84 Amps, as verified by the local minimum in the discharge current.

¹¹ Marrese-Reading, C., T. Markusic, K. Polzin, T. Knowles, J. Mueller, “The Development of a Bismuth Feed System for the Very High Isp Thruster with Anode Layer VHITAL Program”, *International Electric Propulsion Conference*, IEPC-2005-218, Princeton University, 2005.

¹² Hopkins, M. A., J. Makela, R. Washeleski, L.B. King, “Mass Flow Control in Magnesium Hall-effect Thruster”, *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Paper No. AIAA-2010-6861, 25-28 July 2010, Nashville, TN.

¹³ Hopkins, M. A., L.B. King, “Active Stabilization of a Magnesium Hall Thruster in Constant Voltage Mode”, *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Paper No. AIAA-2011-5890, 31 July-3 August 2011, San Diego, CA.