Hollow cathodes are one of the main life-limiting components in ion engines and Hall thrusters. Although state-of-the-art hollow cathodes have demonstrated up to 30,352 hours of operation in ground tests with careful handling, future missions are likely to require longer life, more margin and greater resistance to reactive contaminant gases. Three alternate hollow cathode technologies that exploit different emitter materials or geometries to address some of the limitations of state-of-the-art cathodes are being investigated. Performance measurements of impregnated tungsten-iridium dispenser cathodes at discharge currents of 4 to 15 A demonstrated that they have the same operating range and ion production efficiency as conventional tungsten dispenser cathodes. Temperature measurements indicated that tungsten-iridium cathodes also operate at the same emitter temperatures. They did not exhibit the expected reduction in work function at the current densities tested. Hollow cathodes with lanthanum hexaboride emitters operated over a wide current range, but suffered from lower ion production efficiency at currents below about 12.4 A because of higher insert heating requirements. Differences in operating voltages and ion production rates are explained with a simple model of the effect of cathode parameters on discharge behavior.

1 Introduction

Hollow cathodes used as electron sources for plasma production or beam neutralization in electric thrusters have demonstrated lifetimes of up to 30,000 hours in ground component- or thruster-level tests [8, 9, 10] and up to 16,000 hours in flight [1, 5]. However, potential future deep space missions may require even longer life [4, 7] or may require operation at conditions

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which differ from those of the long duration tests. To address the need for improved cathode lifetime and tools to design and validate new cathodes, we have undertaken a program to investigate three alternate cathode technologies and develop physics-based models of hollow cathode operation.

This paper describes state-of-the-art hollow cathodes, potential benefits of alternate technologies and experiments aimed at characterizing the performance and thermal behavior of laboratory model cathodes. Alternate cathode technologies that provide adequate performance and fulfill the promise of improved lifetime and greater resistance to reactive contaminants represent not only potential product improvements for electric propulsion systems, but also help illuminate the physics of hollow cathode operation. Differences observed in the performance and thermal behavior of the cathodes reflect key features of hollow cathode operation.

2 State-of-the-Art Hollow Cathodes

The electron emitter of a conventional dispenser hollow cathode is an impregnated porous tungsten tube (the insert), as shown in Fig. (1). The emitter is contained in a refractory metal cathode tube with an orifice plate on the downstream end. A small fraction of the thruster propellant is injected through the hollow cathode, and the orifice serves to increase the internal pressure in the insert region. Electron emission from the inner surface maintains an internal plasma which heats the insert to the required operating temperature and helps conduct the current into the main discharge. A heater surrounding the cathode tube is used to preheat the cathode prior to ignition.

The key to long insert life is to maintain a low temperature for a given electron emission current density by establishing a layer of adsorbed oxygen and barium atoms that lowers the surface work function. In state-of-the-art impregnated cathodes Ba and BaO are supplied by barium calcium aluminate source material (the impregnant) incorporated in the pores of the tungsten. Gaseous Ba and BaO are released in interfacial reactions between the tungsten matrix and the impregnant, producing a temperature-dependent vapor pressure of these species inside the pores. The Ba and BaO then diffuse through the pores to the surface and replenish Ba and O adsorbates lost by evaporation.

Figure 2: Thermogravimetric analyses of impregnant material sensitivity to water vapor in the environment.

The lifetime of these emitters is limited by exhaustion of the barium- and barium oxide-producing impregnant [3]. When the supply rate of barium to the surface drops below the value needed to balance evaporative losses due to consumption of the impregnant or reduced transport rates through product layers or through the pores, the electron emission capability of the surface degrades. The emitters are also sensitive to reactive gases, particularly oxygen and water vapor. Prior to launch, the impregnant material absorbs water vapor at room temperature. Figure (2) shows the mass gain observed for various impregnant materials in thermogravimetric analyses [6]. This is to some extent reversible and absorbed impurities can be baked out prior to operation, but experience has demonstrated that only a limited number of air exposure cycles can be tolerated before irreversible damage is done. Flight systems therefore typically use inert gas storage and purges to limit exposure time. At elevated temperatures during operation reactive
impurities in the propellant may cause oxidation of the tungsten substrate or poison the emitting surface by competing with barium adatoms for active adsorption sites. Cathodes operated with impure xenon gas often show significant tungsten material transport resulting in deposition in the emission region that might ultimately limit emitter life [7]. This transport is thought to be driven by formation of volatile tungsten reaction products and subsequent redeposition by dissociation in the plasma or on the hot emitting surface. To avoid these effects, flight systems employ ultra-high purity xenon and undergo extensive propellant system purification followed by point-of-use purity measurements to verify that the feed system does not introduce contaminants.

State-of-the-art hollow cathodes have demonstrated over 16,000 hours of operation in space on the DS 1 mission [1] and over 30,000 hours without failure in a ground test of the DS 1 flight spare engine at JPL [2]. A ground test of a similar cathode as part of the Space Station Plasma Contactor program at NASA GRC resulted in a cathode electron emitter failure after 27800 hours [3], possibly related in part to contaminants in the xenon. The Dawn spacecraft carries two ion thrusters to process the total propellant load and a third engine for redundancy, which limits the total operating time for a single engine to about 30,000 hours. The DS 1 experience and models of conventional cathode failure indicate low failure risk for Dawn [4]. Future missions with solar electric propulsion (SEP) will likely require similar or greater operating time and could fly with fewer engines if they were capable of greater life. Conventional hollow cathodes are sensitive to reactive gases, and as a result the ion propulsion systems on Dawn and on commercial communications satellites undergo special handling and propellant system purification procedures that result in a cost burden of $0.5-1M per spacecraft [5].

3 The Promise of Alternate Cathode Technologies

The advanced cathode technologies under investigation at JPL employ alternate emitter or barium source materials or configurations to address one or more of the limitations of conventional cathodes. These approaches are described in this section.

3.1 Mixed Metal Matrix Cathodes

These cathodes are similar to the conventional cathode shown in Fig. (1), but use a porous tungsten-iridium (W-Ir) alloy as the substrate. W-Ir cathodes have a work function 0.2-0.25 eV lower than impregnated tungsten [8], which reduces the temperature by up to 100°C for
Figure 3: Lifetest data for vacuum tube cathodes from the Crane Tri-Service Lifetest Facility. B-type dispenser cathode emitters are similar to conventional hollow cathode emitters. W-Ir and reservoir cathodes exhibit much more stable operation over periods of time exceeding 100,000 hours. This temperature reduction slows barium loss by a factor of six or more, based on experience in the microwave tube dispenser cathode industry [9]. These types of emitters have been used in vacuum tube applications and lifetest data [10] shown in Fig. (3) demonstrate much better long-term stability with lifetimes over 100,000 hours compared to B-type dispenser cathodes, which use emitters similar to conventional hollow cathodes. W-Ir is also expected to be less reactive with oxygen and water vapor, although there is little quantitative data on this potential benefit. W-Ir cathodes employ the same geometry and many of the same fabrication methods as conventional cathodes and could be essentially a drop-in replacement for state-of-the-art emitters, but have less potential payoff than the other two technologies discussed here. Five W-Ir emitters were fabricated and are being tested to demonstrate the expected temperature reduction and determine if they are more resistant to gas contaminants.

3.2 Lanthanum Hexaboride (LaB$_6$) Cathodes

These cathodes use an emitter machined from lanthanum hexaboride (LaB$_6$) as shown in a typical configuration in Fig. (4). LaB$_6$ has a work function of about 2.67 eV depending on the surface stoichiometry [11], and will emit over 10 A/cm$^2$ at a temperature of 1650 $^\circ$C. Despite the higher operating temperature, LaB$_6$ cathodes are expected to have lifetimes much greater than conventional cathodes because of a lower evaporation rate. Figure (5) shows an evaporation rate approximately a factor of 5 lower than that of BaO cathodes [12]. Because the emitting area increases as the inner diameter erodes, resulting in lower current densities and reduced operating temperature with time, potential lifetime improvements of up to an order of magnitude are possible. Since the bulk material is emitting, there is no chemistry involved in establishing the low work function surface and LaB$_6$ cathodes are insensitive to impurities and air exposures that would kill a BaO dispenser cathode. LaB$_6$ cathode can withstand gas-feed impurity levels two orders of magnitude higher than dispenser cathodes at the same emission current density, as shown in Fig. (6) [13]. LaB$_6$ cathodes are used routinely on Russian Hall thrusters and over 300 have flown in earth orbital applications. No failures have been experienced in flight or ground tests and no extraordinary cleaning procedures are used on the feed systems—they
Figure 4: Lanthanum Hexaboride Cathodes.

Figure 6: Percentage of possible thermionic emission versus partial pressure of oxygen and water showing the poisoning of dispenser cathodes relative to LaB$_6$.

are treated the same was as any other flight gas system. LaB$_6$ cathodes hold great promise for JPL electric propulsion applications, but have only demonstrated about 9000 hours of operation [14].

3.3 Reservoir Cathodes

Figure (7) shows an alternate cathode configuration designed to prevent barium depletion by providing a much larger supply of the consumable barium source material. The cylindrical porous tungsten or W-Ir emitter in this configuration is not impregnated with the source material. Instead, the barium source is contained in a reservoir surrounding the porous central emitter, which serves as the emission substrate and to provide controlled passage of Ba and BaO liberated from the enclosed source material to the emitting surface. Because the source material is separated from the emitter, the porous structure provides a fixed flow resistance over the life of the cathode. The Ba and BaO supply rates are therefore much more stable than in impregnated cathodes, as observed in long duration tests of reservoir cathodes for vacuum devices [10], shown in Fig. 4. The feasibility of this concept was demonstrated in initial tests with three proof-of-concept cathodes like that shown in Fig. 1c [15]. Five more reservoir
cathodes with porous tungsten emitters, several different source material combinations, and an improved structural design were procured under the Prometheus 1 program, but have not yet been tested. Two of these cathodes have conventional barium calcium aluminate source materials, but the other three employ barium scandate or barium calcium tungstate sources. As shown in Fig. 2, the scandate material is much more stable in water vapor environments compared to the aluminates [6]. Similar experiments showed that the tungstate stability is comparable to the scandate. Vacuum cathodes with scandate impregnants have demonstrated high electron emission current densities [10] and post-test analysis of one of the proof-of-concept reservoir cathodes operated successfully for 2000 hours showed that all of the aluminate source material had reacted to produce the barium calcium tungstate with no apparent impact on cathode operation [16]. Both materials are therefore expected to produce an adequate flow of barium with reduced environmental sensitivity compared to conventional cathodes.

4 Advanced Hollow Cathode Research Approach

The assessment of the advanced cathode technologies involves three components. As a realistic replacement for state-of-the-art hollow cathodes, an alternate cathode technology must demonstrate comparable performance. The first component of the program is therefore to characterize the operating range and impact on plasma production efficiency of each of the candidate technologies relative to a conventional hollow cathode. Performance measurements of conventional cathodes, W-Ir dispenser cathodes and LaB$_6$ cathodes have been completed and will be reported below.

The second component of this investigation is to characterize the thermal behavior of the various hollow cathodes. This enables a clearer understanding of certain cathode inefficiencies, provides data for cathode thermal design and, most important, allows an assessment of cathode service life potential, which is driven to a large extent by the temperature of the emitting surface. Comparisons of tungsten and tungsten-iridium dispenser cathodes will be presented.

The final focus is on assessing the sensitivity of the different emitter materials to reactive gases. This involves two separate experiments. The first is designed to study short-term effects on cathode operating temperature due to emitter poisoning from oxygen as a contaminant in the xenon gas. The second is a series of longer duration tests using xenon with higher levels of contaminants to demonstrate less susceptibility to
the erosion of emitter material by reactive gases. Preliminary experiments in oxygen poisoning effects on a conventional cathode have been completed and are reported in [?]. The cathode configurations, facilities and experimental methods used in the performance and thermal characterization are described briefly in this section.

4.1 Test Articles

The porous tungsten and tungsten-iridium impregnated inserts used in these experiments have a standard configuration similar to that shown schematically in Fig. (1) and all have an inner diameter of 3.8 mm. These were tested in refractory metal cathode tubes with orifice diameters of 1 and 2.3 mm. A graphite keeper electrode with an orifice diameter of 4.8 mm was used in the performance tests of these cathodes. A coaxial refractory metal heater is used to condition and preheat the cathode prior to ignition.

The LaB$_6$ cathode is shown in Fig. (4). The emitter is in the form of a cylinder with the same length and inner diameter as the tungsten and tungsten-iridium dispenser cathode inserts, but in this case it is contained in a graphite cathode tube because most refractory metals are not compatible with LaB$_6$ at high temperatures. The insert is constrained axially with a carbon spring. In initial tests this was made from Poco graphite, but in later tests a novel glassy carbon helical spring provided by Energy Science Laboratories, Inc was used. A graphite keeper electrode surrounds the cathode assembly as shown in Fig. (4). In initial tests with orifice diameters similar to those of the dispenser cathodes the LaB$_6$ cathode suffered from higher discharge voltages and was difficult to ignite. Results reported below are for the final configuration, which had a cathode orifice diameter the same size as the emitter inner diameter and a keeper orifice diameter of 5.9 mm. A swaged coaxial heater with an insulator designed for higher temperature operation than conventional heaters is used to preheat the cathode.

The reservoir cathodes are scaled up from the proof-of-concept cathodes shown in Fig. (7) and incorporate design changes that address thermomechanical issues identified in earlier tests. These cathodes, which were originally designed for higher current levels, have an emitter inner diameter of 12 mm and a cathode orifice diameter of 2.5 mm. The preliminary tests completed so far compared the performance of a reservoir cathode with a conventional barium-containing source material and a conventional impregnated cathode with similar insert and orifice dimensions. The graphite keeper electrodes in these experiments had an orifice diameter of 4.8 mm. Swaged coaxial heaters were also used in these assemblies.

4.2 Performance Test Facility and Experimental Method

Performance tests of the cathodes were conducted in a 1 m diameter by 2 m long vacuum facility. This chamber is pumped by two 25 cm diameter CTI cryopumps. Pressure was monitored with a Kurt Lesker ion gauge which was calibrated with nitrogen gas. The base pressure was typically $1.3 \times 10^{-4}$ Pa ($1 \times 10^{-6}$ Torr) and the xenon pressure during cathode operation ranged from $3.3 - 4.8 \times 10^{-3}$ Pa ($2.5 - 3.6 \times 10^{-5}$ Torr).

We have found that cathode performance, measured in terms of discharge and keeper voltage and ion production efficiency, is very sensitive to the anode configuration [?, ?]. Typical cathode diode tests with a keeper electrode only or triode tests with a flat plate anode do not produce results that are representative of performance in ion engine discharge chambers. The discharge chamber shown in Fig. (8) and schematically in Fig. (9) was designed specifically to simulate the environment of a ring cusp ion engine. It incorporates a water-cooled copper anode with cylindrical and conical sections, three rings of SmCo magnets and a water-cooled solenoid around the cathode. Magnetic field strengths of 1500 to 1900 in the cusps, 88 G at the cathode orifice and 30 G closed contours between cusps pro-
provide good plasma confinement and stable operation. Ion current collected by a molybdenum plate that was mounted at the anode exit plane and biased -20 V with respect to the cathode was monitored as an indicator of the discharge ion production rate. The cathode assemblies included the graphite keeper electrodes.

The xenon flow system and electrical configuration are shown schematically in Fig. (9). Ultra-high purity xenon is used as the cathode expellant. The flow rate is measured with a Unit Instruments 1661 flow meter and controlled with an MKS 250C controller and an MKS 248 valve. The valve is mounted in the vacuum chamber so that all external feed lines are above atmosphere pressure to eliminate the possibility of air leaks into the flow system. Main flow is introduced into the discharge chamber through a manifold located in the center of the cylindrical section and controlled with an MKS flow controller. The meters were calibrated with an MKS flow calibrator, yielding flow rate measurements with an uncertainty of less than 2%. An Optomux data system with LabView control software is used for flow setpoint control and flow meter data logging.

Heater and discharge power are provided by Sorenson DLM 40-15 and XXX power supplies, respectively, with the common returns grounded to the vacuum tank. The cathode is also grounded to the chamber through the mounting structure. The keeper electrode is connected to the anode through a 1 kΩ resistor, which allows it to act as a starter electrode when voltage is initially applied to the anode, but operate near the floating potential when the discharge ignites. Currents and voltages are measured to within 1% by the data system using calibrated shunts and voltage dividers.

Each cathode was operated in the facility for 12-24 hours to allow the insert conditions to stabilize after air exposures. The discharge voltage $V_d$, cathode keeper voltage $V_k$, and plate ion current $J_p$ were then measured for each of the cathodes in this specially designed plasma source over a range of discharge current levels $J_d$ and flow rates of interest for Hall and ion thrusters. The minimum cathode flow rate $\dot{m}_c$ was identified by either unacceptably high discharge voltage or transition to plume mode as indicated by large discharge voltage oscillations. For a given current level, the total flow rate $\dot{m}_t$ was maintained at a constant value by increasing the main flow rate $\dot{m}_m$ as the cathode flow rate was decreased. The ion production cost in these experiments was defined as

$$\epsilon_p = \frac{J_d V_d}{J_p}.$$  \hspace{1cm} (1)

4.3 Temperature Measurement Apparatus

Cathode thermal characterizations were performed in a vacuum facility with pumping, flow, electrical and data systems similar to those used for the performance measurements. In these experiments the temperature calibration procedure described below prohibited the use of a keeper electrode and discharge chamber. The cathodes without keeper electrodes were operated with a water-cooled cylindrical anode, as shown in Fig. (??). A water-cooled solenoid surrounding the cathode was used to produce a magnetic field...
Fig. 9: Schematic of the discharge chamber, flow and electrical systems used in performance measurements.

of TBD at the cathode orifice [?].

Insert temperatures were measured using an optical pyrometer system described in detail in [6]. Light emitted by the hot surface of the insert is collected with a high temperature fiber optic probe and transmitted to a two color pyrometer outside the vacuum chamber. The probe is scanned along the axis of the cathode from the upstream end using a stepper motor-driven actuator. The scan speed is sufficiently high to avoid probe heating and minimize contamination by barium deposition. The pyrometer employs sensitive photodiodes to measure the signal intensity in narrow spectral bands surrounding 1260 and 1500 nm, wavelengths chosen to avoid plasma line radiation. The ratio of these signals is proportional to the temperature and independent of source-to-probe geometry.

The pyrometer response was calibrated in situ using the cathode heater. A small cylindrical oven consisting of tantalum radiation shields can be slipped over the cathode using a motion feedthrough in the vacuum chamber door. This oven provides a nearly isothermal region at downstream end of the cathode, so the pyrometer signal there can be related to the temperatures measured with the thermocouples on the orifice plate. The two thermocouples typically agree within 1-10°C when the calibration oven is in place. The photodiode signals are very repeatable from scan to scan. Calibrations were performed frequently to monitor any drift in response. In these experiments the calibrations were repeated after every XXX measurements. Differences in calibrations taken before or after a given set of measurements typically produced differences in the calculated temperature of only XXX °C. XXX-Discussion of uncertainties.

5 Experimental Results

The results of performance measurements for all three cathode technologies are compared to conventional impregnated tungsten cathodes and thermal characterization tests of tungsten and tungsten-iridium cathodes are presented in this section.
5.1 Performance of W and WIr Impregnated Inserts and a Small Cathode Orifice

A subset of the performance measurements on the 1 mm orifice diameter cathode with tungsten and tungsten-iridium impregnated inserts is displayed in Fig. (10). The operating conditions are listed in Table (11). The average neutral density in the discharge chamber is estimated from the total flow rate, open area for neutral efflux from the chamber and residual tank pressure. The top plot shows the discharge voltage variations with cathode flow rate for discharge currents ranging from 4 to 15 A. To make the plots easier to interpret, the curves for 6 and 10.2 A have been excluded, but the trends for these current levels are similar to the others. The second plot displays the variation in the keeper electrode potential with respect to the cathode emitter. The ion current collected by the plate at the downstream end of the discharge chamber as the current and flow rate are varied is shown in the next plot. The final graph shows the plate ion production cost.

<table>
<thead>
<tr>
<th>Discharge Current (A)</th>
<th>Total Flowrate (sccm)</th>
<th>Neutral Density ($m^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>3.5</td>
<td>1.7e18</td>
</tr>
<tr>
<td>6.0</td>
<td>3.5</td>
<td>1.7e18</td>
</tr>
<tr>
<td>8.24</td>
<td>3.5</td>
<td>1.7e18</td>
</tr>
<tr>
<td>10.2</td>
<td>4.0</td>
<td>1.9e18</td>
</tr>
<tr>
<td>12.4</td>
<td>5.0</td>
<td>2.4e18</td>
</tr>
<tr>
<td>15.0</td>
<td>5.0</td>
<td>2.4e18</td>
</tr>
</tbody>
</table>

Table 1: Test conditions for the performance characterization experiments.

The tungsten and tungsten-iridium inserts yielded very similar behavior in this cathode. The discharge voltage increases monotonically as the cathode flow rate is reduced. At a given cathode flow rate, the discharge current increases with discharge current. Equivalently, the flow rate required to achieve a given discharge voltage increases with current. The keeper voltages

Figure 10: Results of performance tests using the 1 mm orifice diameter cathode with tungsten and tungsten iridium impregnated inserts. Individual curves were measured at a constant total flow rate (and therefore constant average neutral density) by varying main flow to compensate for changes in cathode flow rate.
increases as current is decreased, and is only weakly dependent on flow rate. The ion current collected by the plate increases monotonically with current at a given flow rate. For a fixed discharge current, the plate ion current initially increases as cathode flow rate drops, but reaches a peak value and falls again for the lowest flow rates. The peak in plate current and continued increase in discharge voltage as flow is dropped results in a minimum in the ion production cost at intermediate flow rates. The minimum value of ion production cost is not strongly dependent on discharge current, but the cathode flow rate for minimum ion production cost depends on current.

5.2 Performance of Impregnated Inserts and a Larger Cathode Orifice

The performance of the 2.25 mm orifice diameter cathode with the tungsten and tungsten-iridium inserts was measured for the same range of conditions listed in Table (11) and the results are summarized in Fig. (??). As in the cathode with a smaller orifice diameter, the discharge voltage increases monotonically as cathode flow rate is reduced. Voltage increases monotonically with current for flow rates below about 2.5 sccm, but for higher flows the trend is opposite that observed with the smaller orifice. In Fig. (12) the discharge voltages measured with the tungsten-iridium insert in cathodes with large and small orifices are compared. For the two highest discharge current levels the cathode with the smaller orifice has the higher voltage. At low currents, however, the cathode with the larger orifice has higher discharge voltages. At a given discharge current, the discharge voltages for the two orifice sizes tend to converge at low flow rates.

The keeper electrode voltage drops monotonically with increasing discharge current, as in the cathode with the smaller orifice. The keeper voltages are higher with the larger orifice, but again the behavior of the two cathodes becomes very similar at low flow rates, as shown in Fig. (13).

Figure 11: Results of performance tests using the 2.25 mm orifice diameter cathode with tungsten and tungsten iridium impregnated inserts. Individual curves were measured at a constant total flow rate (and therefore constant average neutral density) by varying main flow to compensate for changes in cathode flow rate.
Figure 12: Comparison of discharge voltage trends for a tungsten-iridium insert in cathodes with 1 and 2.25 mm diameter orifices.

Figure 13: Comparison of keeper voltage trends for a tungsten-iridium insert in cathodes with 1 and 2.25 mm diameter orifices.

The plate ion current at a given flow rate and discharge current is lower in the cathode with the larger orifice, but rises as the cathode flow rate is reduced. This results in comparable minimum ion production costs for the two orifice sizes.

5.3 Performance of the LaB₆ Insert

The performance of the LaB₆ cathode is summarized in Fig. (14). This cathode was operated at 20 and 25 A, as well as the operating points listed in Table (11), and at the highest current levels the discharge voltage trends as cathode flow rate is varied are similar to the other cathodes. At discharge currents of 15 A and 12.4 A however, the discharge voltage is relatively insensitive to flow rate. At lower current levels the discharge voltage rises dramatically. The keeper voltages are relatively low at 20 and 25 A, but are much higher than in the other cathodes at lower currents. The plate ion current is quite high at 20 and 25 A, but for the other discharge current levels the ion production rate is generally lower than for the dispenser cathodes at the same conditions. The minimum ion production cost is about 15% higher in the LaB₆ cathode at 15-25 A compared to the dispenser cathodes at 15 A. For the lower discharge currents, however, the high discharge voltage and low ion production rate result in ion costs that are considerably higher in the LaB₆ cathode.

5.4 Thermal Characteristics of Tungsten and Tungsten-Iridium Dispenser Cathodes

The thermal behavior of the tungsten and tungsten-iridium inserts in the cathode with a 1 mm diameter orifice was characterized over a discharge current range of 6 to 15 A at the nominal flow rates listed in Table (??). Representative profiles of the axial temperature distribution measured with the fiber optic probe in the W and WIr inserts at 15 A are shown in Fig. (??) XXX-need figure! The profiles suggest very little difference between the two cathodes. This is demon-
Figure 14: Results of performance tests using the 3.8 mm orifice diameter cathode with the LaB$_6$ insert. Individual curves were measured at a constant total flow rate (and therefore constant average neutral density) by varying main flow to compensate for changes in cathode flow rate.

Figure 15: Comparison of peak insert and orifice plate temperatures for the tungsten and tungsten-iridium inserts in the 1 mm orifice diameter cathode.

strated over the entire discharge current range in Fig. (15), which displays the peak insert temperature based on the probe measurements and the orifice plate temperatures measured with thermocouples. For both inserts the temperatures increase monotonically with discharge current, and the orifice plate temperature is always lower than the insert temperature by 50-100 °C (XXX-check this!).

6 Discussion

The different materials and geometries of these cathodes result in performance and thermal trends that help illuminate the physics of hollow cathode operation. The fundamental performance parameter, ion production cost, scales with flow rate and discharge current in a way that depends critically on the distribution of potential in the discharge. A conceptual view of the potential distribution is shown in Fig. (16).

The potential in the insert region, $V_i$, consists of the cathode sheath voltage and the radial potential drop through the high density, collisional insert plasma. This contribution to the total voltage drop serves primarily to heat the insert to the temperatures required for thermionic emission. The electric field in the orifice is determined by
the competing effects of Ohmic dissipation and the electron pressure gradient. Resistive effects dominate, resulting in an increase in potential of \( V_o \) through the orifice. The Ohmic heating causes an increase in electron temperature from about 2-3 eV in the insert plasma to 4-6 eV in the cathode plume region [3]. The insert and orifice drops form the cathode potential, \( V_c \).

As the density drops in the expanding gas downstream of the orifice, emitted electrons are accelerated from the cathode potential to the discharge plasma potential through a drop of \( V_p \), forming the population of primary electrons. Primaries are collected at the anode or lose energy in inelastic ionization and excitation collisions with neutrals and equilibrate with the population of maxwellian electrons. For a stable discharge, the plasma must be positive of the anode, typically by a few volts [2]. The difference between the bulk discharge plasma potential and the anode voltage is the anode sheath \( V_a \) and presheath \( V_{ap} \) that serves to accelerate ions to the Bohm velocity. The discharge voltage \( V_d \) represents the difference between anode and cathode emitter potentials.

The ionization rate is strongly dependent on the primary electron energy and the maxwellian electron temperature, so the partitioning of terminal voltage among the various contributors is largely responsible for the ion production efficiency. XXX-need to make this argument quantitative. The cathode behavior influences the electron temperature and can affect the primary electron energy through changes in \( V_i \) and \( V_o \).

Cathode material and operating conditions have a significant impact on the insert potential \( V_i \). This can be seen most clearly in the results with the LaB\(_6\) cathode. At a discharge current of 15 A the discharge voltage of the LaB\(_6\) cathode is similar to that of the impregnated cathodes, but the ion production rate is much lower. This occurs because the insert voltage drop \( V_i \) is a larger fraction of the total voltage, resulting in lower primary electron energies. Because it must operate at a higher temperature to maintain a given current density due to a higher work function compared to the other materials, it requires a higher heat flux during operation. This can also be seen in the voltage trends of the keeper electrode, which is essentially floating and therefore responds to the local potential downstream of the cathode orifice. The LaB\(_6\) cathode keeper voltage is much higher than the keeper voltages measured in the other cathodes at 15 A.

At higher discharge currents less internal voltage drop is required to keep the LaB\(_6\) insert hot, so \( V_i \) is lower and the keeper voltage is depressed. Lower internal voltage drop and higher discharge voltages result in much higher ion currents to the plate. Lower discharge currents require higher internal potentials, which result in soaring discharge and keeper voltages with poorer ion production efficiency.

Insert heating requirements largely determine the trends observed in the dispenser cathodes with varying flow rate and discharge current as well. Previous experiments show that the insert plasma potential \( V_i \) increases with decreasing current and flow rate [7] in order to maintain the required insert heating. Additional discontinuous jumps in \( V_p \) may occur downstream of the orifice at lower flow rates in order to produce sufficient plasma locally to carry the discharge cur-
 Increases in \( V_i \) and \( V_p \) result in rising discharge voltage as the flow rate drops. The similar behavior of the tungsten and tungsten-iridium inserts noted in the performance tests is explained by the thermal characterization experiments. The two inserts have essentially the same operating temperature and thermal design, so the internal voltage drops are the same.

The cathode orifice diameter also influences ion production efficiency through its effect on the orifice potential drop \( V_o \). This can be seen clearly in the comparisons of large and small orifices with dispenser cathode inserts. At high currents the small orifice diameter cathode exhibits higher discharge voltages than the corresponding large orifice cathode. The higher discharge current densities dictated by the smaller orifice result in a higher resistive potential drop \( V_o \). As flow rate is decreased the large and small orifice cathode discharge voltages converge due to increased contributions from \( V_i \) and \( V_p \) and reduced orifice resistivity as a result of dropping neutral density. At lower current levels the large orifice cathode has higher discharge voltages. This opposite trend in this regime is caused by reduced Ohmic dissipation in the orifice and a greater effect of reduced insert pressure on the internal voltage drop \( V_i \).

In fact, both cathodes operate with essentially the same performance in the discharge voltage range of interest. To avoid excessive double ion production and resultant internal sputter erosion, discharge voltages should not exceed 26 V. The plots in Fig. (17) show the cathode flow rates required to maintain a constant discharge voltage of 26 V over the entire discharge current range and the resulting performance. The large and small orifice cathodes operate with approximately the same ion production rate and keeper voltage, indicating that they have the same distribution of voltage between \( V_c \) and \( V_p \). The small cathode requires higher flow rates at the highest currents to maintain 26 V compared to the large orifice cathode. At these current levels the small orifice cathode suffers from a higher Ohmic drop in the orifice and higher cathode flow is required to compensate by suppressing \( V_i \). The LaB\(_6\) cathode has poorer ion production efficiency at 26 V, and cannot operate at that low a voltage for currents below the 10.2 A condition.

The large orifice cathode operates at 26 V at current levels of 4 to 15 A with very little variation in cathode flow, which could yield operational advantages in throttleable systems. In addition, the low internal pressure in this cathode allows greater plasma contact area and therefore reduced current density requirements on the emitter. The resulting reduction in operating temperature could provide significantly longer cathode life.

References

Figure 17: Comparison of cathode technologies with a 26 V discharge. The cathode flow rate is varied to maintain a constant 26 V discharge over the range of currents. Voltages this low could not be achieved with the LaB$_6$ cathode at current levels below the 10.2 A case.


