Hollow Cathode Without Low-Work-Function Insert

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Abstract: An all-tantalum hollow cathode was developed that had a lifetime of 1726 hr at a 2 A emission (1 A keeper, 1 A net) and a xenon flow of 1 sccm. Compared to hollow cathodes with low-work-function inserts, this hollow cathode is relatively simple to fabricate and should have a long "shelf life" after qualification testing.

I. Introduction

The objective of this investigation was the development of a small hollow cathode, with a net electron emission of about 1 A and a lifetime upwards of 1000 hr. The intended use of this hollow cathode was as a cathode-neutralizer in a small closed-drift thruster.

Hollow cathodes have been used as long-life electron sources in electric thrusters for many years. The main line of development has included a refractory-metal tube through which a working gas (such as mercury, cesium, argon, or xenon) flows, with a low-work-function insert near the end through which the electrons are emitted. This insert can be coated with a low-work-function material,[1] impregnated with such material,[2] or even consist entirely of such material (lanthanum hexaboride).[3] Much of the development effort has been directed at obtaining lifetimes of 10,000 hours or more.[4] While the interest in very long lifetimes has not diminished, the use of closed-drift thrusters with lower specific impulses than gridded thrusters has resulted in some lifetime requirements for hollow cathodes that are only several thousand hours.[5]

Early studies[6] reached generally accepted conclusions. First, for a given configuration and operating condition (emission and gas flow), a specific operating temperature is required, and this temperature can be reached with various combinations of internal and external heating power. Second, the internal heating power consists of ions generated in the plasma inside the hollow cathode bombarding the internal emissive surface, with the coupling voltage to a nearby anode (or virtual anode) a qualitative indication of the energy of these bombarding ions. Other studies[2,7] reached the related conclusion that the higher operating temperatures necessary without a low-work-function emissive material, together with the higher coupling voltages, were not consistent with the long lifetime requirements of electric propulsion.

A separate line of development for hollow cathodes, in which no low-work-function material was involved, is also pertinent. These hollow cathodes were apparently not used in electric propulsion and used simple refractory metal tubes, usually tantalum. No quantitative lifetimes were given in an otherwise comprehensive survey of this technology.[8]

Despite the lack of any significant lifetimes for electric propulsion hollow cathodes without low-work-function materials, such cathodes had been developed for industrial ion sources. When operated at emissions of 5 A[9] and 15 A,[10] these hollow cathodes had demonstrated moderate lifetimes of several hundred up to 1000 hr.

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II. Cathode Development

A. General Approach

It has been observed that a hollow cathode designed to utilize a low-work-function material will not operate in a normal manner when that material is depleted or removed.[2,7] This is because the temperature of the emissive surface must rise to a very high value, which requires a large increase in heating power, which in turn results in the coupling voltage rising to a value that results in rapid damage to the hollow cathode. The inverse approach has mostly been ignored - to reduce the thermal losses sufficiently so that thermionic emission can be obtained without either a low-work-function material or a large coupling voltage.

A fundamental requirement for reducing these thermal losses is to make the hot portions of the hollow cathode small. This is because both radiation and conduction heat losses are reduced by making the areas for these losses small. Hollow cathodes with emissive inserts, whether coated/impregnated with low-work-function material,[6,11] or not,[9,10] have used a minimum outside diameter of the hollow-cathode tube of about 3 mm. With wall thickness of the order of 0.5 mm, this leaves an inside diameter of only about 2 mm for an insert. The presence of an emissive insert, with or without a low-work-function material, thus presents a practical difficulty in reducing the size of a hollow cathode.

Rather than trying to miniaturize an emissive insert, the decision was made to use a simple refractory metal tube, similar to that described by Delcroix and Trindade,[8] but to reduce thermal losses by making the hollow cathode quite small and improving the radiation shielding. This approach was also of interest because it followed a development path that was mostly ignored in previous electric-propulsion hollow cathodes.

B. Thermal Calculations

Preliminary designs and tests used a 1.6-mm diameter of the hollow cathode tube and argon as the working gas. These designs and tests were conducted as part of an earlier investigation that resulted in a patent application,[12] but also constituted part of the total development process for the hollow cathode described herein.

Thermal calculations were made using a tantalum tube 38 mm long, with about 30 mm extending from support to open end. As described by Delcroix and Trindade,[8] the internal surface of a tantalum tube near the emissive (open) end reaches a temperature of about 2400 K. (This maximum temperature should actually be reached a short distance from the open end, but this short distance is not important for the calculations described here.) The support end and the surrounding enclosed keeper were both assumed to be at a temperature of 773 K (500°C). Dividing the tube length into five segments at different temperatures, the temperature distribution is shown by the circular symbols in Fig. 1. The corresponding heat loss, both radiation from the entire outside surface together with the conduction along the tube, was 91 W. If the radiation shielding is assumed to reduce the radiation loss at any temperature by 90%, the temperature distribution is shown by the triangular symbols in Fig. 1 and the corresponding radiation and conduction loss is reduced to 60 W. These losses do not include the cooling due to electron emission, but show that a substantial reduction in heat loss is possible. The calculated temperature distributions in Fig. 1 also show that: (1) the temperature distribution does not change greatly as the radiation loss is reduced, and (2) the temperature changes in roughly a linear manner from the hot emitting end to the cooler support end.

C. Radiation Shield Approach

The temperature variation of Fig. 1 has important implications for the design of the radiation shielding. In Fig. 2, the heat flow pattern for simple, full-length radiation shielding is illustrated by arbitrarily dividing the flow into paths Q_1 through Q_4. Assuming a typical heat shield with 15 turns of dimpled tantalum foil, 0.013 mm thick, the cross section for heat flow parallel to the axis of the tube in the radiation shielding is substantial, about 2/3 of the cross section for the tube itself. There is, therefore, a large axial component to the heat flow paths in the shielding. In the case of the heat flow through the inner shield (Q_4), there will actually be heat radiated back to the hollow-cathode tube at the cooler end, so that the radiation shield will be, in part, a parallel path to the tube for thermal conduction back to the support.

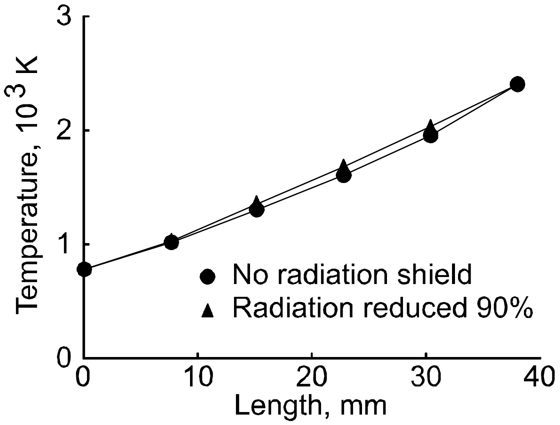


Figure 1. Calculated temperature distributions for hollow cathode.

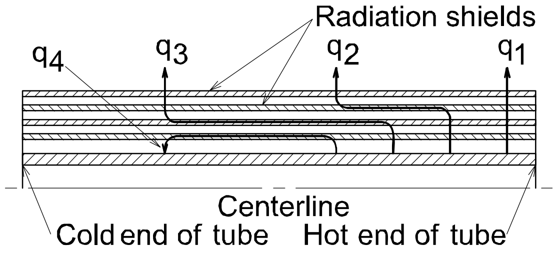


Figure 2. Heat flow with full-length radiation shields.

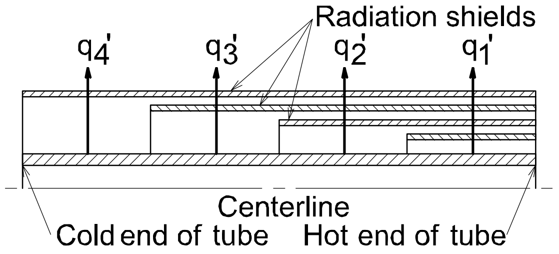


Figure 3. Heat flow with graduated-length radiation shields.

The heat flow distribution in Fig. 3 illustrates the unobvious result of selectively reducing the axial dimensions of the radiation shield. The lengths of the layers of the shield can be progressively reduced as the tube is approached, so that there is little axial variation in the temperature of each layer and the heat flow direction is essentially radial - see paths Q_1' through Q_4'. It should be apparent that, at the hot end of the tube where the reduction in heat loss is most important, restriction of the heat flow to the radial direction results in a higher heat flux density, hence *higher* temperatures for each of the corresponding layers in Fig. 3. With higher shield temperatures and the same tube temperature, there will be a *reduced* heat loss near the hot end of the tube.

D. Preliminary Tests

Several tests were conducted to verify the above conclusion, that a *reduction* in the axial length of radiation shielding could reduce the heat loss and, through decreased voltage, increase lifetime. A commercially available hollow-cathode body with an enclosed keeper[13] was used (see Fig. 4) which employed a glow discharge for initial heating of the hollow cathode to operating temperature (see Fig. 5 for the electrical schematic). The electron emission was to the ion beam generated from a commercially available end-Hall ion source.[14,15] A test with a bare tantalum tube was used as the baseline for performance. Using a tantalum tube with an outside diameter of 1.6 mm, an inside diameter of about 0.8 mm, and a length of 38 mm with about 30 mm extending outside of the support fitting (see Fig. 6(a)). The same operating conditions of 6.5 A total emission (1.5 A keeper and 5 A net emission) and 10 sccm of argon were used for the baseline configuration and two configurations of radiation shields that were tested. The background pressure in the vacuum chamber was in the low 10^{-4} Torr range.

The baseline configuration gave a lifetime of about 60 hr. The voltage of the enclosed keeper is indicative of the coupling voltage. The keeper voltage started low and rose near the end of the lifetime, but remained in a fairly small range of 16-17 V over most of the lifetime. This operation corresponds generally to the N (normal) regime of Delcroix and Trindade.[8] The slightly low emission for the N regime (6.5 A versus >10 A) may appear to place the

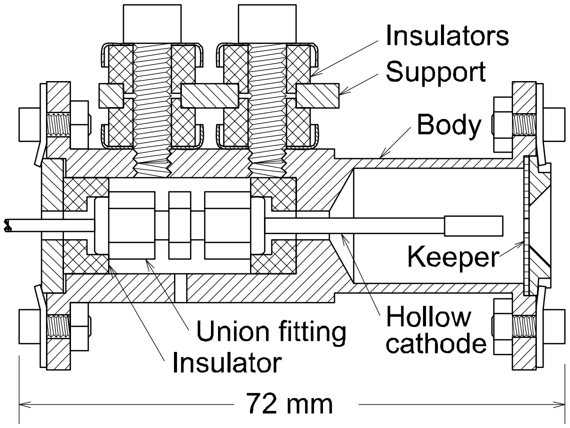


Figure 4. Crosssection of hollow-cathode body.

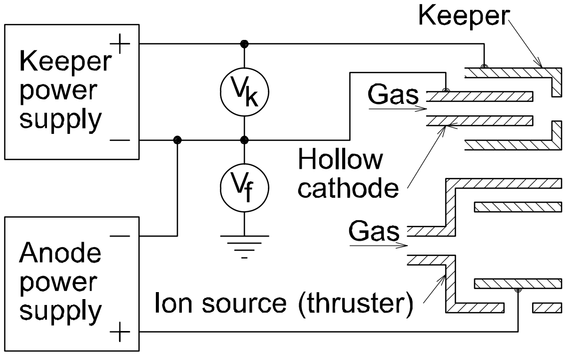
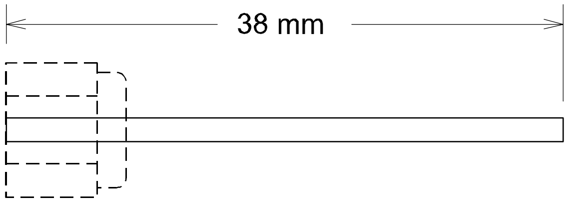
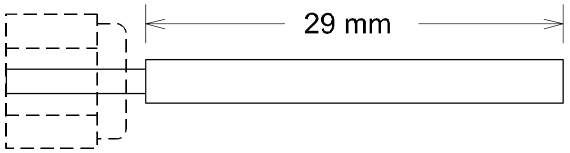


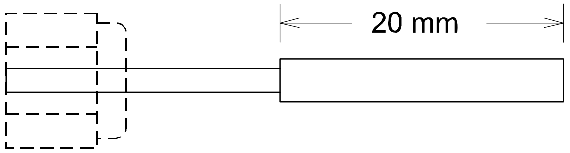
Figure 5. Electrical schematic.



a) Baseline (no shield).



b) Long radiation shield.



c) Short radiation shield.

Figure 6. Argon hollow-cathode configurations used in preliminary tests.

operation in the LI (low current) regime, but the steady operation and low coupling voltage would be inconsistent with such a classification. The ability to have normal operation with this low emission is attributed to the small diameter of this cathode, compared to most of cathodes described by Delcroix and Trindade.

The first radiation shield started approximately flush with the open end of the tube and consisted of 15 turns of tantalum foil, 0.013 mm thick, with a length of 29 mm, which was about the longest length that could be used without interfering with the support fitting used in the commercially available hollow-cathode body[13] (see Fig. 6(b)). The addition of this heat shield increased the lifetime from about 60 hr for the baseline configuration to 170 hr. The keeper voltage was 15-16 V over most of this lifetime.

The second radiation shield again started approximately flush with the open end of the tube and consisted of 15 turns of tantalum foil, 0.013 thick, but with the length reduced to 20 mm (see Fig. 6(c)). The keeper voltage decreased further to 13-15 V and the lifetime increased to 600 hr.

Several things are shown by these tests. One is that small reductions in keeper voltage can result in substantial increases in lifetime, This is, of course, because the damage by the bombarding ions can vary substantially with small changes in ion energy near what has been called the sputtering threshold. Comparison of the last two shield configurations also shows that even a fairly simple approach to reducing the length of the radiation shielding can have significant benefits.

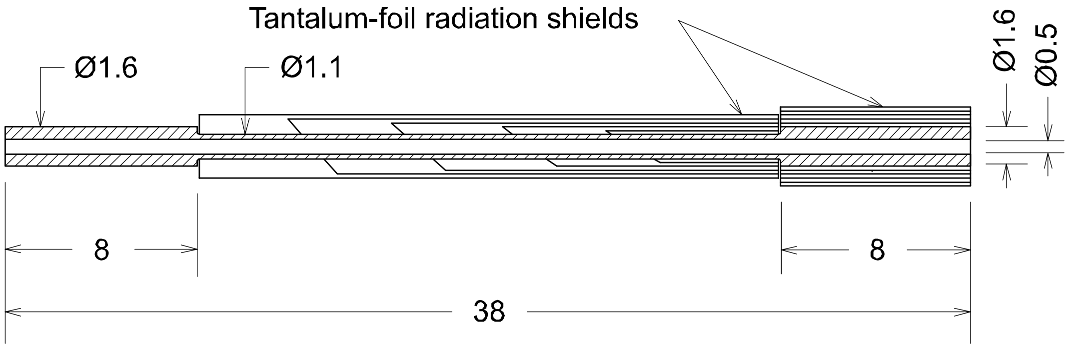


Figure 7. Cross section of xenon hollow-cathode configuration.

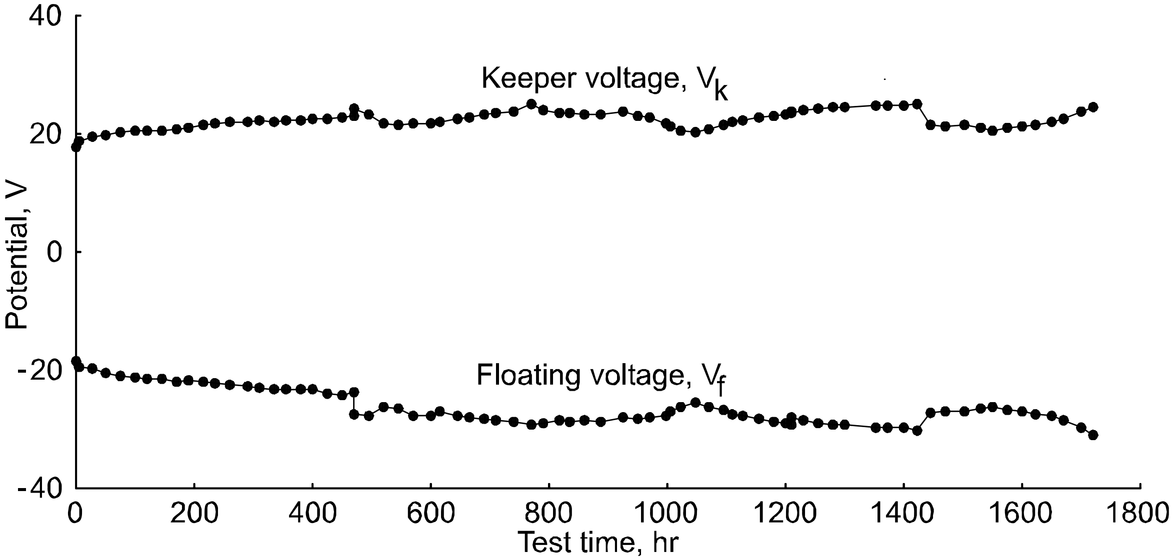


Figure 8. Variation of keeper and floating voltages with operating time for cathode of Fig. 7.

III. Duration Test

A. Cathode Configuration

The most important difference between the 1 A xenon hollow cathode described in this paper and the preliminary tests described above is the emission level. The total emission dropped from 6.5 A (1.5 A keeper, 5 A net) to 2 A (1 A keeper, 1 A net). That reduction in the total emission resulted in unstable operation and/or excessive keeper voltage in the preliminary configurations described above. To provide stable operation and a long lifetime, the heating power required to maintain a tip temperature of about 2400 K would have to be reduced substantially from that of the preliminary configurations.

The hollow-cathode configuration selected is shown in Fig. 7. The tube is tantalum with the same 1.6 mm outside diameter used for the preliminary tests described above, but with the outside diameter reduced to 1.1 mm

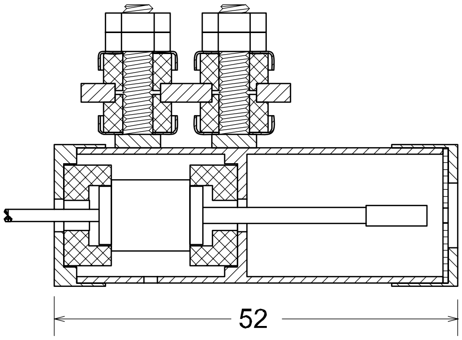


Figure 9. Cross section of hollow-cathode assembly with reduced-mass body.

over most of the 38 mm length. This reduced diameter was expected to reduce the thermal conduction loss to the support. Two 8 mm lengths at the two ends were left at their original 1.6 mm diameter. The larger diameter was left near the open end to provide additional mass for durability, while the larger diameter at the other end was

required to match the support fitting. The inside diameter of the tantalum tube was 0.5 mm. Two radiation shields were used, each with about 15 turns of tantalum foil, 0.013 mm thick. The first shield was 8 mm long and was wrapped around the 1.6 mm diameter section near the open end. The second shield was wrapped around the reduced diameter section and was of variable length, constructed in a manner closer to that shown in Fig. 3.

B. Performance

The configuration of hollow cathode shown in Fig. 7 was endurance tested using the commercially available hollow-cathode body shown in Fig. 4 and the electrical circuit shown in Fig. 5. The keeper current was held at 1.0 A and the ion source was operated so as to require a net hollow-cathode emission of 1.0 A. The variation of keeper and floating voltages are shown in Fig. 8 over the 1726 hour duration of the test. The measurements of keeper and floating voltages are indicated in the electrical schematic, Fig. 5.

There was gradual overall rise in keeper voltage with operating time. The floating voltage is almost a mirror image of the keeper potential, and the sum of the two is the voltage of the keeper relative to the surrounding vacuum chamber. Sudden changes in keeper potential corresponded to interruptions of the test for inspections, which occurred every 400-600 hours. The only precautions taken during these inspections were to permit the cathode to cool before exposing it to atmosphere and to flow 5-10 sccm of xenon through the cathode for about 15 minutes before restarting it. Being of all-metal construction, the length of an atmospheric exposure should not matter, which in turn should mean a long "shelf life" after qualification testing.

The all-metal construction, however, does not permit an unlimited *number* of exposures to atmosphere. Similar hollow-cathode configurations were operated for short periods of a few hours and then exposed to atmosphere. After five or more such exposures in rapid succession, the keeper potential would rise sharply and the cathode would be difficult to restart.

C. Failure Mode

The hollow cathode failed after 1726 hr. The failed cathode had two holes through the side of the tube and radiation shield, one at the junction of the 1.6 mm and 1.1 mm diameters near the open end, and one about 15 mm from the open end. These holes are believed to be the result of both imperfect fabrication and a less than optimal design. The hole farthest from the open end is believed to be the result of a crack or very thin section produced in the fabrication by grinding. To avoid this type of failure, the tube should probably used in the as-drawn outside diameter. The hole closer to the open end may have also originated at a crack or thin spot, but it is located close to the transition to the diameter of 1.6 mm. There is a sharp temperature gradient there which could have aggravated the failure. So, directly or indirectly, the failures are believed due to the fabrication of the hollow cathode tube by reducing the diameter from the as-drawn diameter. A longer lifetime would therefore be expected from a moderate redesign of the hollow cathode.

A minor problem should also be mentioned. Tantalum tends to creep under mechanical force at high temperature. For the hollow cathode operating temperatures, the small tube diameter, and the length of the endurance test, the force of gravity caused some shift in alignment. If allowed to continue, this shift would have affected alignment enough to degrade performance. This shift was counteracted in the endurance test of Fig. 6 by inverting the cathode to reverse the direction of creep during alternate portions of the test.

D. Mass of Hollow Cathode

The mass of the hollow cathode assembled in the commercially available hollow-cathode body was 146 g. This mass could be reduced to an estimated 75 g by omitting features that permitted reuse of the body, as well as by using a smaller custom gas fitting (see Fig. 9). All the thicknesses important for erosion and the volume of the discharge region around the hollow cathode are unchanged in this conceptual redesign, so the performance should be unchanged. Further reductions in mass should be possible by going to thinner, sheet-metal thicknesses, but performance would have to be verified with these more significant changes.

There is also a mass efficiency to consider, i.e., the mass of the hollow-cathode assembly relative to the mass of the xenon passing through it. The mass of 1 sccm of xenon over 1726 hr is about 600 g, which is about eight times the 75 g mass of the hollow-cathode assembly with a moderate redesign. This large number assures that the hollow-cathode mass is small compared to overall thruster system mass, and the mass penalties for the use of multiple hollow cathodes to obtain longer operating lifetimes is also reasonable.

IV. Concluding Remarks

A significant lifetime of 1726 hours was obtained with a small hollow cathode of all-tantalum construction. The xenon consumption was moderate (1 sccm) at a total emission of 2 A (1 A keeper and 1 A net emission). Obtaining this lifetime without the use of a low-work-function material required careful thermal design, which made use of both a small size for the hollow cathode and the use of a radiation shield with graduated lengths for the layers of this shield. This lifetime test indicates that relatively simple all-refractory-metal hollow cathodes could be practical options for thrusters with projected lifetimes of several thousand hours.

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