THE COMPATIBILITY OF HOLLOW CATHODE CHARACTERISTICS WITH A VARIETY OF ION THRUSTER DESIGNS

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ABSTRACT

Many different electric propulsion devices are under development and others are in operational use. A common element found in a majority of these devices is the hollow cathode employed to provide electrons for ionisation and, in some cases, neutralisation of the space charge of the ion beam exhaust. In most development programmes, this cathode is included as an integral part of the work. This expensive exercise can be avoided by employing the same basic design for many applications. This paper considers this concept, concentrating on ion and Hall-effect thrusters with total power levels of 1 to 10 kW. It is suggested that the cathode described, which was originally designed for the T6 ion thruster, is suitable for a wide variety of very different applications, possibly also including arcjets.

INTRODUCTION

As spacecraft masses and lifetimes increase, and new, more challenging missions are devised, the need for advanced propulsion systems has led to the development of many different electric propulsion (EP) devices, some of which are now in operational use. With the continuation of this trend in spacecraft and mission design, electric thrusters with higher power and thrust levels are increasingly in demand, prompting much additional development effort.

The wide variety of propulsion devices aimed at this market includes gridded ion thrusters, employing both direct current (DC) and radiofrequency (RF) discharges, Hall-effect thrusters (HETs), and arcjets. A common element found in many of these devices is the hollow cathode employed to provide electrons for primary ionisation and, in some cases, for ion beam neutralisation. In the past, a new cathode design has usually been produced for each thruster, although they have generally been based on a common understanding of the relevant physics and technology. This was the case with DERA's T6 Kaufman-type thruster, which has a beam diameter of 22 cm and a nominal thrust of 150 mN. However, it is now evident that such a cathode can be applied to many other advanced propulsion devices, and this paper examines the very wide range of possible uses.

Although based on the cathode employed in the UK-25 ion thruster, which has a thrust of 200 to 300 mN, the T6 variant is considerably improved. It is of simplified design, which eases construction, reduces cost, and enhances reliability. It also incorporates a dual heater, thereby providing essential redundancy.

After describing the cathode and its operation, the paper discusses the requirements for such a device if it is to be applicable to a very wide range of thrusters. From the point of view of ionising electrons in gridded ion engines, the T6, the NASA/Hughes 30 cm thruster flown on the Deep Space 1 (DS-1) mission, and the Hughes 25 cm thruster utilised on HS-702 communications satellites are included. Neutraliser applications are also considered, and are extended to the RIT-15, and ESA-XX RF ionisation thrusters. Hall-effect thrusters are represented by the SPT-100, the PPS-1350, the ROS-99, the T-160 and ESA's new 5 kW device. Although they do not use hollow cathodes, two arcjets are considered, the Olin ATD thruster and the MR-508, to illustrate that they also fit within the performance envelope of the T6 cathode.

It is shown that this cathode can accommodate all of these varying applications, since it has an emission capability ranging from 1 to 30 A, and can operate at xenon flow rates from less than 0.1 mg/s to well over 1 mg/s. Extensive characterisation of the discharge has shown that certain regions are best avoided, since they permit coupled power supply-discharge
oscillations to be generated. However, their positions can be changed to ensure stability at each operating point. The influence of various parameters on cathode temperature, and thus on lifetime, has also been taken into account.

THE HOLLOW CATHODE

The cathode designed to meet the demanding T6 specification is based on that used successfully in the earlier UK-25 thruster\textsuperscript{7},\textsuperscript{9}, although adopting the more reliable constructional and heater technologies developed later in the T5 programme. These include a fully redundant heater, which eliminates the need for a cold-start capability.

The basic features\textsuperscript{7} are depicted schematically in Fig 1; they are essentially unchanged since the start of the development programme leading to the T5, UK-25 and T6 thrusters\textsuperscript{16}. In operation, a stream of propellant gas is fed through a tantalum tube closed at the downstream end by a 2 mm thick disc having a countersunk central orifice of diameter $d_2$. In the work reported here, $d_2$ has varied from 0.75 to 1.6 mm. The tube and disc can be machined from the solid, or can be welded together. Both approaches have been used, although the former is now favoured.

A cylindrical porous tungsten dispenser of 5 mm outside diameter is located within the tube, with its downstream end buttressed against the tip. It is impregnated with a low work-function material, usually barium-calcium-aluminate, and has an internal diameter and length of 2 and 20 mm, respectively. The upstream end of the dispenser is held mechanically to ensure that there is a low resistance electrical path into the xenon feed tube, which acts as the negative discharge terminal.

The cathode tube of 7 mm outside diameter is surrounded with a bifilar tungsten heater winding, insulated with a ceramic material. Up to recently, flame-sprayed alumina has been used, but a machinable ceramic is now employed for ease and consistency of manufacture. A radiation shield made from rolled molybdenum foil surrounds the complete assembly. Two completely separate but identical heater windings are fitted for redundancy. They have independent terminals.

To commence operation, the heater is used to raise the temperature to about 900 to 1000 °C. If propellant gas is passed along the tube and a voltage is applied to the external keeper electrode, a discharge spontaneously occurs and transfers automatically into the cathode body. This can be random in nature\textsuperscript{17} and is not fully understood. Similarly, the transfer through the orifice requires additional study, since the mechanisms involved are not entirely clear. The heater current can be turned off once initiation has occurred, because ion bombardment heating then provides the necessary input of energy.

![Figure 1 Schematic section of the hollow cathode.](image-url)

Physics of Cathode Operation

Although simple in concept, the hollow cathode is, in reality, very complex due to the many possible electron emission mechanisms that may play a part in its operation and the wide variety of plasma phenomena associated with the discharge. Moreover, the cathode interacts directly with the thruster, which is itself a complex device, making it more difficult to understand experimental observations.

To aid interpretation, a summary is provided below of possible emission mechanisms and of the ways in which these cathodes interact with external discharges. In the experimental situations reported here these are diode discharges, which only partly simulate the situation in a gridded ion thruster, but which are more representative of the neutraliser application, and of operation in HETs and arcjets.

There are many emission mechanisms available to explain the high current densities obtained from the surface of the dispenser\textsuperscript{16}, which are often of the order of 50 A/cm\textsuperscript{2}. Although some of these will depend on the atomic parameters of the propellant, the field-enhanced thermionic process\textsuperscript{2,16} possibly dominates under many circumstances. This occurs because a dense internal plasma is generated within the cathode, as confirmed by both probe\textsuperscript{17} and spectroscopic\textsuperscript{18} measurements. A very thin sheath then forms to separate this plasma from the wall, and it is the appearance of the plasma potential across this that provides the high electric field needed to enhance the normal thermionic emission.

This mechanism may be enhanced further by the long residence times in the sheath expected for the low work function atoms and ions\textsuperscript{16}. These atoms adsorb readily onto the metal surface of the dispenser. They may be desorbed as either atoms or ions and, under certain conditions, the ion density close to a negative
surface can be raised by orders of magnitude. This would result in a considerable increase of the electric field and of the current emitting capacity of the surface.

In an effort to explain the intrinsic electrical noise generated by these cathodes, Malik found that microscopic transitory aluminium filaments can form on the surface of the dispenser under certain conditions. These emit copiously by the field-enhanced thermionic process, aided by the sharp radii of curvature at their points. Self-heating soon causes their vaporisation, but others then replace them, resulting in the generation of random noise. The current density produced by these filaments can be a significant proportion of the total drawn.

Other possible mechanisms also exist. For example, with mercury propellant the impact of metastable atoms with the wall of the dispenser can provide a current density as great as that from field-enhanced thermionic emission. This may also be applicable to xenon, and perhaps to other propellants. Additional mechanisms include photoemission and secondary emission due to the bombardment of the dispenser by ions accelerated from the dense internal plasma.

**Discharge Modes**

It is clear that the cathode is a complex device, and that additional study is required to understand it fully. A further complicating factor is that previous investigations have revealed at least two modes of operation, especially when tested in diode configurations. They, the spot and plume modes, depend critically on the current $I_d$ drawn from the cathode to the anode and the propellant flow rate $\dot{m}$, and are shown in Fig 2 for the T6 cathode.

![Figure 2](image)

*Figure 2* **Modes in a diode discharge.**

At very low $\dot{m}$ an attempt to extract a large current at first merely results in a relatively high anode voltage and significant electrical noise (curve O in Fig 2). The discharge is then very luminous around the cathode tip, and is in the plume mode. As $\dot{m}$ is increased, higher currents gradually become accessible (curve P). Eventually a sudden transition occurs to the spot mode, in which $I_d$ can be increased as much as required and voltages remain low (curve Q). This transition includes a region in which there is a negative voltage-current relationship. In the spot mode, there is no general luminosity, the only emission of radiation being from the orifice of the cathode. When $\dot{m}$ is increased further, the transition moves to lower currents (curve R). Eventually, at sufficiently high flows, the plume mode is absent and its accompanying noise disappears (curve S).

At least one further mode has been identified, the so-called neutraliser mode. This occurs when both $\dot{m}$ and $I_d$ are small, and the cathode is exposed to a hard vacuum. It can then operate very stably at relatively low temperatures. It is appropriate to the neutraliser application, where it dominates the electromagnetic interference (EMI) produced by a thruster.

**Oscillations and noise generation**

Oscillations and noise generation within the cathode discharge, including any associated with mode transitions, are important because amplification by the plasma processes occurring in the thruster is likely; indeed, this could be one explanation of the oscillations observed in HETs under certain conditions. This can influence overall stability, determine the positions of performance boundaries, and have a major effect on efficiency.

One mechanism for noise generation mentioned above concerns transitory emission from aluminium filaments on the surface of the dispenser. This would not seem to be relevant to the transition region depicted in Fig 2, which appears to be related to the fluctuating and oscillatory behaviour associated with changes of mode. However, this noise source may partly explain the random EMI detected from the neutraliser discharge.

Other noise sources are to be found in the plasma processes occurring within the cathode. Some involve the strong self magnetic field generated by the extraction of large currents through the orifice. These currents were as high as 30 A in the present work and the smallest orifice studied was 0.75 mm in diameter. This gives a mean current density of $6.8 \times 10^7$ A/m$^2$. Assuming that the plasma does not pinch, the magnetic field at the edge of the orifice is then significant, at 0.016 T. However, very much higher values are possible with pinching.

The experiments providing the data reported below, coupled with gridded ion thruster experience, suggest that dynamic interactions between the
cathode/thruster plasmas and the anode power supply can be crucial to stability, and thus to overall performance. The use of a battery power supply has demonstrated conclusively the existence of such interactions, which can produce severe oscillations.

**EXPERIMENTAL MEASUREMENTS**

The experimental equipment used and procedure adopted in this work were similar to those of previous cathode investigations. Major differences concerned the range of diagnostics available and the initial decision to operate with an external pressure approximating to that in the T6 thruster. However, an open diode arrangement has also been employed, together with a variety of keeper configurations.

The apparatus was described in detail in Ref. 8. To summarise, the cathode was mounted within a cryo-pumped vacuum chamber with an ultimate vacuum of about $5 \times 10^{-8}$ Torr. It was supported on a micro-manipulator, which allowed its position to be varied with respect to the keeper electrode. In most of the experiments, its orifice was positioned just inside the closed end of a cylindrical discharge vessel. The concentric keeper electrode had a central orifice of 5 mm diameter, and the circular stainless steel anode of 114 mm diameter was 60 mm from the cathode. A central hole in the anode allowed the cathode tip to be viewed by an axial optical pyrometer.

Other studies used an open diode configuration, in which a thick anode was placed just 6 mm from the cathode tip (when hot), to simulate the set-up employed in testing certain cathodes intended for HETs. To avoid excessive heating, its thickness was 13.5 mm and it was drilled with a hexagonal pattern of 5 mm diameter holes. Measurements were made both with and without a keeper electrode.

Xenon was supplied from a high pressure cylinder, via an electronic regulator giving an output pressure of 2 bar. This was fed via a needle valve, an oxygen absorber and a thermal flowmeter, into the rear of the cathode. To avoid any contamination, all joints at below atmospheric pressure were brazed, welded, or contained within an auxiliary vacuum chamber.

Standard commercial power supplies with current regulation were used for the cathode heater, and for the keeper and anode discharges. On occasions, batteries were substituted for the anode supply. The current was then controlled using a high power variable resistance.

The diagnostics were as follows:
1. A commercial pressure transducer connected to the xenon feed pipe at the rear of the cathode.
2. A DERA flowmeter$^{24}$ in the xenon feed pipe downstream of the needle valve. This was calibrated from 0 to 1.4 mg/s, with an accuracy of $\pm 1$ to $2\%$.
3. A cylindrical Langmuir probe located 10 mm downstream of the keeper orifice.
4. Chromel-alumel thermocouples to measure the temperature at various points on the cathode. The tip temperature was found using an optical pyrometer.
5. A digital storage oscilloscope to measure the noise on the various electrodes and Langmuir probe.

Parameters that were varied during the diode tests included $d_{a}, I_{a}, m$, the cathode to keeper separation, $d_{k}$, and the keeper current, $I_{k}$. A DERA flowmeter$^{24}$ in the xenon feed pipe downstream of the needle valve. This was calibrated from 0 to 1.4 mg/s, with an accuracy of $\pm 1$ to $2\%$.

**REQUIREMENTS**

As mentioned above, the aim of this paper is to illustrate that a single hollow cathode design can be applied successfully to a number of very different plasma-based thruster types, with multi-kW power consumptions, extending from gridded ion thrusters, through HETs, to arcjets. It is therefore necessary to establish the range of requirements, which are summarised below in Table 1.

Although representative thrusters of all relevant categories are listed, it is recognised that not every device under development or in operational service is included. However, these examples are thought to cover the complete range of interest. The cathode parameters given are restricted to those of operational significance, which are $I_{a}$ and $m$. The lifetime required will vary greatly with mission specification, so it has been assumed that 10 000 to 15 000 hours will be sufficient for most applications, implying a tip temperature of less than about 1200 deg C$^{25}$.

It can be seen that the range of $I_{a}$ is 1 to 20.4 A, and that $m$ varies from 0.1 to 1.0 mg/s, excluding the arcjets. Operation with and without keeper current is necessary, since not all HETs provide a power supply for this. Another important aspect, not covered in Table 1, is the need for easy and reliable discharge initiation. In addition, to avoid sputtering damage, the keeper should, in general, be below 20 V.

**CATHODE CHARACTERISTICS**

The characterisation of the T6 cathode revealed a number of unexpected phenomena, some of which have not been reported previously in the literature. This was especially true of those concerning interactions between the discharge and the laboratory power supply used, and the resulting generation of low frequency oscillations.

In general, electrical noise was observed over the
Table 1  Cathode Requirements for a Variety of Electric Thrusters

<table>
<thead>
<tr>
<th>Thruster Type</th>
<th>Beam Diam. (cm)</th>
<th>Thrust (mN)</th>
<th>Power (kW)</th>
<th>Cathode Use</th>
<th>Flow Rate (mg/s)</th>
<th>Current (A)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>XIPS-25</td>
<td>25</td>
<td>165 nom</td>
<td>4.2 nom</td>
<td>Discharge</td>
<td>?</td>
<td>6-17</td>
<td>1</td>
</tr>
<tr>
<td>DS-1</td>
<td>30</td>
<td>19-92</td>
<td>0.5-2.3</td>
<td>Discharge</td>
<td>0.25-0.37</td>
<td>4-13</td>
<td>10</td>
</tr>
<tr>
<td>T6</td>
<td>22</td>
<td>150 nom</td>
<td>3.7</td>
<td>Discharge</td>
<td>1.0</td>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td>ESA-XX</td>
<td>25</td>
<td>240 max</td>
<td>8.5</td>
<td>Neutral</td>
<td>?</td>
<td>3.1</td>
<td>11</td>
</tr>
<tr>
<td>RIT-15LP</td>
<td>14.2</td>
<td>50</td>
<td>1.3</td>
<td>Neutral</td>
<td>0.1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>SPT-100</td>
<td>10</td>
<td>83</td>
<td>1.35</td>
<td>Discharge</td>
<td>0.28</td>
<td>4.5</td>
<td>4</td>
</tr>
<tr>
<td>PPS-1350</td>
<td>10</td>
<td>88</td>
<td>1.5</td>
<td>Discharge</td>
<td>0.4</td>
<td>4.3</td>
<td>12</td>
</tr>
<tr>
<td>ROS-99</td>
<td>10</td>
<td>78</td>
<td>1.35</td>
<td>Discharge</td>
<td>0.3</td>
<td>4.5</td>
<td>13</td>
</tr>
<tr>
<td>ESA HET</td>
<td>14</td>
<td>180</td>
<td>3</td>
<td>Discharge</td>
<td>≤0.7</td>
<td>10.5</td>
<td>14</td>
</tr>
<tr>
<td>T-160</td>
<td>16</td>
<td>260</td>
<td>5</td>
<td>Discharge</td>
<td>0.7</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Olin ATD Arcjet</td>
<td>-</td>
<td>190-260</td>
<td>2</td>
<td>*</td>
<td>22-42</td>
<td>17.5-20.4</td>
<td>15</td>
</tr>
<tr>
<td>MR-508 Arcjet</td>
<td>-</td>
<td>200 nom</td>
<td>1.62</td>
<td>*</td>
<td>40</td>
<td>14-16</td>
<td>6</td>
</tr>
</tbody>
</table>

*Does not currently use a hollow cathode.

frequency range from well below 1 Hz to more than 100 MHz\textsuperscript{26}, although often at the mV level. In some parts of this spectrum, the noise contained definite frequencies which could be ascribed to specific plasma mechanisms. The frequencies well below 1 Hz occurred only at low power, were due to thermal effects, and are not relevant to normal thruster operation. Conversely, the high frequencies are explainable in terms of plasma processes, were of low to moderate amplitude, and can be tolerated by any thruster under normal circumstances.

Power Supply/Discharge Interactions

In addition to this electrical noise, very large amplitude oscillations were generated under some conditions, with frequencies of the order of 1 to 100 Hz. That these were due to an interaction between the cathode and the anode supply was demonstrated conclusively when they were eliminated by using a battery as the anode power source. This difference is shown in the anode voltage-current characteristics, \(V_aI_a\), in Fig 3; here, the open diode configuration was employed with no keeper electrode, but this did not affect the observed phenomena. Using the power supply, violent oscillations were observed in the regions denoted by B and D in Fig 3a. With the battery, these were shown to be regions of negative impedance, as indicated in Fig 3b.

In the latter case, if the slope of the load line of the battery/series resistor combination was steeper than the \(V_aI_a\) characteristic, the transition was smooth. However, if the load line was less steep, there was an instantaneous transition between high voltage/low current and low voltage/high current states. This is shown in the inset of Fig 3b, which is for \(d_m = 1.3\) mm, \(\dot{m} = 0.3\) mg/s, and \(I_t = 1\) A. This latter effect appears as of a region of “forbidden current”. A hysteresis effect also occurs, in that the regions of interaction appear to depend on whether \(I_a\) is increasing or decreasing; this is thought to be due to
the long thermal time constant of the cathode.

A comprehensive plot of the discharge regions indicated in Fig 3 is provided in Fig 4, from which it will be seen that the positions of the oscillatory regions depend on both \( \dot{m} \) and \( I_e \). These positions and the widths of the two main regions are influenced significantly by \( d_o \), \( d_w \), \( I_e \) and the thermal design of the cathode. It is thus possible to select design parameters and discharge conditions to ensure that normal operation is not within these regions and that any required throttling range can be achieved.

![Figure 4](image)

**Figure 4** Full map of discharge regions for \( d_o = 1.3 \, \text{mm} \).

Two additional regions, E and F, are indicated in Fig 4. Region F is at very low \( \dot{m} \), where there is experimental evidence of significant pinching in the orifice. Operation is then at high voltage, in order to sustain the required current, with the excess energy appearing as severe anode heating. Hence this region is very inefficient, and sputtering damage can be significant. The narrow region E separating D and F may correspond to the "neutraliser mode" found earlier in the T5 cathode. It is characterised by low flow and power, but relatively quiet discharge conditions.

As an example of the ability to tailor thruster requirements to these characteristics, the nominal T6 thruster operating point for 150 mN thrust is shown in Fig 4, for which \( d_o = 1.3 \, \text{mm} \) and \( I_e = 1 \, \text{A} \). This point provides a very wide throttling range, as required. In addition, a suitable power conditioning unit (PCU) design could permit successful operation within regions B and D, and an increase in flow to beyond 1.1 mg/s would eliminate entirely any restrictions. There is a suitable region for T6 neutraliser operation in region E at the nominal emission current of 2.7 A and \( \dot{m} = 0.1 \, \text{mg/s} \).

As an illustration of the effect of other parameters on the positions of the interaction regions, Fig 5 shows how the transitions from region A to B, and from B to C, depends on orifice diameter, for \( d_o = 0.75 \) and 1.6 mm. There is clearly a major shift to higher currents and flow rates as \( d_o \) is increased.

**RF Noise**

As mentioned above, the discharge noise, measured on the anode, keeper and Langmuir probe, changes considerably according the regime of operation. The noise is sometimes random, and on other occasions it has a repetitive waveform with a specific frequency. Amplitudes can vary from the mV level to volts. To explain these features it is necessary to invoke many different physical processes; this is beyond the scope if this paper, but has been addressed elsewhere.

An example of the variation of amplitude of keeper noise with current, flow rate and discharge regime is presented in Fig 6. It is clear from this that the noise is predominantly seen in the power supply interaction regions B and D, and that high flow rates are very beneficial in this regard.

![Figure 5](image)

**Figure 5** Effect of \( d_o \) on discharge characteristics.

![Figure 6](image)

**Figure 6** Effect of \( I_e \) and \( \dot{m} \) on keeper noise.

**Cathode Temperature and Lifetime**

As the lifetime of the cathode is very dependent upon temperature, this parameter was measured under a wide range of conditions. The aim was to achieve values of tip temperature, \( T_o \), of the order of 1100 deg C, certainly below 1200 deg C, since calculation and previous experience suggests that this is compatible with a lifetime in excess of 10 000 hours.
Although $T_r$ varies strongly with current, selection of $d_o$ permits operation within these limits. Examples of the values measured in the HET simulation configuration are shown in Fig 7, which is for a 15 A discharge with $d_o = 1.6$ mm. As can be seen, there is only a slight dependence upon $m$ and 1100 deg C is exceeded by only 10 to 20 deg. The beneficial influence of increasing $d_o$ in the T6 cathode test arrangement is shown in Fig 8, in which $T_r$ and the cathode case temperature are plotted against $m$ for various values of $d_o$. This effect is probably due to the dependence of orifice impedance on diameter.

![Figure 7](image1.png)  
**Figure 7**  
*Tip temperature as a function of $m$.*

Also of relevance to lifetime is the plasma potential immediately outside the orifice, since this determines the energy of ions which bombard the surface and cause damage via sputtering. The keeper voltage, which is a good guide to this potential, was typically 4 to 5 V at a current of 25 A, rising to 6 V at 15 A and 7 to 8 V at 5 A. These values present no concerns regarding sputtering damage to the cathode.

![Figure 8](image2.png)  
**Figure 8**  
*Effect of $d_o$ on cathode temperature.*

**Discharge Initiation**

The discharge initiation characteristics of the cathode were also measured, providing further unexpected data. In previous work on the cathode for the T5 thruster, it had been found that potentials of a few hundred volts were required on the keeper to initiate a discharge with the cathode at about 1000 deg C and flow rates somewhat higher than the operational values. This was not the case with the T6 cathode, much lower potentials sufficient, with considerable potential operational benefits.

![Figure 9](image3.png)  
**Figure 9**  
*Typical discharge initiation data.*

Typical data are presented in Fig 9 for $d_o = 1.6$ mm and flow rates suitable for the T6 main discharge cathode and for the neutraliser. In both cases, reliable and reproducible initiation was achieved with $V_k$ below 30 V and $T_r$ as low as 750 deg C. This substantial improvement can be ascribed to the large orifice diameter, which permits the external electric field to penetrate into the cathode much more readily than in the case of the T5 device.

**CATHODE APPLICATIONS**

From the above data, it appears that the T6 cathode is capable of meeting the requirements of all the thrusters included in Table 1. To illustrate this conclusion, Fig 4 is reproduced below as Fig 10 with the operating points of all these applications noted in suitable positions. It will be noted that the proposed flow rates do not correspond with those in Table 1 in cases where a reduction would be beneficial in improving overall efficiency. Examples of this are the HETs and grided ion thruster neutralisers. The suggested flow rates for the arcjets are high, to minimise cathode heating and erosion.

![Figure 10](image4.png)  
**Figure 10**  
*Illustration of the operating points of a wide range of electric thrusters.*

Bearing in mind that the shapes and positions of the power supply interaction regions can be moved substantially by changing various design and
operating parameters, and that these regions can also be restricted in size and effect by power supply design methods, it is clear that this cathode has very wide-ranging applications.

CONCLUSIONS

This paper has described the hollow cathode developed for the T6 ion thruster and its complex characteristics. The latter include the effects of interactions between this plasma device and a typical power supply, which can result in severe oscillations in regions of negative discharge impedance. Other characteristics described include the way in which temperature varies with operating conditions, and an indication is given of the influence of orifice diameter on this and other parameters. Examples of electrical noise measurements are also given. It is also shown that discharge initiation occurs at very low keeper electrode potentials, usually below 30 V, even with small xenon flow rates.

A survey of representative electric propulsion devices operating in the 1 to 10 kW regime is included. It is shown that these can all make use of a single version of the T6 cathode, perhaps with some adjustment to flow rates. Modifications to orifice diameter and thermal design will permit an even broader range of applications to be accessible.

It can therefore be concluded that this cathode is extremely versatile. It is applicable to many electric propulsion devices, including gridded ion thrusters, Hall-effect thrusters, and arcjets.

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