High Specific Impulse Vacuum Arc Thrusters with Novel Electrode Designs and Arc Operation

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Abstract: **Vacuum arc thrusters (VATs) have shown potential as a simple, safe and lightweight pulsed plasma microthruster solution for micro-and nano-satellites. However, most low-power VATs (1–20 W) to date typically experience relatively modest levels of specific impulse (300–600 s). Limits to VAT performance are largely due to (1) the significant fraction of pulse energy used for ionization of the cathode fuel, and (2) excess melting of the cathode during arcing, which does not contribute towards thrust but contributes as much as 50% of the overall fuel consumption rate. The electrode arrangement also exerts a contributing influence on the behavior of the VAT plasma jet and overall performance. To address and mitigate these undesirable characteristics of the VAT, design improvements such as the use of an axial magnetic field to collimate and accelerate the outgoing plasma jet, have been previously demonstrated in literature to improve VAT thrust by up to 50%. However, a large variety of new and alternative thruster designs and arc behavior remain unexplored. This paper reviews the authors' latest efforts to further enhance the performance of the VAT by non-magnetic means. A number of novel electrode designs, fuels and thruster operating techniques were identified and characterized. These included the use of millisecond-long arc pulses, conically-shaped cathodes, discrete anode switching, and carbon graphite cathode fuels. Performance testing on several enhanced experimental VAT prototypes demonstrated significant improvements in average thrust production rates as high as 380 µN/A and average cathode fuel erosion rates as low as 33 µg/C. Specific impulse values of I_{sp} = 800–1000 s were measured in a number of these thruster prototypes, a substantial improvement over the current state-of-the-art and higher than any previously published specific impulse value experimentally measured in a VAT. The role of cathode spot motion and cathode material properties on VAT performance were recognized as key design factors. These findings extend both the possible performance range of VATs and present understanding of VAT design.**

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Nomenclature

C_T	=	thrust correction factor
E_r	=	erosion rate
I	=	arc current
I_i	=	ion current
I_{sp}	=	specific impulse
g	=	gravitational constant, 9.81 m/s^2
$\dot{m}_i$	=	ion mass flow rate
Q	=	total cumulative arc charge
T	=	thrust
T/I	=	thrust per arc current
T/P	=	thrust-to-power ratio
v_i	=	average ion velocity
Z	=	average ion charge state
η	=	thruster efficiency

I. Introduction

THE Vacuum Arc Thruster (VAT) is a form of electric propulsion (EP) that operates by producing a current-driven pulsed arc discharge between two electrodes (cathode and anode) by means a pulsed power circuit or pulse forming network (Ref. 1). The discharge, termed a 'vacuum arc', forms microscopic emission sites on the cathode surface. These sites (called 'cathode spots') eject vaporized and ionized cathode material, creating a dense high-speed plasma jet for thrust. Fig. 1 illustrates the basic operation of the VAT and the products resulting from the vacuum arc discharge.

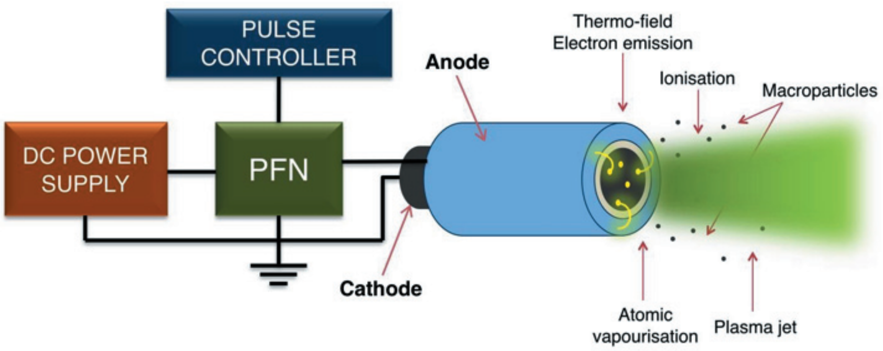


Figure 1. Schematic of VAT system components, main processes and products. In this illustration, the VAT is comprised of a central cathode rod (black) surrounded by an insulator (grey) and outer anode tube (blue).

Although similar in operation to Pulsed Plasma Thrusters (PPTs), VATs offer several distinct advantages – (1) any solid conducting fuel can be used as propellant (usually metals); (2) the VAT can operate over a wide range of pulsed arc discharge characteristics (1–100 A peak arc current, from µs to ms pulse lengths); (3) average thruster power can be throttled arbitrarily, e.g. from 1 to 100 W without loss of efficiency; and (4) arc initiation voltages can be no more than ~1 kV, greatly simplifying and improving the safety of the pulsed power circuit.

Other features that make VAT systems an attractive EP solution are their relatively low mass (< 0.5–1 kg), simple operation and few moving parts, relatively low cost, and absence of complexity and failure modes associated with gas and liquid propellant handling, storage, piping and valves. As such, VATs have seen renewed interest in recent years as micropropulsion systems. In particular, a number of groups are presently developing VAT systems for use on CubeSats (Refs. 2–4).

However, the typical performance levels experienced by present VAT microthrusters remains modest compared to other EP, delivering specific impulse (I_{sp}) levels of 300–600 s and thrust-to-power ratios (T/P) of 5–10 μN/W (Ref. 5). This is mainly due to the large fraction of discharge energy used for propellant ionization and the significant erosion of propellant as non-thrust-producing microdroplets during arc operation (contributing as much as 50% of the total fuel consumption rate). One major effort to improve the performance of the VAT was the development of a magnetically enhanced version of the VAT (see Refs. 6 and 7), which collimates the plasma jet in order to increase total thrust output. We explore four alternative (i.e. non-magnetic) thruster designs and operational modes that could improve VAT performance. Potential areas of performance enhancement are briefly described and an overview of key test results are given.

II. Areas of Exploration

A. Long-pulsed arcs

VATs typically operate with a pulse length roughly between 200 and 500 μs, likely influenced by vacuum arc and VAT research performed by Gilmour & Lockwood (Ref. 8) and the Lawrence Berkeley National Laboratory (Ref. 9). From a practical point of view, restrictions on the pulse circuit capability, size and thermal management of the thruster also limit the pulse length to within the 100–1000 μs range. As such, VAT operating conditions and performance outside this range have received little attention in literature (Fig. 2). We report on performance measurements for a number of VATs operating under millisecond long pulses (1–5 ms).

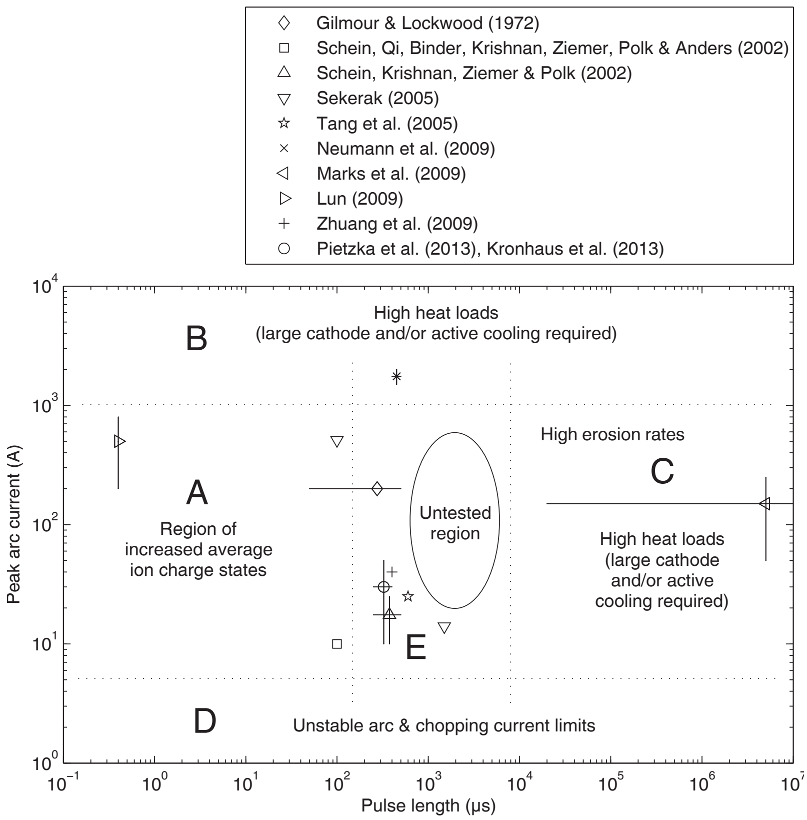


Figure 2. Map of arc operating conditions (peak arc current and arc pulse length) for several published VAT designs. Approximate areas identifying extreme (Regions A–D) and desirable (Region E) operating limits are shown. A previously untested region of VAT operation within Region E is highlighted.

B. Conically-shaped cathodes

VATs employ simple cathode shapes such as a rod, block or tube for convenience and to allow the exposed face to approximate a point source of thrust. The portion of the cathode exposed to the vacuum arc is usually flat and normal to the thrust direction (see Fig 3a). However, no VAT studies have been previously published on cathode surface shapes other than a flat rod or tube face. Expanding on our previous study (Ref. 10), we present recent performance results for a VAT operating with conically shaped cathode heads (Fig 3b).

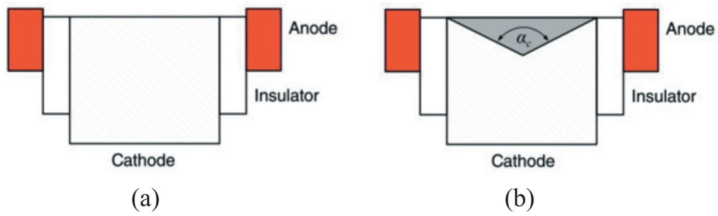


Figure 3. Cathode profile shapes – (a) flat and (b) conical (cone angle defined by *α*).

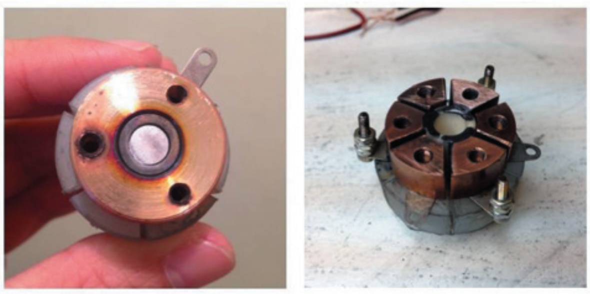
C. Carbon cathode materials

Nearly all VATs developed and tested to date utilize metal as cathode fuel. Metals serve as excellent fuels given their high density, good conductivity, high temperature resistance and high atomic mass. However, one class of materials that has not been sufficiently explored until now is the carbon-based group of materials, i.e. graphite and graphite-metal alloys. These materials possess properties distinct from metals, notably a very high boiling point, a negative temperature-resistance relationship and modest-to-poor thermal conductivity. We report on the performance of VATs using a variety of carbon and graphite cathodes.

D. Discrete anode switching

Sufficient heat dissipation within the VAT remains a careful balance of thruster design and operation. In particular, cathode spot motion is a key factor that directly affects cathode heating and erosion, where the faster the spot motion is, the better the overall heat distribution and the less microdroplets are generated. Thus, controlled motion of cathode spots is a desirable feature in a VAT.

Traditionally, magnetic fields have been used to influence spot motion in vacuum arc applications and VATs (e.g. see Ref. 8). However, there also exist non-magnetic methods of controlling spot motion that could be applied to the VAT. Based on work by Ref. 11 in the area of industrial thin film applications, we have developed a discrete anode switching (DAS) mechanism for a VAT (Fig. 4). This mechanism forces the active cathode spot(s) to cycle their location over the cathode surface by changing the portion of the anode that is active. Practical implementation and potential usefulness of the DAS technique was initially explored and results are reported here.



(a) (b)

Figure 4. VAT anode designs – (a) traditional ring and (b) discrete segments.

III. Experimental Setup & Description

A. Test facility and pulse circuit

All tests were conducted at high vacuum (1–5 × 10^{-5} Torr) inside the main test chamber installed at the Wits Space Propulsion Research laboratory, School of Physics, University of the Witwatersrand, Johannesburg (Fig. 5). The chamber is a stainless steel ring shape (760 mm inner diameter x 200 mm height) sealed with a hemispherical lid and populated with high voltage and multi-pin feedthroughs installed on the chamber side walls.

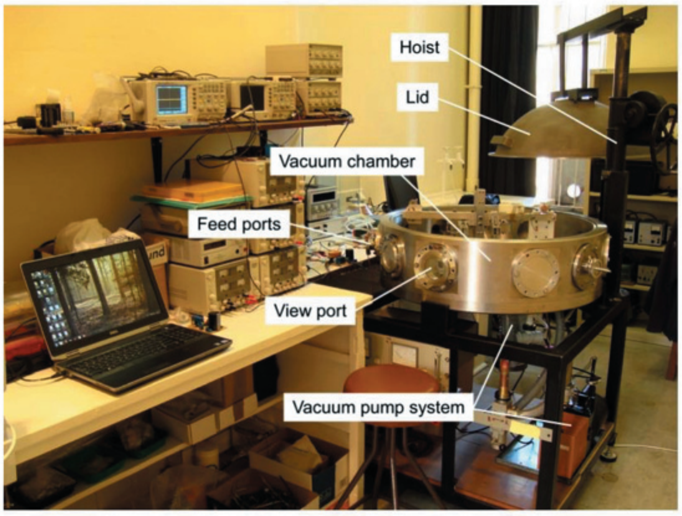


Figure 5. Test ring vacuum chamber and high-vacuum pump system at the Wits Space Propulsion Research laboratory, School of Physics.

B. Pulse circuit

All thrusters were driven by an inductive energy storage pulsed power circuit based on the design of [Schein et al.], where the discharge energy is stored in a large inductor coil (L1 in Fig. 6). A fast-acting MOSFET switch controls the charge and discharge time of the inductor in the circuit and is externally controlled by a pulse generator. The circuit delivers triangular-shaped arc current pulses ranging from 5 to 100 A peak arc current and 50–5000 µs pulse length (see Table 1 for circuit specifications). Typical arc pulse waveforms are shown in Fig. 7.

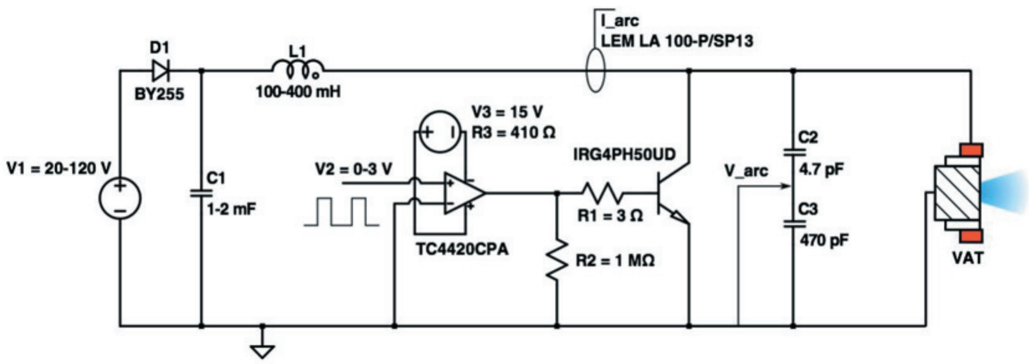


Figure 6. Schematic of VAT pulsed power circuit.

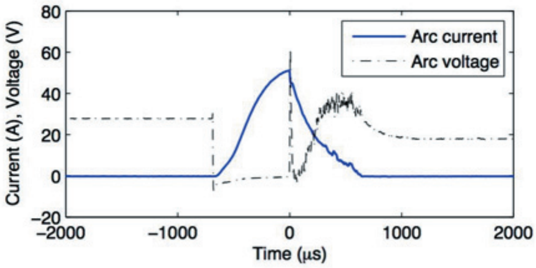


Figure 7. Typical arc pulse waveforms delivered to VATs. In this example, an Fe cathode was used.

Table 1. Pulsed power circuit specifications

Parameter	**Min**	**Max**
Supply voltage (V)	20	180
Arc voltage (V)	10	120
Peak arc current (A)	5	100
Avg. arc current (A)	10	50
Pulse length (µs)	50	5000
Pulse frequency (Hz)	1	50
Avg. arc power (W)	0.01	30

C. Baseline thruster design

A baseline thruster design was developed and several prototypes built and tested in order to measure newly proposed designs against the current state-of-the-art. A coaxial electrode geometry was chosen for modularity and ease of manufacture and assembly (see Fig. 8). The thruster was comprised of the following components: a cathode rod of 6 or 6.35 mm diameter and 50 mm length, a copper anode ring of 25 mm outer diameter, 10 mm inner diameter and 8 mm length, an alumina insulator tube of 10 mm outer diameter, 6 or 6.35 mm inner diameter and 25 mm length, and a thruster housing made of ultra-high molecular weight polyethylene (UHMW-PE). Aluminum (Al), iron (Fe) and bismuth (Bi) cathodes were selected to cover a wide range of cathode material thermophysical properties and thruster performance.

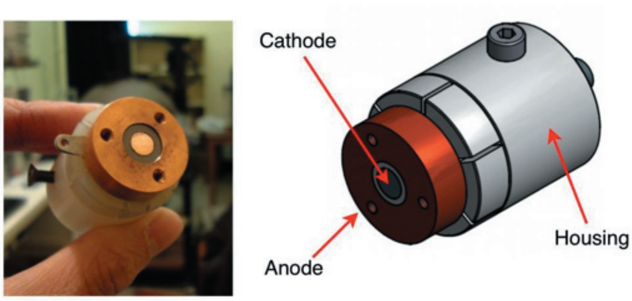
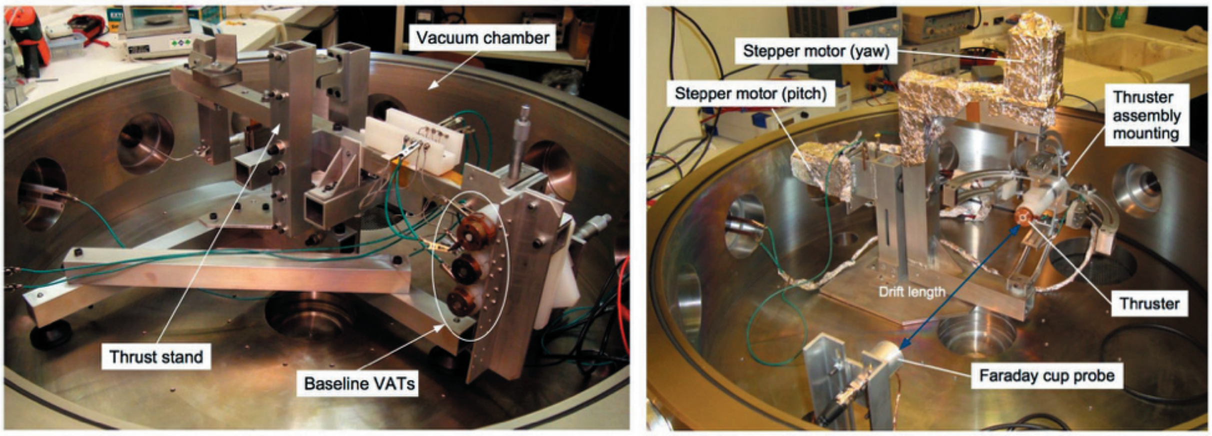


Figure 8. Baseline VAT design

Arc triggering of the thruster was accomplished using the 'triggerless' arc initiation technique developed by Ref. 12. A thin conducting layer of graphite was applied on the insulator interface between the anode and cathode electrodes to enable vacuum arc pulses to initiate across the electrode gap with a 1.2 kV voltage spike. This voltage spike occurs whenever the MOSFET switch is opened to dump stored current from a large inductor coil into the VAT as an arc current pulse. Typical thruster lifetime was on the order of 10^4 pulses (sufficient for this study) until the conducting layer (a) dissipated over time and made the inter-electrode gap too great for arc initiation to occur or (b) built-up over time such that the electrodes were short-circuited by a sufficiently thick conducting bridge of deposited cathode material.

D. Diagnostics tools

A number of diagnostic tools were developed in-house to measure thruster performance. These included a micro-Newton resolution thrust stand to measure direct thrust output (Fig. 9a), and a Faraday cup and two-axis rotation system (Fig. 9b) to capture and map the ion flux emitted from the thruster head at various incidence angles (ion current density distribution or ICDD). Detailed descriptions of each system can be found in Refs. 10 and 13.



(a) (b)

Figure 9. Photographs of (a) thrust measurement stand with multiple VATs installed and (b) ICDD setup with single VAT being tested.

The thrust stand is able to resolve static forces as low as 2.7 μN and allow the mounting of multiple thrusters for testing. Impulse bits in the range 0.27–600 μNs can be measured with a maximum precision of 2%. The Faraday cup is able to collect ion currents in the μA range and the two axis rotation system can rotate a thruster up to ±90 degrees in both pitch and yaw axes with respect to a probe for remote ICDD mapping with an accuracy of ±2 degrees.

Cathode erosion rate was measured using the weight loss method where the cathode's mass was weighed before and after test firing the VAT for several thousand pulses (typically a total cumulative arc charge of 80–100 C).

IV. Empirical VAT performance model

Polk et al. (Ref. 5) defines VAT thrust as a function of ion mass flow rate, ion velocity and plume jet shape factor. The ion mass flow rate is determined by the ion current released, the average ion charge state and the ion mass. The shape of the plasma jet plume determines the fraction of ion momentum traveling in the normal thrust direction and is quantified as a thrust correction factor (C_T). This correction factor is calculated using the VAT plume's ICDD (see Ref. 5 and 10 for details). In a flat cathode, $C_T \simeq 0.64$, i.e. 64% of the ion momentum produces normally-directed thrust. Most parameters are determined empirically or measured from vacuum arc test data (see Appendix).

$$T = C_T\left(m_i \frac{I_i}{eZ}\right)v_i$$

The ion current can also be defined as a fraction of the total arc current, i.e.

$$I_i = fI$$

where f is called the ion-to-arc current ratio (on the order of 0.1).

The VAT's specific impulse can be found using the thrust, arc current and erosion rate (in μg/C)

$$I_{sp} = \frac{T}{IE_r g}$$

Thrust-to-power ratio is merely T/P where $P = IV$.

Finally, efficiency can be defined as

$$\eta = \frac{T^2}{2PIE_r}$$

V. Test Results

A. Baseline thruster performance

Three lifetime and performance tests were conducted on baseline VATs using Al, Fe and Bi cathodes. Measured performance results are listed in Table 2 and compared to the empirical model (input parameters are listed in the Appendix). Test results indicate that the performance of the baseline VATs is reasonable, where Fe's values are typical of most metal cathodes.

Table 2. Measured mean performance of baseline VATs compared to empirically predicted performance (in brackets).

Performance metric	Al		Fe		Bi	
Thrust per arc current, T/I (μN/A)	117	(161)	221	(181)	502	(449)
Thrust-to-power ratio, T/P (μN/W)	3.2	(6.8)	10.5	(8.0)	42.5	(28.8)
Specific impulse, I_{sp} (s)	382	(584)	398	(385)	40	(217*)
Efficiency, η (%)	0.6	(1.9)	2.0	(1.5)	0.8	(3.1)

* Erosion rate used for calculating I_{sp} for Bi is from predicted ion erosion only (Ref. 14).

B. Long arc pulse lengths

Baseline VAT thrusters using Al, Fe and Bi cathode rods were repetitively fired (1–10 Hz) with arc pulses of 50 and 100 A peak arc current and a range of pulse lengths (150–4500 µs). ICDD measurements shown in Fig. 10 reveal that a generally increasing level of ion charge per given amount of arc charge is collected by the probe as the pulse length increases. This effect was observed with varying degree across all materials. These results suggest that ion production rates increase with arc pulse length in this range, an effect not previously observed before.

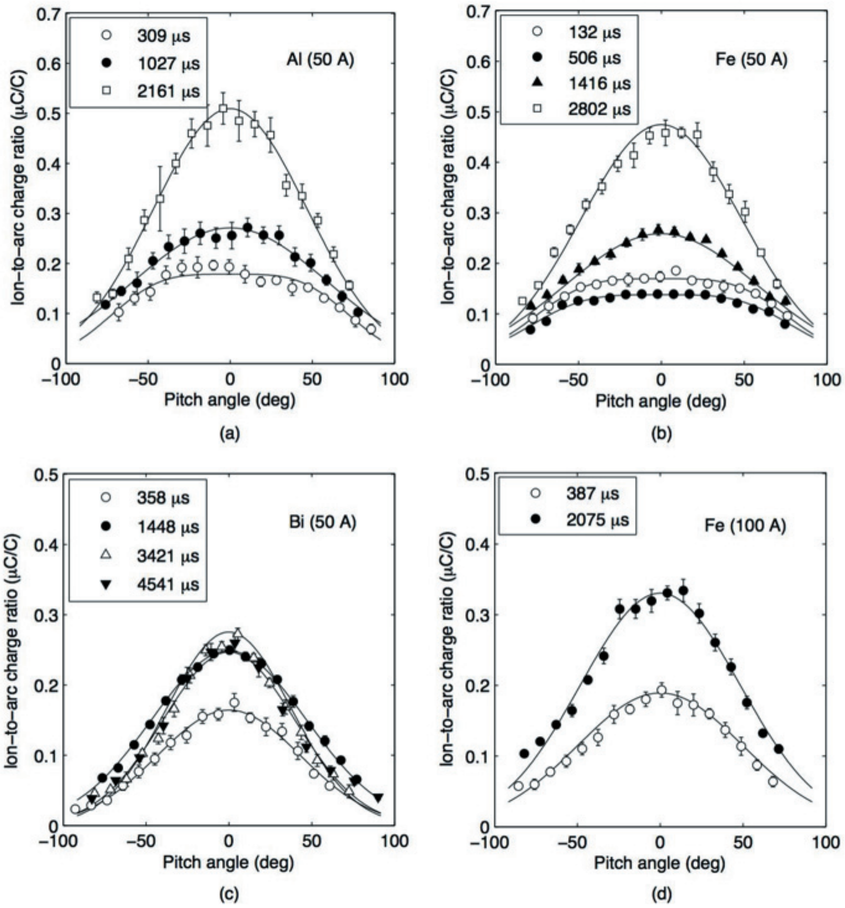


Figure 10. ICDD results for baseline VATS operating at various pulse lengths using (a) Al, (b) Fe and (c) Bi cathodes. Peak arc currents *I* = 50 A for (a)–(c) and *I* = 100 A for (d). For conciseness, only pitch data is shown in detail here. Each data point represents an average of 20 ion current samples taken at that individual incidence angle.

Further evidence for enhanced ion production is presented in extensive thrust data taken for a variety of cathode materials and pulse lengths (see Fig. 11), where thrust per arc current values increase with increasing pulse length. The cause of the enhanced ion and thrust production is speculated to be due to the increase of charge exchange collections with excess neutrals emitted by the vacuum arc during longer pulsed discharges.

However, erosion rate data in Fig. 12 shows that the additional heat present as a result of the longer pulse length also increases the erosion rate. In summary, operating the baseline VATs with millisecond pulse lengths generally serves to increase thrust production, but at the expense of an increased heat load. Depending on the material, the resulting increase in erosion rate can have an overall negative impact on I_{sp} (see Table 3 below). In this study, all materials expect for Al experienced at 13–30% drop in I_{sp} despite a ~20% rise in thrust production.

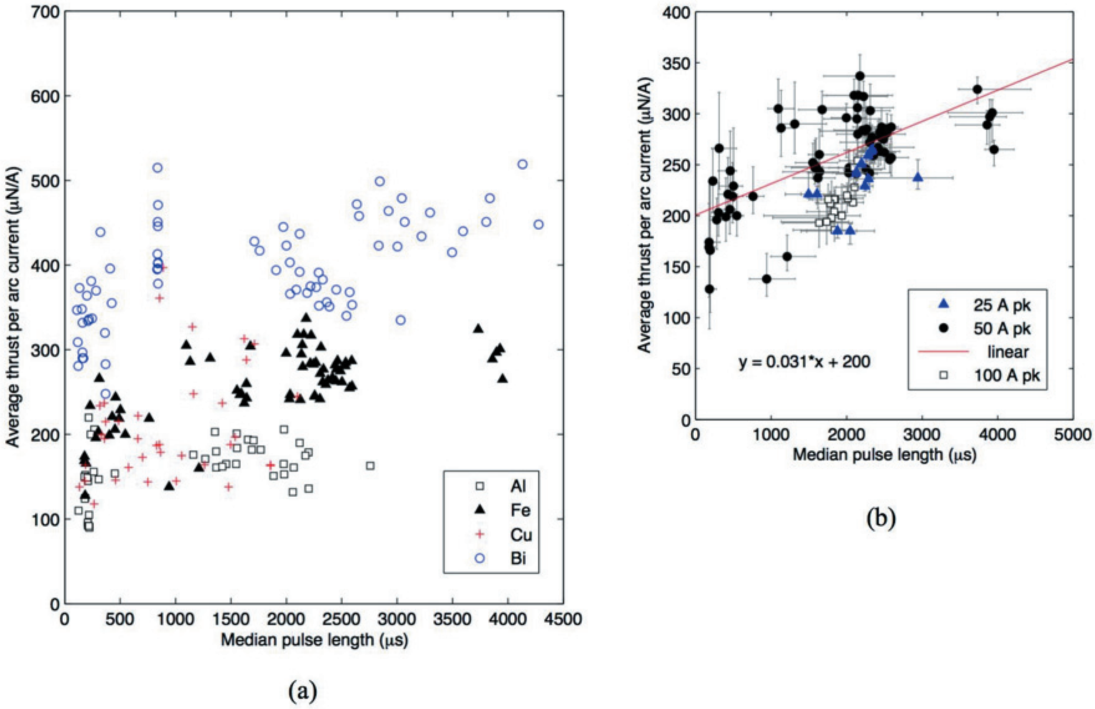


Figure 11. (a) Average thrust per current results for baseline VATs using Al, Fe, Cu and Bi cathodes operating at 50 A peak arc current at various pulse lengths. All thrust data here is shown for VATs firing up to no more than a total cumulative arc pulse charge of ~80 C; (b) Detailed thrust data for Fe at 25, 50 and 100 A peak arc currents. A linear fit through 50 A data shows an increase in average thrust production with increasing pulse length from 216 μN/A at 500 μs to 262 μN/A at 2000 μs (21.3% increase).

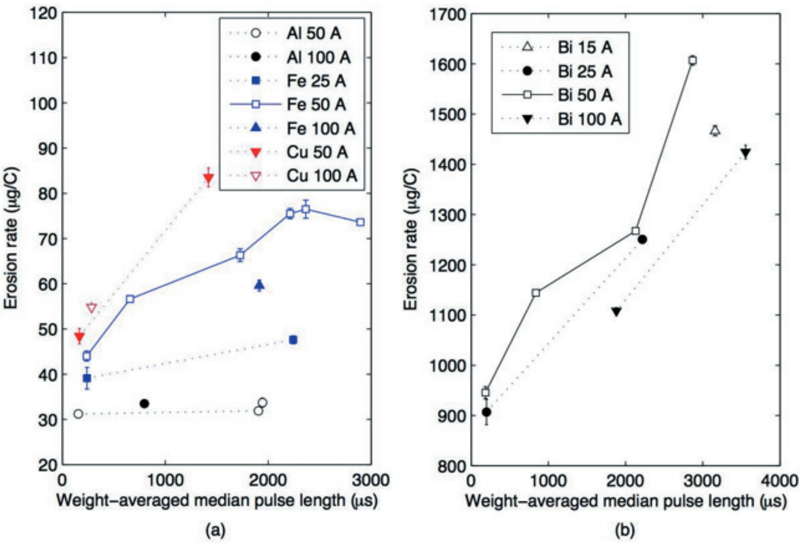


Figure 12. Erosion rate results for baseline VATS operating at various pulse lengths for (a) Al, Fe, Cu and (b) Bi cathodes.

Table 3. Comparison of thruster performance for selected baseline VAT designs for Al, Fe, Cu and Bi cathodes operating with short and long pulses. Peak arc current at I = 50 A.

	t_p (µs)	T/I (µN/A)	E_r (µg/C)	I_{sp} (s)	**Diff.**
Al	156	133.3	31.2	436	+24.5%
	1906	170.0	31.9	543	
Fe	236	207.3	44.0	480	-24.4%
	2213	268.6	75.5	363	
Cu	166	185.5	48.4	391	-29.2%
	1420	226.9	83.5	277	
Bi	185	355.0	945.5	38	-13.2%
	2130	407.5	1267.4	33	

C. Conical cathodes

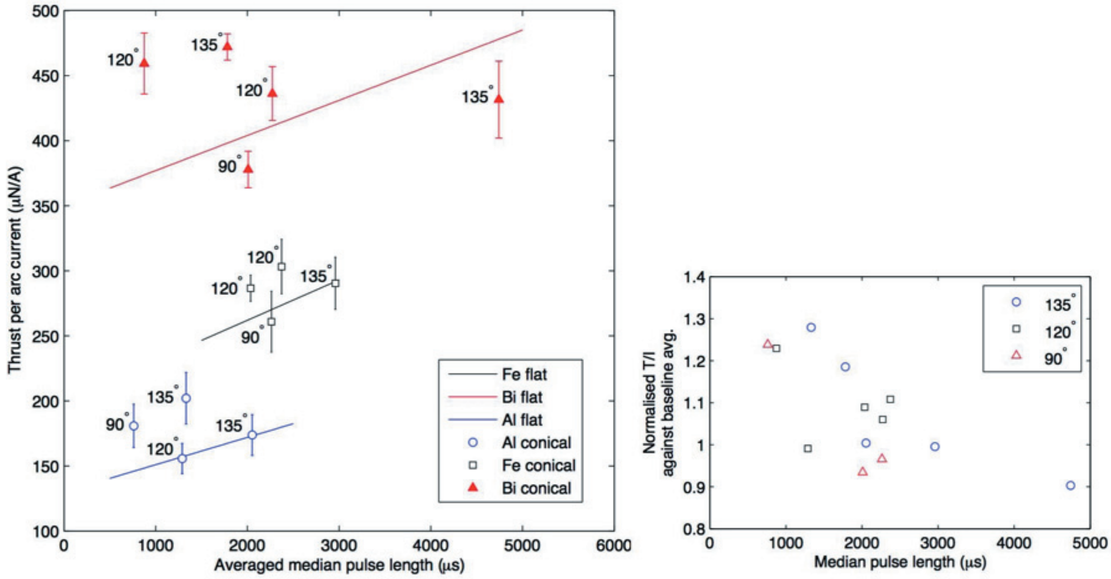
Three different cathode concave cone angles were tested, namely 90º, 120º and 180º (flat). Only long pulse lengths were used in this study since they allowed better erosion coverage of the cathode and enabled the overall cathode shape to have a more dominant role in VAT performance. This paper expands on our previously reported results on the effect of a conical cathode shape in a VAT (Ref. 10).

Further study on erosion rate indicated that the conical shape is conducive towards reducing the cathode erosion rate (see Table 4). It achieves this by presence of the inward slope of the cathode surface, which encourages cathode spot travel away from the ignition edge. This results in greater spot motion and coverage over the cathode surface. Little change to the erosion rate, however, was experienced below a cone angle of 120º.

Table 4. Comparison of average erosion rates of baseline (180º) and conical VATs for selected cone angles (120º and 90º). Weight-averaged pulse lengths (in milliseconds) during each E_r measurement are included in brackets.

	Erosion rate, E_r (µg/C)					
Cone angle, α (deg)	**Al**		**Fe**		**Bi**	
180º (flat)	33.7 ±1.0	(1.9)	75.5 ±1.1	(2.2)	1606.9±9.4	(2.9)
120º	29.5 ±1.1	(1.3)	50.5 ±1.1	(2.2)	952.6 ±1.7	(2.8)
90º	24.9 ±0.9	(1.4)	49.6 ±0.8	(2.6)	938.7 ±3.8	(3.1)

In our latest results, thrust data was resolved to include the effect of arc pulse length, a parameter now known to influence ion production. Figure 13a shows revised thrust results, recognizing the coupled effect of cathode shape and pulse length in our tests. It is worth noting that the majority of conical cathode shape data produced greater thrust compared to their baseline flat cathode counterparts, in some cases as much as 20–30%. Figure 13b consolidates these results to show that the conical cathodes produced the greatest thrust in the t_p = 1–1.5 ms pulse length range and delivers no thrust advantage when operating beyond t_p = 2 ms. This shows that the pulse length is just as important as the cone angle in affecting the final performance of the cathode. A summary of conical cathode performance is given in Table 5, with some test cases achieving as much as a 68% increase in specific impulse.



(a) (b)

Figure 13. (a) Thrust measurements (*T/I*) measured at various cathode cone angles (α = 90º, 120º and 135º) resolved against pulse length. Each data point is an average of 16 thrust tests run up to $Q \approx 50$ C; (b) Consolidated average *T/I* values for various cathode cone angles (α = 90º, 120º and 135º) and materials normalized against baseline average thrust trend lines in (a).

Table 5. Comparison of VAT performance for selected conical and equivalent baseline VAT designs operating with Al, Fe and Bi cathodes at I = 50 A. Thrust and erosion rate data taken at similar millisecond-range pulse lengths for each case pair.

	Cathode design	t_p (ms)	T/I (μN/A)	E_r (μg/C)	I_{sp} (s)	**Diff.**
Al	Baseline flat	1.3	158.0	31.6	510	+34.7%
	135º cone		202.1	30.0	687	
Fe	Baseline flat	2.2	273.6	75.5	369	+65.9%
	120º cone		303.2	50.5	612	
Bi	Baseline flat	2.3–2.8	411.4	1483.6	28	+67.9%
	120º cone		436.2	952.6	47	

D. Carbon cathodes

Performance characterization of various grades of carbon cathodes in VAT prototypes were undertaken. Samples included pure graphite EDM grades AF-5, EDM-3, EDM-200, copper-graphite EDM grades C-3, C-200, TTK-4C and Glassy Carbon. These cathode materials were found to behave and perform differently to traditional metal cathodes. For instance, erosion of pure carbon was notably restricted to the ignition edge of the cathode due to the poor thermal conductivity of graphite. On the other hand, copper-graphite samples delivered comparable erosion characteristics to pure metals due to their higher thermal conductivity. Figure 14 shows the thrust behavior and levels for pure carbon cathodes. All carbon-based samples were found to deliver superior thruster performance (except T/P values) over baseline metal cathodes (see Table 6). Material C-3 was found to achieve the highest specific impulse measured in a VAT at close to 1000 s.

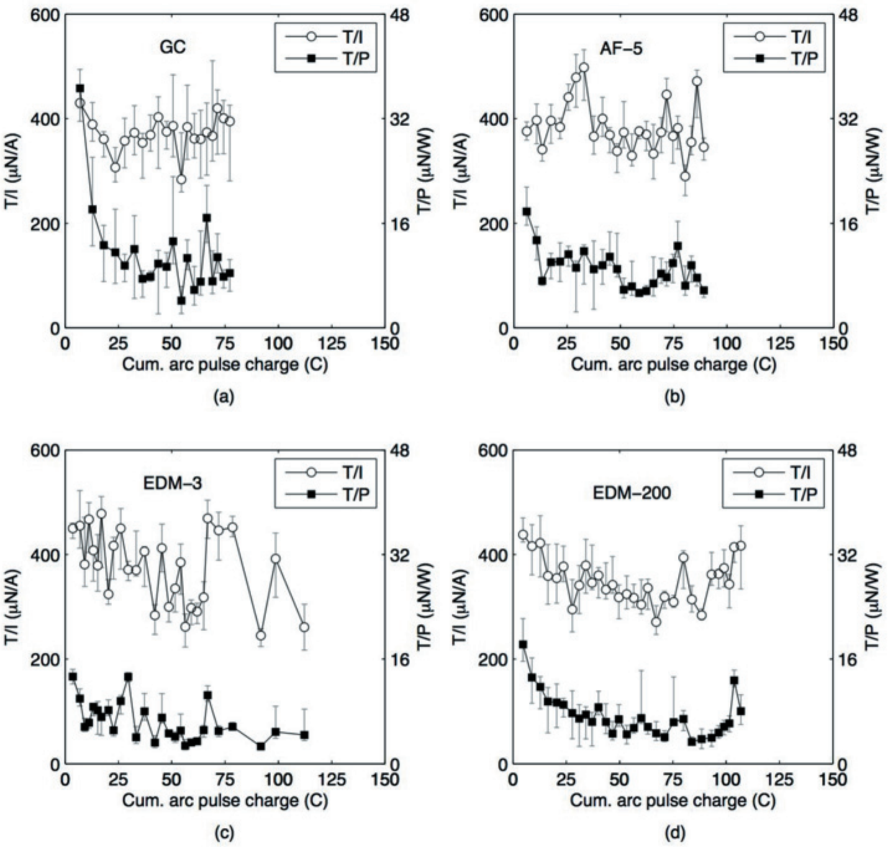


Figure 14. Measured thrust per arc current (left vertical axis) and thrust-to-power ratios (right vertical axis) over test duration for pure carbon cathodes. Materials include (a) GC, (b) AF-5, (c) EDM-3 and (d) EDM-200. Total cumulative pulse charges range from 80 to 120 C. Peak arc current at *I* = 50 A. Lines through data points are for visual aid only.

Table 6. Summarized performance test results for baseline VATs operating with carbon-based cathodes (t_p = 0.7–1 ms). Fe cathode baseline performance is provided for comparison.

	E_r (μg/C)	T/I (μN/A)	T/P (μN/W)	I_{sp} (s)	η (%)
GC	49.2	372	12.8	771	4.8
AF-5	40.4	383	9.6	966	4.6
EDM-3	42.3	378	6.6	911	2.9
EDM-200	42.1	350	8.0	847	3.3
TTK-4C	39.3	267	7.7	693	2.6
C-3	33.4	327	5.1	998	2.5
C-200	38.1	298	4.9	797	1.9
Fe (t_p = 658 μs)	56.6	221	10.5	398	2.0

E. Discrete anode switching (DAS)

The anode was split into six segments, where three segment pairs were made active (current-carrying) in a cyclical fashion during the course of each arc pulse. Switching cycle times of 45, 120 and 520 μs were tested. Figure 15 shows that the DAS technique was most effective during long pulses and least effective at short pulses. Shorter DAS switching times also resulted in lower erosion rates. These results support the view that a direct relationship exists between spot motion, the local surface heat load and final cathode erosion rate.

In the case of Fe, DAS switching was able to completely mitigate the increased heat load due to the longer pulse durations. Thrust and performance measurements of a DAS-enhanced VAT in Table 7 also show that *both* thrust and erosion rate perform better compared to the baseline long-pulsed operation, with a 27.9% gain in I_{sp} over the baseline short-pulsed VAT. Thus, the thrust benefits of long-pulsed operation could be attained without the erosion rate penalty associated with the expected higher heat load.

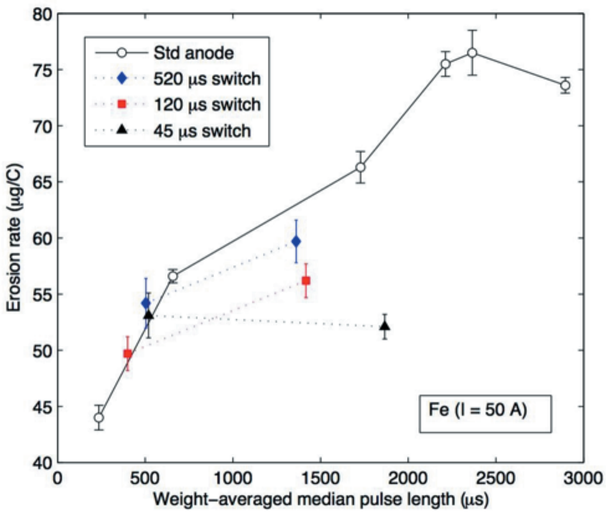


Figure 15. Erosion rate results for different switching times as a function of arc pulse length. Tests performed on Fe cathode running at *I* = 50 A peak. Erosion results for the baseline VAT operating with the standard anode ring is included for comparison.

Table 7. Comparison of thruster performance for three selected Fe VATs operating with (1) short pulses (baseline design), (2) long pulses (baseline design) and (3) long pulses and DAS implementation. Peak arc current at *I* = 50 A.

Fe VAT design	t_p (μs)	T/I (μN/A)	E_r (μg/C)	I_{sp} (s)	**Diff.**
Baseline (short)	156	207	44.0	480	
Baseline (long)	1997	262	71.4	374	-22.1%
DAS, 45 μs switch	1997	319	53.0	614	+27.9%

VI. Conclusions

Much development work on the VAT remains in order for the technology to become an attractive system for satellites. This study found that design factors such as arc pulse length, cathode shape/size and cathode spot motion have a much more critical influence on overall VAT performance than was previously appreciated and should be carefully considered in future VAT designs. In an effort towards improving VAT performance, a number of alternative thruster designs and operational modes were explored and (in a number of cases) were found to produce substantial improvements to over typical baseline thrust and specific impulse values. Firstly, operating VATs in the millisecond range revealed a new operating regime for VATs where ion production was enhanced, but also increased the cathode's thermal load. The mechanism for enhanced ion production is speculated to be increased charge exchange collisions between ions and neutrals, but this requires further investigation. Secondly, conically-shaped cathodes were found to also produce improved performance, but an exact understanding of how this is accomplished also remains incomplete. Thirdly, a new range of cathode materials based on carbon and graphite was tested and demonstrated to deliver superior performance over traditional metal cathodes, reaching the I_{sp} = 1000 s milestone. Further testing is required to expand this class of materials (carbon-based alloys or matrices) and better qualify and integrate them into a practical VAT system. Finally, increasing spot motion using the discrete anode switching technique was successfully demonstrated to improve VAT performance by controlled distribution of spot locations and thus local heat load on the cathode surface.

Appendix

Empirical values used to predict baseline VAT performance for Table 2 is shown in Table 8 below.

Table 8. Empirical values used for predicting baseline VAT performance of Al, Fe and Bi cathodes

Parameter	Al	Fe	Bi	Source
Ion-to-arc current ratio	0.112	0.08	0.102	Refs. 15 and 16
Average ion charge state	1.73	1.82	1.17	Ref. 17
Average ion velocity (km/s)	15.4	12.6	4.7	Ref. 18
Thrust correction factor	0.590	0.564	0.505	Measured in this work
Arc voltage (V)	23.6	22.7	15.6	Ref. 17
Erosion rate (μg/C)	28	48	211*	Ref. 19

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