Multiple Orifices and Integrated Radiation Shielding in the Hollow Cathode Keeper

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I. Abstract

We present initial validation of two new patented techniques for hollow cathode keeper performance improvement: multiple orifices and integrated radiation shielding. Both techniques are demonstrated in a common LaB6 cathode testbed sized for nominal 20 A, 15 sccm operation. We compare a keeper with a traditional single orifice to one with an array of 169 smaller orifices sized to maintain the same total open area in a 2.7 A keeper discharge. The multiple orifice keeper delayed deterioration of keeper voltage to 10% above nominal from 12 sccm in the single orifice case to 6 sccm in the multiple orifice case. It decreased absolute keeper voltage by 40-50% across gas flow rates from 4-15 sccm. Initial results also suggest that the multiple orifice keeper reduced the gas flowrate required for ignition at a fixed keeper voltage. We also compare two electron-beam melted titanium Ti6Al4V keepers of identical outer dimensions, one a simple shell and the other with several concentric layers of printed metal interior to the cathode serving as radiation shields with a torturous conductive path linking the shells. The integrated radiation shielding reduced heating power by 10-30% (20-40 W) to achieve insert temperatures in the 1000-1300°C range and increased the temperature at fixed powers from 120-170 W by 80-200°C. These two new types of keepers can preserve the physical envelope of the traditional keeper while reducing propellant usage, reducing discharge voltage, and increasing thermal efficiency, making them of interest for future testing in thruster systems.

II. Introduction

The hollow cathode keeper serves several purposes including ignition of the discharge, constriction of the gas flow path through the keeper orifice, and occasionally protection of the internal cathode components from the outside plasma. In this work, we explore two additional options afforded by the rise of rapid and relatively affordable metal additive manufacturing: decoupling keeper orifice electrical and gas conductance with multiple orifices, and the incorporation of integrated radiation shielding in the keeper body.

Two of the traditional roles of the hollow cathode keeper are first to provide a nearby high potential electrode to achieve ignition, and second, to raise local gas pressure around the cathode to ease both ignition and operation. A smaller keeper orifice reduces the gas flow required to sustain the minimum pressure for ignition and operation, but also increases resistive losses by forcing the current to exit through a more constrictive opening. A larger orifice reduces resistive losses but requires a higher gas flow for ignition and subsequent stable operation. It is desirable for efficient cathode operation to reduce the required gas flow to ignite and sustain the hollow cathode as much as possible while still providing a low-resistance path for the electron current to leave the cathode through the keeper orifice. Breaking up the traditional single cathode orifice into an array of multiple, smaller diameter orifices is one method to achieve this result. This decouples electrical conductance from gas conductance, as described in this paper and in a related patent filing.[1]

In addition to its electrical and gas conductance roles, the keeper is also the outermost surface of the cathode and thus the final radiative thermal interface between the cathode and the external environment. Maintaining high temperature

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(T) in a thermionic hollow cathode can require large power inputs due to radiation losses ($\propto T^4$) and conduction losses ($\propto T$) through the cathode structure. The inner cathode body is typically a long tube with thin walls, with the emitter at the tip to minimize conductive losses and the tip wrapped in several layers of refractory metal foil to reduce radiation losses. However, these long, thin tubes are difficult to fabricate and the radiation shielding can increase the risk of an electrical short in the cathode. The tube also requires sufficient mechanical strength to survive launch. These constraints effectively limit the maximum tube aspect ratio (length/diameter) and minimum wall thickness. This limits efforts to reduce conductive losses with ever longer and thinner tubes. Additionally, radiation shielding reaches a point of diminishing returns due to inter-layer conduction.

In this work, we use 3D printing to create a keeper structure with integral layers of radiation shielding connected by thin, offset radial supports to provide a torturous, conductive path for heat to travel from a hot inward-facing layer of the keeper to a cooler outward-facing layer. Construction of the keeper with integrated radiation shielding as a single printed piece makes adding additional layers of radiation shielding no more difficult than printing a conventional keeper. The additional layers and the radial supports linking them also effectively form a truss structure to increase mechanical strength, allowing thinner walls and further reducing thermal conduction losses down the body of the cathode. Printed titanium is readily available and reduces the overall thermal conductivity of the structure. This is not ideal for current cathodes operating well over 1000 C, but should be increasingly suitable for future, lower temperature emitters (i.e., scandate, C12A7, cermet, thermal-field emitters or others), especially those using so-called heaterless ignition schemes. Taken together these factors suggest that keepers with integral radiation shielding may be worthwhile to improve cathode thermal performance and/or mechanical strength, as discussed in this paper and a related patent.[2] Indeed, it may well be possible to dispense entirely with a foil heat shield in some cases in place of a shielded keeper to reduce cathode complexity and cost.

III. Keeper Design

A. Multiple Orifice Keepers

To design a multiple orifice keeper we consider two simple models, the first for illustration of the potential benefits and the second to identify potential limitations. First, consider electrons passing through a keeper orifice of diameter D and length L as passing through a uniform wire with electrical conductance $\propto D^2/L$. A larger opening means more conductance, or less resistance. Consider also gas molecules passing through a keeper orifice as flowing down a long tube, such that gas conductance varies similarly but as $\propto D^3/L$ (molecular flow) or $\propto D^4/L$ (continuum flow). Again, a larger opening means more conductance, but with a dramatically different dependence on the orifice diameter.

In the case of a single orifice, there is only one diameter so gas and electrical conductance are coupled – choosing one constrains the other. However, for the case of a multiple orifice keeper this constraint is lifted. For example, splitting a single keeper orifice of diameter D into 100 smaller holes of diameter d = D/10 maintains the total open area. For fixed L, the electrical conductance in the simple model above is unchanged while the gas conductance drops profoundly. The difference is that electrons passing down the wire in the simple model do not bounce back, while neutrals are free to bounce in any direction off the walls of the tube.

Keeper orifices are not tubes with L>>D, so the difference in gas conductance is smaller than the simple model suggests. The orifice length L is just the thickness of the front face of the keeper, presumably chosen based on mechanical strength, fabrication cost, and survivability against plasma erosion. For finite length tubes a better model to use is the Clausing factor, which is the transmission probability for a particle to transit the tube including diffuse wall collisions. These values were initially tabulated by Clausing and can be looked up or computed numerically by Monte Carlo methods.[3] Starting from a single keeper orifice with D/L < 1, Figure 1 shows the Clausing factor for hexagonal-packed arrays of increasingly numerous circular tubes of fixed L and diameter $d = D/\sqrt{N}$ to maintain total orifice area. The Clausing model shows that the transmission probability per unit area reaches a point of diminishing returns as N increases beyond a few hundred, as ever-larger numbers of ever-smaller diameter holes produce minimal further reduction in gas conductance.

Flow exiting the keeper is likely not an ideal molecular flow well-treated by the Clausing factor either; it is probably reasonable to expect continuum flow at the upstream end of the keeper orifice. The above analysis admittedly neglects this and other features, and is intended only to suggest that a) spreading the keeper orifice area across multiple smaller orifices will reduce gas conductance, thus potentially reducing cathode gas flow requirements, and b) that there will be a point of diminishing returns beyond which the cost of additional orifices outweighs the benefits.

This technique may be most valuable for lower current cathodes typically found in small thrusters on small satellites, where size, weight, and power are at a premium. It has not traditionally been done because such orifices are already quite small, often no larger than .010”- .020” in diameter, and fabricating large arrays of substantially smaller holes is challenging to machine and the survivability of such small hole arrays over typically long cathode operating lifetimes is unclear. However, with improvements in fabrication capabilities, reduced space launch costs, and typically shorter mission durations associated with smaller satellites, the possibility for such multiple orifice cathodes now appears possible.

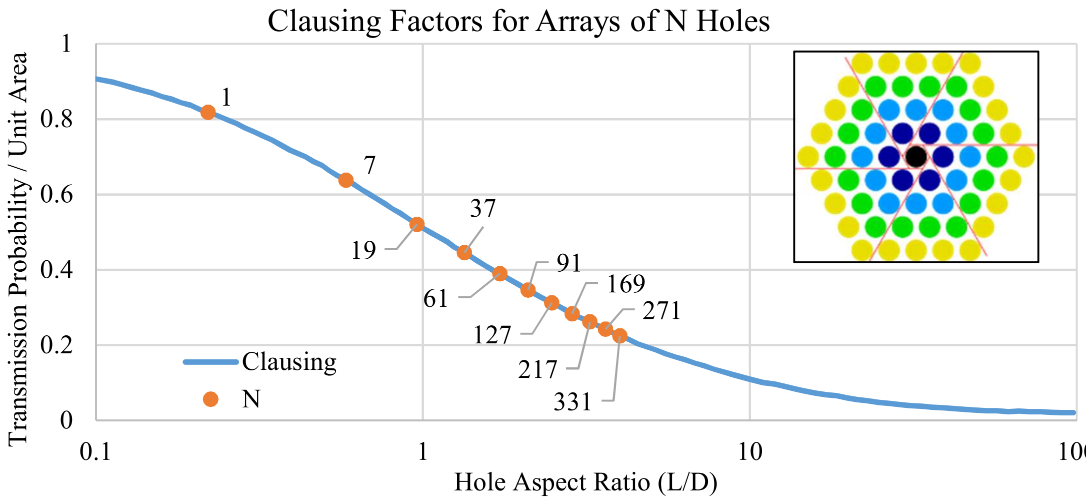


Figure 1: Clausing factor for arrays of *N* circular tubes with diameter d, for fixed L and $d = D/\sqrt{N}$ to preserve total open area independent of *N*. Inset: hexagonal packing arrangements for *N* = 1 - 61. Clausing factors taken from O’Hanlon.[4]

B. Radiation Shielded Keepers

The basic principle of a radiative heat shield is to reflect radiated thermal energy back toward a source, reducing the power required to maintain the heat source at temperature. Consider a heat source radiating power P into space. If a thin blackbody heat shield is placed between the heat source and space, it will heat up until it radiates equal power P/2 in both directions, back to the heat source and out into space. The reflected power reduces the external power needed to heat the source. It still radiates the same initial power P, but now absorbs power P/2 from the heat shield and so only needs additional input power P/2 for a reduction of 50%. Additional layers halve the power further, so that a heat source with N ideal blackbody heat shield layers requires 2^N times less input power to offset radiative heat losses. This is the appeal of multi-layer insulation or MLI for spacecraft components.

A challenge using 3D printing for multi-layer keeper heat shielding is to minimize inter-layer conductive heat transfer through the printed connections between each layer. To do so we introduce a torturous path for conduction using a minimal number of axially offset supports between each nested layer. This leaves no direct radial path from one interconnect to the next and forces the inter-layer heat transfer to be primarily radiative.

IV. Experimental Equipment

C. Plasma Test Facility (PTF)

The Plasma Test Facility (PTF) is a cylindrical stainless steel vacuum chamber 39” long x 30” in diameter. A Varian TriScroll 600 dry scroll pump backs an Agilent Turbo-V 10001 Navigator turbopump mounted on top of the chamber with nominal 950 L/s pumping speed on air. A CTI Cryo-Torr 400 cryopump mounted on the bottom of the chamber provides an additional nominal 6000 L/s pumping speed on air. A Lesker 392 series hot ionization gauge monitors high vacuum pressure. The chamber reaches the low 10^{-7} Torr range in base pressure using the turbopump alone, and the high 10^{-8} Torr range using the cryopump. For cathode testing we use both the turbopump and cryopump, and based on a measured 5 sccm argon flowrate and an argon-corrected operating pressure of 1.5×10^{-5} Torr we find an actual pumping speed of about 4000 L/s.

D. Cathode Testbed

We use a common cathode testbed based off a published design for a compact LaB6 hollow cathode by Goebel and described previously.[5], [6] The central cathode tube is made of graphite for LaB6 compatibility and a rhenium/boron nitride refractory heater (Ref. [7]) heats the end of the central tube until the tubular insert achieves thermionic emission. A Keysight N5772A 600V, 2.6A DC power supply biases the keeper to ignite the discharge, while a Keysight N5771A 300V, 5A DC power supply provides heater current. All testing presented in this work is limited to keeper-only operation; no data with an external anode is included. Results from two pairs of keepers are reported: a "control" and modified configuration demonstrating relative advantages for both multiple orifices and integral radiation shielding.

1. Multiple Orifice Keeper

We compare two keepers in the multiple orifice investigation: a conventional single orifice keeper and an otherwise identical keeper with a hexagonally packed array of 169 holes. The diameters D of the large single orifice and d of the smaller orifices are related by d = D/13 to preserve the total open area of the orifice(s) between keepers. Figure 2 shows both keepers during operation, approximately to scale. The need for inter-hole spacing to support the array means that the open orifice area extends over a slightly larger area in the array than in the single orifice case. The inter-hole spacing is chosen to balance mechanical robustness and strength (too high a packing fraction leaves fragile webbing between the holes) and a desire to keep the holes closely packed to provide efficient extraction of the plasma over the central exit of the tubular electron emitter. Both keepers are made from stainless steel.

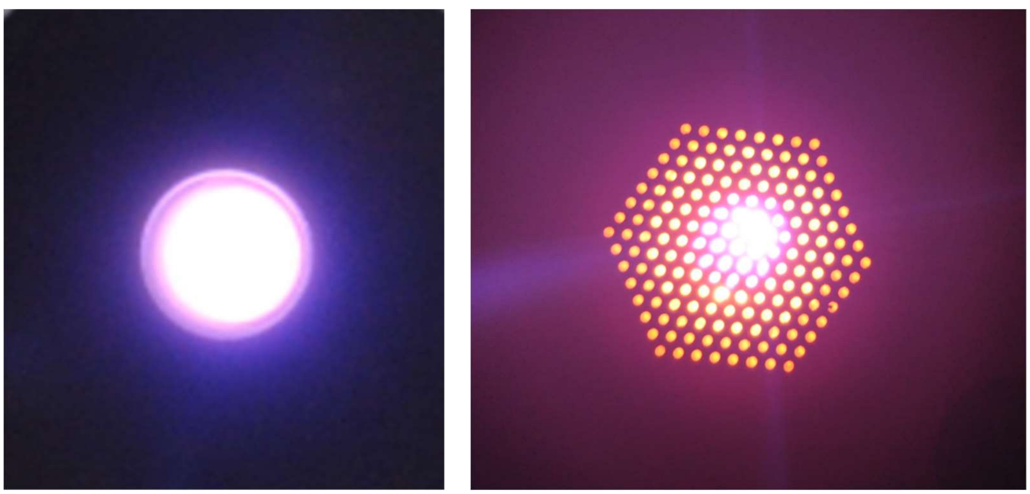


Figure 2: Closeup images of a single-orifice (left) and multiple-orifice (right) hollow cathode keeper during operation. The multiple orifice keeper contains 169 holes, each with diameter d = D/13 where D is the single orifice diameter.

2. Radiation Shielded Keeper

We compare two keepers of identical outer dimensions and wall thicknesses, one a simple shell and the other with several concentric layers of printed metal interior to the cathode serving as radiation shields with a torturous conductive path linking the shells (Figure 3). Both keepers were printed on an Arcam A1 electron-beam melting (EBM) machine at Walter Reed National Military Medical Center (WRNMMC) using titanium alloy Ti6Al4V. For both keepers the outer diameter was substantially enlarged to permit several nested shells in the keeper with integrated radiation shielding while accommodating the heater and matching the outer dimensions for both keepers. The open front face of the layers of keeper with integrated radiation shielding permits easy post-build inspection of powder removal.

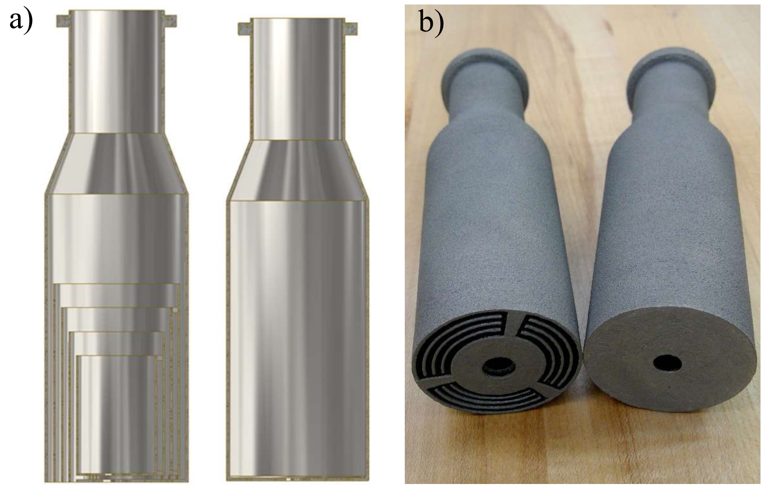


Figure 3: The keeper with integrated radiation shielding (left) and a simple shell keeper of matching outer dimensions (right), shown both in cross section (a) and as-printed in EBM Ti6Al4V prior to testing (b).

E. Data Acquisition

General analog operating telemetry data including keeper voltage and chamber pressure were acquired via an Agilent 34970A data acquisition unit with a 34901A 20-channel multiplexer. Keeper and heater currents were digitally queried directly from the Keysight DC power supplies. All data except mass flow rate and keeper orifice temperature were acquired automatically every several seconds using a background LabView program while the cathodes were operated manually. Mass flowrate was manually recorded. An Ircon Modline 5 two-color pyrometer was used to manually monitor cathode orifice temperature during the radiation shielding testing, with the approximately 1/8" diameter spot size centered on the open cathode orifice and adjusted via tripod to maximize the temperature reading. Only temperatures with the plasma off are reported since plasma ignition was observed to instantly and significantly alter the optical pyrometer reading, suggesting an artifact due to the plasma light emission.

V. Experimental Results and Discussion

A. Operation with a Multiple Orifice Keeper

For initial validation, the LaB6 testbed cathode was operated at the nominal 15 sccm flowrate on argon in a keeper-only discharge at 2.7 A. This was chosen as the maximum discharge current for the keeper power supply). The testbed cathode is nominally a 20 A device, so this current is relatively low and the keeper voltage is correspondingly relatively high, of order 50 V at the 2.7 A condition. After equilibrating at 15 sccm for at least 30 minutes, the flowrate was varied back and forth from the nominal flowrate to successively higher and lower flowrates in relatively rapid 5-minute intervals to identify the approximate operating voltage at each off-nominal flowrate to within +/- 1 V. This simple sweep illustrates some of the hoped for benefits of the multiple orifice keeper, discussed below, and motivates more rigorous follow-up to ensure steady state equilibrium and include full electron extraction to an external anode.

First, as seen in Figure 4 at left, the absolute operating voltage is substantially reduced across all discharge flowrates at the same discharge current. The 50 V operation at the nominal 15 sccm is reduced to 31 V, a 38% reduction. The lowest flowrate achievable for the single-holed keeper before the discharge extinguished was 4 sccm, and at that flowrate the keeper voltage dropped from 68 V to 36 V, a 47% reduction. The 169-hole keeper discharge was operable down to 3 sccm at 38 V. Thus, even with an 80% reduction in flow from 15 sccm to 3 sccm, the multiple orifice keeper operated at about 25% lower voltage (38 V) than the single orifice keeper at the nominal 15 sccm (50 V).

Second, as seen in Figure 4 at right, the increase of discharge voltage at reduced flowrate is delayed in the multiple orifice case. An increasing keeper voltage corresponds to a decreasing electrical efficiency of the discharge. When the absolute voltage is normalized to the value at the nominal 15 sccm flowrate, the relative increase in operating voltage over nominal is 103% (multiple) vs. 110% (single) at 13 sccm and 117% (multiple) vs. 139% (single) at 4 sccm. The same relative deterioration to 110% of nominal voltage occurs at 12 sccm for the single orifice case, or at

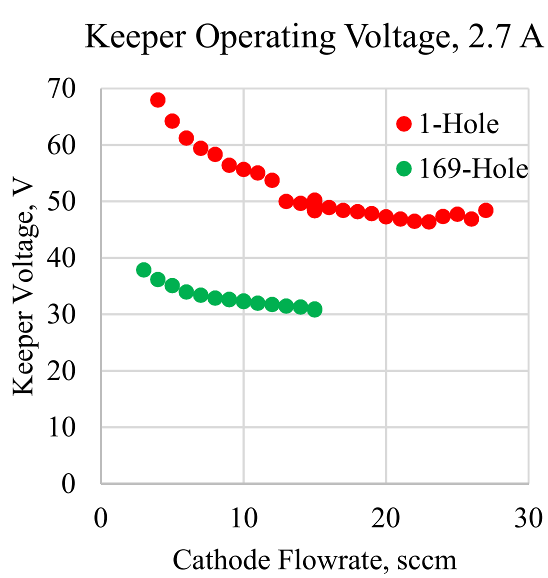
20% reduced flowrate below nominal, while it is delayed until 6 sccm for the multiple orifice case, or 60% reduced flowrate below nominal.

Third, while not evident from the figure, ignition was observed at reduced gas flow in the multiple orifice configuration. This effect was only briefly noted during this initial parameter sweep, and was not directly quantified in favor of a focus on the steady state operating characteristics. After pre-heating the insert and applying fixed keeper current and voltage limits to the power supply, ignition was observed with lower flowrates in the multiple orifice keeper during several ignitions compared with single orifice keeper. Cathode ignition was performed manually during these tests, so this result bears further investigation with an automated ignition process from cold temperatures to ensure repeatability and establish the limits of the ignition flow benefit.

The reduced gas flow requirements during operation and, potentially, ignition are broadly consistent with expectations of a multiple orifice keeper. Multiple orifices form a gas conductance choke compared to the single orifice case, boosting upstream pressure and thus neutral density for a given gas flow. To the extent that neutral density influences cathode operation, in a keeper-only discharge one would expect the leftward slide of the voltage vs. flowrate curve seen in the normalized chart of Figure 4 when switching from a single to multiple orifice cathode.

Less clear are the reasons for the unexpectedly strong improvement in operating voltage in this simple keeper discharge seen in the right chart of Figure 4. The voltage vs. flowrate curve shifts not just leftward, but substantially downward. Some of this change is surely due to the physical extension of the multiple orifice keeper into the formerly empty region on cathode centerline. The multiple orifice keeper bridges part of the distance electrons would otherwise travel to close the circuit, thus reducing the energy they require to do so. However, the ~40-50% reduction in voltage seems extreme to be explained by this effect alone.

Testing the multiple orifice keeper in a full discharge to an external anode with the keeper allowed to float may shed light on this voltage reduction mechanism. If the gas and voltage benefit remains it would motivate further testing in an actual thruster discharge, ideally with an industry transition partner to whom lower propellant or power consumption would be attractive. The external anode and thruster environments present several additional challenges including plasma instabilities, the presence of a thruster magnetic field, and erosion of the keeper face due to ion bombardment. These risks tend to be highly thruster- and requirement-specific and would be best addressed in specific thruster implementations.



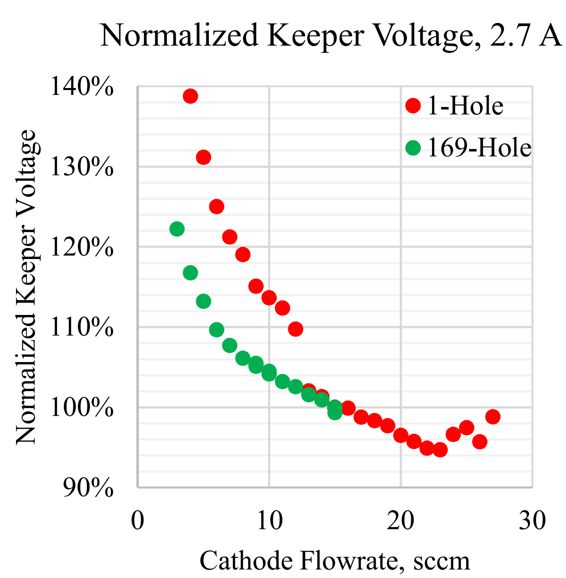


Figure 4: Left, keeper operating voltage during a keeper-only discharge at 2.7 A; right, normalized operating voltage to the nominal conditions at 15 sccm showing a delay in voltage rise with decreasing flowrate for the 169 hole case.

B. Radiation Shielded Keeper

We explored the thermal benefits of integrating radiation shielding directly into the cathode keeper body both experimentally in our standard LaB6 testbed as well as in COMSOL Multiphysics software. We report experimental results only during the heating cycle; no immediately noticeable changes were observed during brief ignition and operating tests of the cathodes, suggesting that the benefit of the design is primarily power reduction during pre-ignition heating, rather than improved thermal power efficiency during self-heated cathode operation. Additionally, due to the high heater temperatures of the LaB6 cathode and the limited temperature range of the titanium printed parts, these tests were run with a traditional refractory metal foil shield also in place around the heater.

The two experimental heating cases are shown in Figure 5, where the internal glow of the heater is clearly visible through the central orifice in both keepers as well as through the radiation-shielded keeper's open front face. Sample temperature surface plots from a COMSOL Multiphysics simulation of conductive and radiative heat transfer for these cases are shown in Figure 6, illustrating the simulation geometry. The left plot shows the temperature profile for the unshielded keeper with an input power of 70 W and a peak temperature of 1010°C. The right plot shows the profile for the unshielded keeper, requiring only 35 W to reach a peak temperature of 1020°C. Simulated peak temperatures for input powers from 0-100 W for both cases are shown in Figure 7 together with optical pyrometer measurements in the cathode orifice.

The pyrometer showed modest reductions of about 20-40 W (10-30%) in heater power to maintain the same peak insert temperature over the range 1000-1300°C. Expressed another way, the shielded keeper operated at the same power increased peak internal cathode temperature by about 80-200°C. The simulations showed larger differences than encountered experimentally, indicating a potential 50% reduction in heating power required to reach 1000°C (chosen as an arbitrary operating temperature), and a ~300°C increase in peak internal cathode temperature achieved at 100 W input heating power. These differences are discussed below, but the modeling trends are qualitatively, if not quantitatively, consistent with the experimental results.

The experimental results show that keepers with integral radiation shielding improve cathode thermal efficiency, but use of current widespread 3D printable metals with a LaB6 emitter operating at 1500-1700°C is problematic. A more suitable initial use case would be for a BaO cathode, with typical 1000-1100°C insert temperatures, or alternative emitters with lower operating temperatures still hot enough to see power benefits from radiation shielding.

3. Differences between radiation shielding experiment and modeling results

Major differences between the model and experiment include: elimination of the resistive heater with foil radiation shield in the model, the use of idealized "floating" shells with no physical interconnects in the model, and the use of a solid front face for the shielded keeper in the model instead of the open front visible at right in Figure 5. Instead of a heater, the model imposes a fixed power deposition on the internal diameter of the emitter. Simulations with and without the torturous path interconnects showed that the idealized shells produced very similar temperature profiles only about 10°C hotter than the true geometry with greatly reduced mesh complexity and simulation times. The open face of the experimental shielded keeper permits excess powder removal after printing, but in the model the closed face was deemed more representative of what an ultimate keeper design would look like with more mature printing technology.

The most significant of these differences is probably the replacement of the heater with direct power deposition to the emitter making the emitter the hottest point in the cathode. While this is representative of cathode operation, during heating the heater is actually the hottest point in the cathode. Ignition heater power is less efficient than plasma self-heating during operation, contributing to the higher power seen experimentally to reach a given temperature. The refractory metal foil heat shield between the heater and keeper in our experiments may also contribute. The experimental pyrometer measurements effectively show the benefit of introducing a radiation-shielded keeper in additional to a foil heat shield, rather than the effect of introducing a radiation-shielded keeper alone in the model. Finally, the open front face of the shielded keeper in Figure 5 allows thermal radiation to escape, making it slightly less efficient than the model.

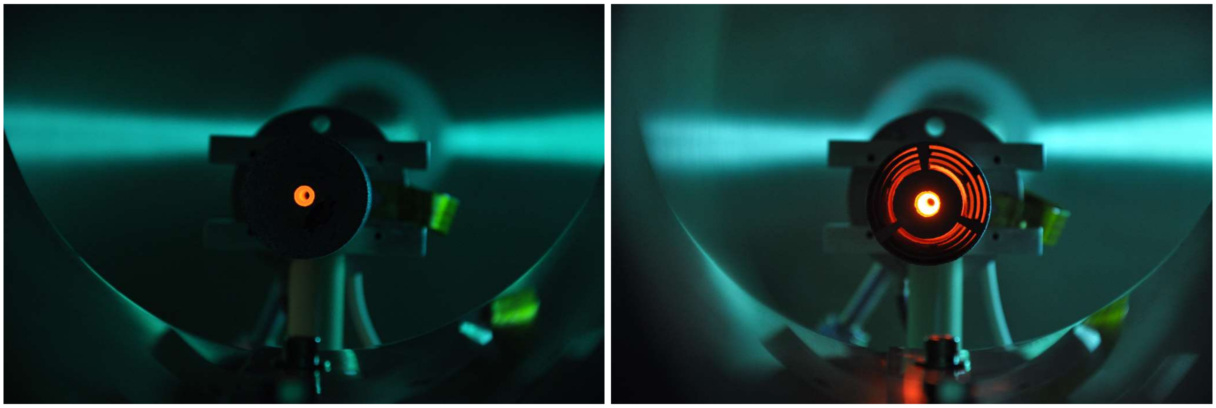


Figure 5: 3D printed Ti6Al4V keepers on the LaB6 cathode tested without (left) and with (right) integrated radiation shielding during pre-ignition heating.

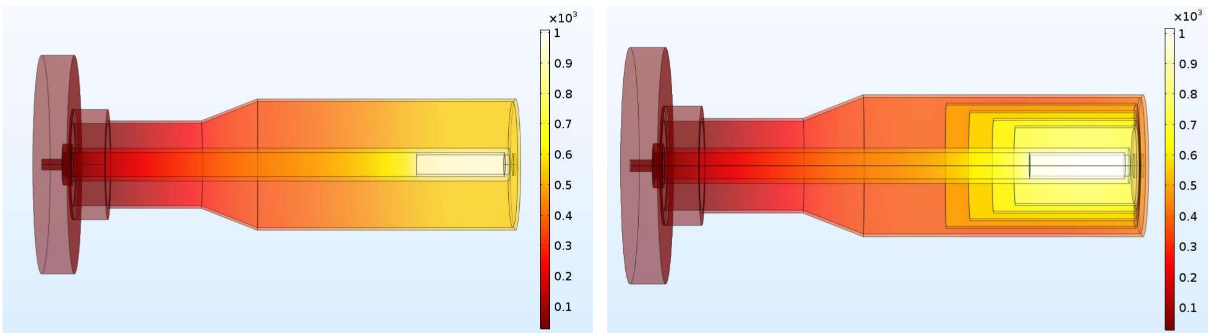


Figure 6: COMSOL Multiphysics simulation results for thermal profiles of a Ti6Al4V keeper with fixed input power applied to the insert and peak temperature ~1000°C. Left, a simple shell keeper used as a control requiring 70 W to reach a peak insert temperature of 1010°C; right, a keeper with integral radiation shielding requiring just 35 W to reach 1020°C.

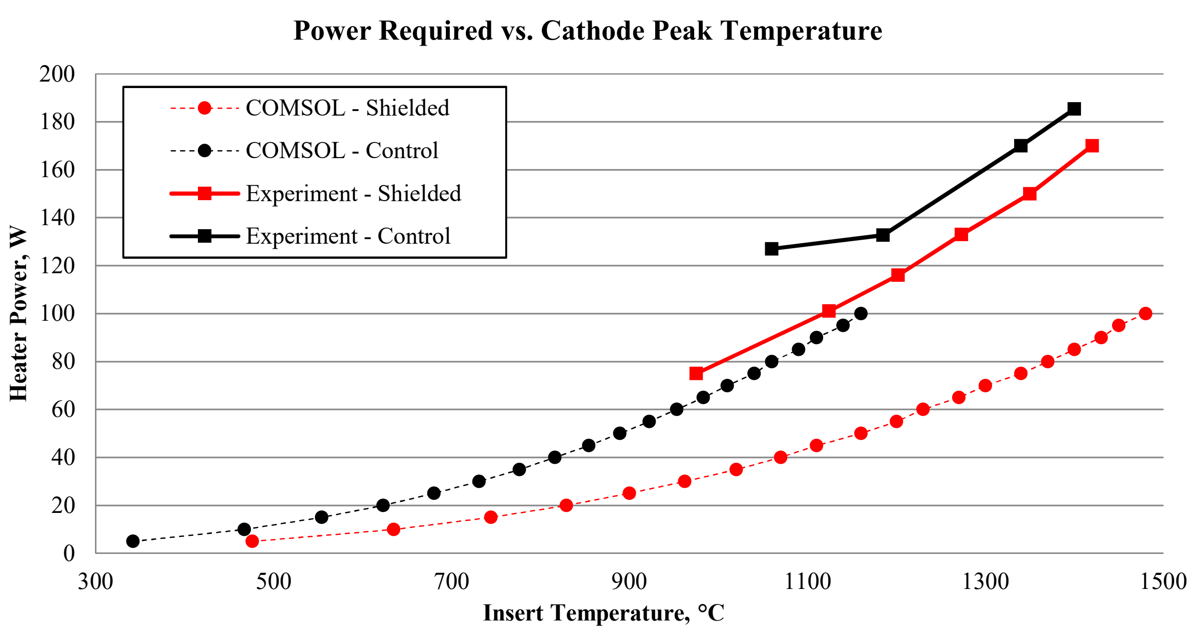


Figure 7: Required heater power as a function of peak cathode temperature for the keeper with integrated radiation shielding (red) and a simple shell keeper as a control (black) for both experimental heating (solid with squares) and in COMSOL Multiphysics simulation of an idealized geometry (dashed with circles)

VI. Conclusions

We have presented initial validation of two new patented techniques for hollow cathode performance improvements: multiple orifices and integrated radiation shielding for keepers. Multiple keeper orifices decouple the keeper electrical and gas conductance, significantly reducing cathode propellant consumption, operating voltage, and, potentially, ignition voltage as well. Integrated radiation shielding improves cathode thermal efficiency during ignition pre-heating and may enable the elimination of foil radiation shields in cathodes with moderate to lower temperature emitters such as BaO.

Breaking up a single-orifice keeper into multiple orifices of reduced diameter with matched total area decreased the keeper operating voltage in a 2.7 A keeper discharge by 40-50% across gas flow rates from 4-15 sccm. Taking keeper voltage at the nominal 15 sccm flowrate as a benchmark, voltage deterioration (i.e., increase) by 10% was delayed from 12 sccm in the single orifice case to 6 sccm in the multiple orifice case. Initial results also suggest that the gas flowrate required for ignition at a fixed keeper voltage was reduced for the multiple orifice case.

Incorporating concentric nested shells as radiation shields inside a hollow cathode keeper using 3D printing reduced heating power by 10-30% (20-40 W) to achieve insert temperatures in the 1000-1300°C range. The shielded keepers also increased temperature at fixed powers from 120-170 W by 80-200°C. Unfortunately the high operating temperature of the LaB6 cathode and the limited operating temperature of the printed Ti6Al4V keepers prevented testing whether integrated radiation shielding permits removal of a traditional foil radiation shield.

Both of these improvements are potential drop-in replacements to current cathode keeper designs. They can preserve the physical envelope of the keeper, presenting a nearly identical electrode boundary condition to a thruster plasma. Thus, they should be suitable for delta-qualification in existing thrusters or to expand the design envelope in new thrusters under development. They are also mutually compatible, i.e., as a multiple orifice keeper with integrated radiation shielding, to produce benefits in propellant usage, operating voltage, and thermal efficiency in a single package.

VII. Acknowledgments

The authors are grateful to the Walter Reed National Military Medical Center (WRNMMC) 3D Medical Applications Center for printing the titanium Ti6Al4V keepers with radiation shielding.

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