Low Current Heaterless Hollow Cathode Development Overview

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This paper overviews the development of a low current heaterless hollow cathode, designed and produced by Rafael, and denoted the RHHC. The RHHC generates discharge current of 0.3-1.2 A and is ignited using initial breakdown voltages below 400 V. Each of the development phases is elaborated upon. These phases included activities such as a technology study, the development of manufacturing processes, the study of Failure Modes, performance characterization and culminated with two primary tests – a 5,000 hour endurance test and a 3,500 cold ignition cycles test. In its current state of development, the RHHC proves suitable for a wide range of low power electric thrusters and was even successfully coupled with two different Hall thrusters in a wide range of discharge current levels.

I. Introduction

HEATERLESS Hollow Cathodes (HHC) are a subclass of hollow cathodes that do not require external heating for cathode ignition[1]. In this type of cathodes the heating process is by plasma discharge generation in the emitter-keeper gap. As a consequence, HHCs employ a unique ignition technique. Firstly, a high voltage pulse is applied between the emitter and keeper so to electrically breakdown the injected gas. Immediately after initial discharge creation a separate power supply controls the emitter-keeper current, a process during which the emitter is heated. The heating process lasts until the emitter reaches its operation temperature. Lastly, after steady discharge has been initiated the electric thruster is turned on by applying the required emitter-anode current. The overall thruster ignition duration is usually less than 100 seconds.

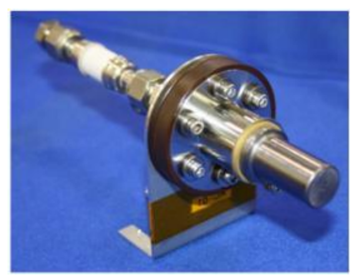

Figure 1. Picture of Rafael Heaterless Hollow Cathode (RHHC).

Conventional hollow cathodes include a heater to raise the temperature of the low-work function electron heating material prior to cathode ignition[2,3]. These cathodes have been used, and are still in use, extensively both in laboratory experiments and as part of in space electric thrusters. However, several drawbacks can be identified for heater-utilizing hollow cathodes in comparison with HHCs: (1) a designated power supply is required to provide the necessary current for heater activation, (2) to reduce thermal strains on the heating element its heating process is gradual and takes several minutes[4] and (3) the heating element is susceptible to thermal fatigue failure due to multiple heating cycles; thus limiting cathode

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lifetime.[5-6] These drawbacks lead to high electrical power demand during ignition, additional mass to the Power Processing Unit (PPU), propulsion system readiness duration of several minutes and limited cathode lifetime. The Heaterless ignition mechanism of HHCs comes to confront these drawbacks by reducing power demand during ignition, eliminating the need for a heater power supply, minimizing the propulsion system readiness duration to tens of seconds and extending cathode lifetime.

During recent years Rafael, in cooperation with the physics department at the Technion, is engaged in HHC development[7]. The cathode, denoted Rafael Heaterless Hollow Cathode (RHHC)(see Figure 1), is designed to operate at the low current regime (0.5-1.1 A) and couple with low power Hall Thrusters (100-300 W). The cathode was designed following a rigorous mechanical and thermal design process and is made of a combination of refractory metals and other conventional materials with geometry that maintains the required temperatures throughout the cathode parts and components. A barium oxide impregnated tungsten emitter (also referred to as the insert) is utilized to generate the electrons during operation. The RHHC is structured in such a way that different emitters can be integrated in it and still operate adequately.

Current cathode development is part of the Micro-satellite Electric Propulsion System (MEPS) project – a joint Israeli-European endeavor to develop a full low power EP system for small satellites[8,9,10]. Currently an Engineering Model (EM) of the cathode is under extensive testing and a Qualification Model (QM) is being manufactured. Key features of the RHHC are presented in Table 1.

In this paper we present the development path of the RHHC from first numerical models and prototype experimentation, through the development of ignition techniques, and to a 5,000 hour cathode endurance test. Lastly, future activities are described.

Table 1. Key features of the Rafael Heaterless Hollow Cathode (RHHC).

#	Requirement	Value
1	Discharge Current	0.3-1.2 A
2	Xenon Mass Flow Rate	0.1-0.25 mg/s
3	Lifetime	>4,000 A×hr
4	No. of Startups	3,500
5	Ignition Voltage	< 400 V
6	Mass	170 gr

II. Development Campaign

The main motive for developing a HHC rather than conventional hollow cathodes is the advantages embedded in HHC technology, as specified above. The RHHC development program is presented in Figure 2. The development program commenced with the study of existing HHC technologies and currently is in the midst advanced models design.

An elaborated description of each of the development stages is presented hereafter.

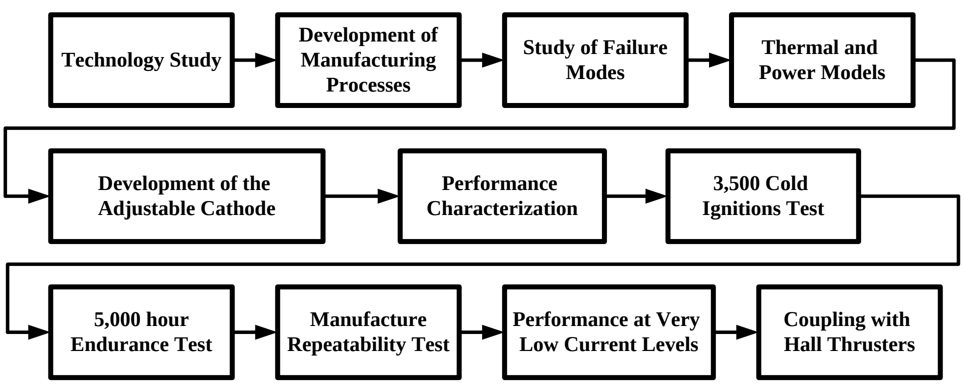

Figure 2. The RHHC development program

A. Technology Study

Prior to any cathode experimentation the required theoretical background of HHC was studied. Subsequently, numerical models of cathode operation under steady state conditions were constructed[11-13]. These models gave the possibility to assess the influence of the change in operational parameters on cathode behavior. The models also provided guidelines to basic cathode design and the knowledge of expected plasma parameters in the cathode cavity and plume.

In parallel to the numerical work, hands on experience operating an actual HHC was gained[14]. The HHC was operated in a variety of conditions and produced discharge current of about 1 A.

B. Development of Manufacturing Processes

Due to the high temperatures generated inside hollow cathodes these devices are made of non-conventional high temperature materials. The cathode external module, referred to as the keeper module, as well as the internal module, referred to as the emitter module, are mostly composed of known refractory metals - tungsten (W), tantalum (Ta) and molybdenum (Mo). Since Ta has the lowest thermal conductivity it was used as the main structural material in high temperature regions. Machining techniques were developed to fabricate large aspect ratio refractory metal parts with thicknesses as low as 0.35 mm.

Connections between two refractory metal parts as well as refractory metals to stainless steel parts were performed using special welding and brazing techniques developed particularly for this purpose. Pictures of metallographic samples are presented in Figure 3. The welding techniques allow for localized Heat-Affected Zones (HAZ) around a weld; hence avoiding the temperature raising of the entire part, maintaining it below the Ductile to Brittle Transition Temperature (DBTT) and keeping its grain size unchanged.

Apart from standard weld quality checks, to validate proper mechanical connectivity all welding processes were leak tested and found leak-sealed. Lastly, to adequately monitor cathode manufacturing and assembly processes the manufacturing design allowed for separate examination and leak test of each cathode module and subassembly, therefore allowing proper quality assurance in the manufacturing and assembly phases.

Following the development of manufacturing processes first Development Models (DM) of HHCs were produced. The various models consisted of different metal arrangements with different geometries, given manufacturing limitations.

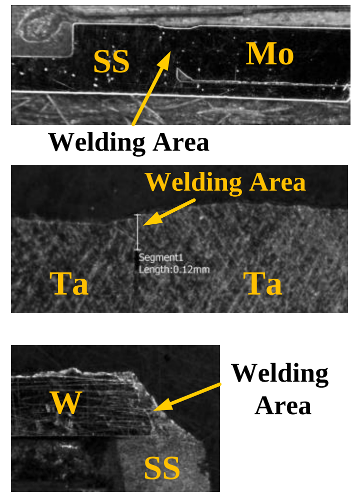

Figure 3. Pictures of metallographic samples of welded joints.

C. Study of Failure Modes

Initial operation of the HHC development models composed of operation under extreme ignition and steady state conditions. These conditions included a variety of ignition power levels, fast and slow ignition processes, high keeper current levels, high or low discharge current levels and operation with two different types of emitters.

After each experiment the cathode was opened and analyzed. The observed phenomena were correlated to the investigated operational schemes and root cause for each failure was documented. Material migration, such as deposition of refractory metals or re-deposition of Barium, was investigated and assessment of operating temperatures performed.

For example, in one case of cathode operation under extreme discharge and keeper current levels emitter tube plug was observed. It was found that the inner emitter tube diameter was essentially reduced to zero (Figure 4). The materials covering the tube channel were molybdenum (Mo) and tantalum (Ta), which are the materials encapsulating the emitter and emitter tube. Furthermore, molybdenum and tantalum melting or coating may occur at elevated temperatures of over 2600°C, thus indicating on the cathode physical mechanisms in the emitter region. Essentially the emitter tube looked as if its interior melted and mixed with the exterior sections. Additionally, little to no traces of Barium were found on the emitter surface; indicating that either barium oxide depletion occurred or that the emitter surface was covered with molten metal.

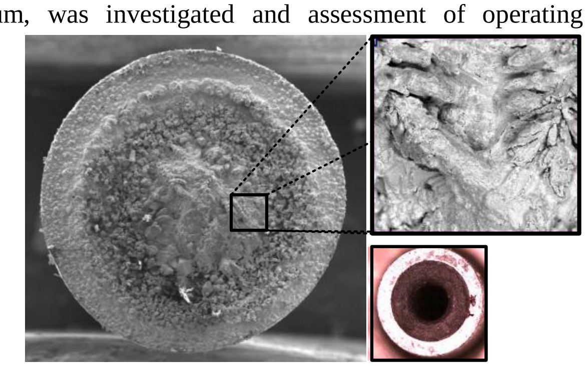

Figure 4. Left: Micrograph of the "plugged" emitter tube after cathode end-of-life. Top-Right: Image enlargement showing Mo melting traces. Bottom-Right: micrograph of a fresh unused emitter.

D. Thermal and Power Models

Since no direct experience in low current cathode thermal design existed in Rafael prior to the design phase the goal of the laboratory model was to gain thermal design capabilities by designing a cathode able to operate at a nominal current of less than 0.5 A. Developing such design capabilities will enable future design campaigns of higher current cathodes. The thermal design phase included thermal analysis with the purpose of reaching simulated steady state emitter temperatures of around 1000°C which are necessary for sufficient electron emission[15].

Before a cathode thermal model could be constructed a proper power input model had to be established. The model takes into account cathode geometry, materials, gas type, mass flow rate and discharge current levels. The cathode power model outputs the power exerted on internal cathode surfaces, primarily the emitter. Using the power model the boundary conditions to the thermal model were set and cathode body temperatures could be predicted.

An example of the predicted cathode body temperatures, for one of the development models for two values of discharge current levels (0.5 A and 0.8 A), is presented in Figure 5. It can be seen from the figure that external cathode body temperatures may reach acceptable values of 400°C at the cathode tip region. In addition, thermal simulation results of the emitter region were used to predict and explain some of the cathode failure mechanisms occurring due to excessive heating[16].

The thermal model was also adjusted and used for more advanced models of the HHC, as presented in this paper.

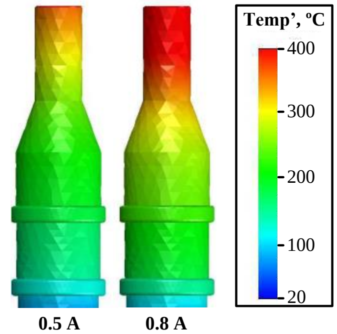

Figure 5. Thermal simulation results of the cathode external body for discharge current of 0.5 A and 0.8 A.

E. Development of the Adjustable Cathode

Harnessing the knowledge and experience gained from experimenting with the development models of the RHHC a new engineering model was designed and manufactured (see Figure 6). A modular adjustable design was pursued in order to allow for geometry adjustments as well as the alteration of different materials. Additionally, the modular design gives access to the internal parts of the cathode, after the experiment ends; therefore enabling simple and non-destructive analysis. In case of possible cathode failure only the damaged part may be replaced, and without the need to manufacture any of the other cathode parts.

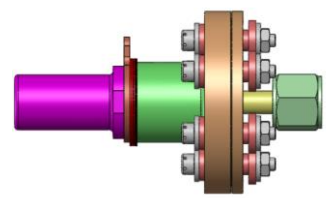

Figure 6. CAD illustration of the adjustable Rafael Heaterless Hollow Cathode (RHHC).

During the design process the previously-developed thermal model was employed in order to assure sufficiently high emitter temperatures while maintaining all cathode parts temperatures below each part's melting point. Since the thermal design is critical in hollow cathodes substantial margin of error was taken.

Lastly, in view of future space applications for the cathode its design also targeted any foreseen launch strains. To do so structural simulation was used to verify that no structural integrity issues may rise with the adjustable HHC.

Following the design phase the RHHC was manufactured and put through a series of tests.

F. Performance Characterization

The first test performed on the RHHC is a performance characterization test. As part of the test the cathode was operated in diode mode against a stainless steel plate, serving as the anode. All experiments were conducted at Rafael's cathode research facility[17]. The cathode was operated at various mass flow rate and discharge current levels while its electrical and thermal characteristics were monitored. In particular, the keeper floating voltage, anode voltage and cathode external body temperatures were recorded so to assess the cathode vitality, energy consumption and influence on its surroundings[18,19].

Floating keeper voltages as a function of mass flow rate for different discharge currents are presented in Figure 7. It can be seen in the figure that an increase in cathode current and mass flow rate leads to a decrease in keeper-emitter voltage; therefore a decrease in cathode sheath voltage fall. This behavior was observed in the past in various studies conducted with conventional 'orificied-emitter' type cathodes[2,20-22]. We can therefore assume similar physical mechanisms on the emitter surface in 'open-end emitter, orificed keeper' cathodes.

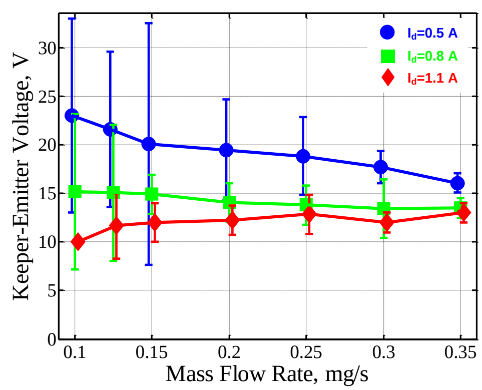

Figure 7. Floating keeper voltage as a function of cathode mass flow rate for three different discharge current values (0.5A,0.8A,1.1A).

In addition, the keeper-emitter voltage trends were also reported for 'open-end emitter, orificed keeper' type cathodes[23]. This phenomenon is due to the lower sheath voltage required to maintain the required electron emission with increasing discharge current and mass flow rate.

Lastly, for almost all cases presented the keeper-emitter dependence on the mass flow rate seems mild with no sharp voltage changes. This behavior indicates cathode operation at spot mode, as suggested by Brophy[24]. Additionally, no distinct transition point from spot mode to diffusive, or plume, mode is observed except for some voltage increase at low mass flow rate, below 0.15 mg/s, and low current. At this operational regime large keeper-emitter voltage instabilities were observed – indication for plume mode operation.

G. 3,500 Cold Ignitions Test

One of the major technological challenges of heaterless cathode operation is the cathode ignition phase. Previous developments of HHCs resulted in cathode destruction due to multiple cold cathode starts[25]. The destruction mechanisms were characterized by the creation of cathode spots accompanied by local melting of cathode parts and ultimately cathode deformation. To combat these destruction phenomena suitable ignition scheme was developed that both maintains cathode integrity and enables fast ignition within less than 10 seconds. The ignition scheme, which required the knowledge of plasma science, heat transfer and electrical engineering, may be implemented for cold cathodes with initial temperature lower than room temperature, as expected in spacecraft.

To demonstrate cathode ignition capabilities the cathode was operated in an automatic multiple ignition cycles test. For each ignition cycle the cathode was ignited, in diode mode, using the special ignition scheme. At each ignition cycle the cathode was operated at its nominal anode current value of 0.8 A and cathode mass flow rate of 0.25 mg/s. Immediately after cathode ignition the keeper power supply was turned off and the cathode let to operate continuously for 5 minutes. After 5 minutes the cathode was intentionally turned off and let to cool down for 15 minutes. This 20 minute cycle was repeated automatically for 3,500 cycles while the cathode's electrical characteristics were recorded. The ignition cycle test scheme is presented in Figure 8.

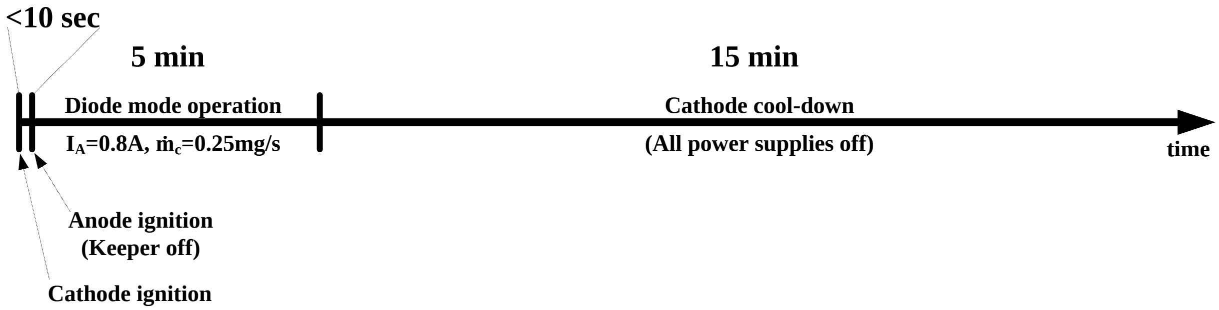

Figure 8. Ignition test operation scheme of one cycle.

To determine the duration of the cathode cool-down phase cathode body temperature, at the cathode keeper external tip where temperature is highest, was measured and correlated to emitter temperature using the thermal model of the RHHC. The measured temperature over the duration of 20 minutes is presented in Figure 9. The target threshold cathode tip temperature, needed to assure emitter temperature less than 250°C, was calculated to be approximately 100°C. Under this value cathode ignition is considered cold[26]. It can be concluded from the figure that after cool-down duration of 15 minutes the cathode, and emitter, are sufficiently cold at the beginning of each ignition attempt. In addition, at the beginning of each ignition cycle cathode pressure, measured on the feed line, was less than 5% higher than the pressure inside a cold cathode at 0°C which was measured separately.

During the ignition test a total of 3,500 ignitions were performed with 100% success rate. All ignitions were performed at initial breakdown voltage lower than 400 V.

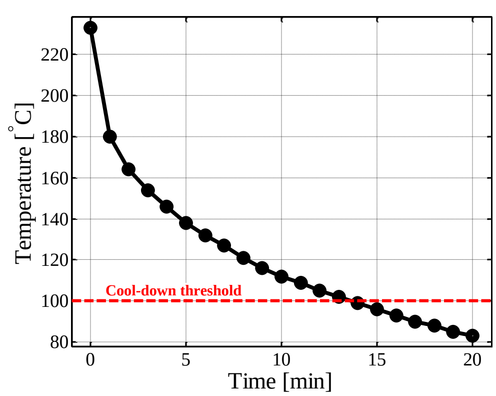

Figure 9. Measurements of cathode body temperature during a 20 minutes cathode cool-down.

H. 5,000 hour Endurance Test

The main purpose of the cathode endurance test phase was to validate the lifetime requirement and to determine any possible cathode operation issues during extended operation durations. This was done by monitoring the keeper-emitter voltage, cathode temperature 10 mm from cathode tip and cathode breakdown voltage for heaterless ignition. Keeper-emitter voltage is an indication for barium oxide depletion that occurs near the emitter's end of life[27]. Keeper temperature is an indirect measure of the power deposition onto the emitter. As such the temperature is expected to increase near the cathode's end of life after sufficient amount of barium oxide has depleted to increase the emitter's work function[28]. Ignition voltage was also monitored in order to assess the effect of prolonged cathode operation on the ability to start the cathode at the desired voltage. Since the initial breakdown voltage depends on internal cathode geometry (of the ignition electrodes), at a constant mass flow rate, consistency in ignition voltage indicates on negligible mechanical deformation of the ignition electrodes. Consistency in the above three parameters monitored indicates on sufficient cathode lifetime and stable performance.

The chosen mass flow rate value for the test was chosen as 0.25 mg/s due to the relative stability of the discharge voltage for the various discharge current values. The discharge current value chosen for the endurance test phase was 0.8 A as it is the mean value of the required discharge current range. During the entire length of the endurance test the cathode was operated in a self-sustaining mode; that is with the keeper power supply turned off and sufficient emitter temperatures sustained by the main plasma discharge. For this reason keeper-emitter measurements correlate to the cathode sheath voltage drop and electron temperature within the emitter-keeper gap. Schematic showing the endurance test experimental setup is presented in Figure 10.

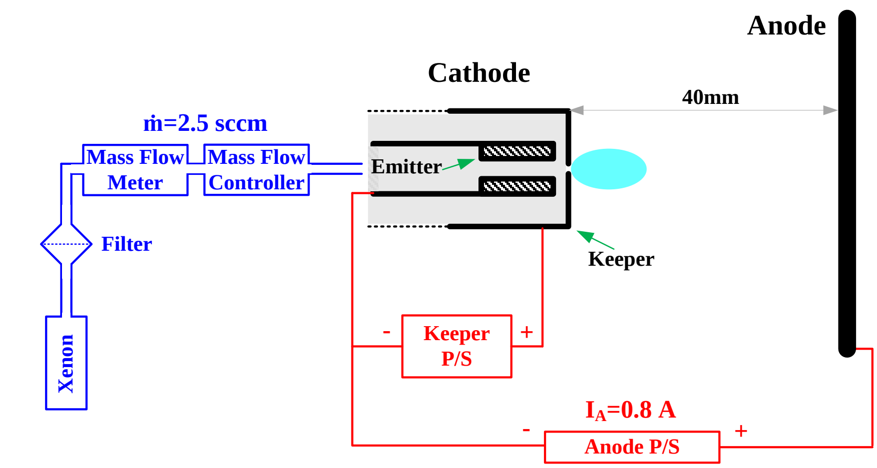

Figure 10. Experimental setup used in the 5,000 hour cathode endurance test.

Floating keeper voltages throughout the 5,000 hour cathode endurance test are presented in Figure 11. The measurements show that keeper voltage values are approximately 14 V during the initial phase of the test and decrease to approximately 8.5 V near the end of the test. This decrease in floating keeper voltage might be the results of cathode cleanliness which was naturally improved throughout the endurance test as xenon plasma was operating inside the cathode. Another possible source for this electrical behavior might be the erosion of the keeper orifice on the internal side of the cathode. The gradual expansion of the keeper orifice diameter might have led to lower plasma power losses in the orifice channel. This postulation is strengthened by the fact that cathode pressure gradually decreased throughout the endurance test.

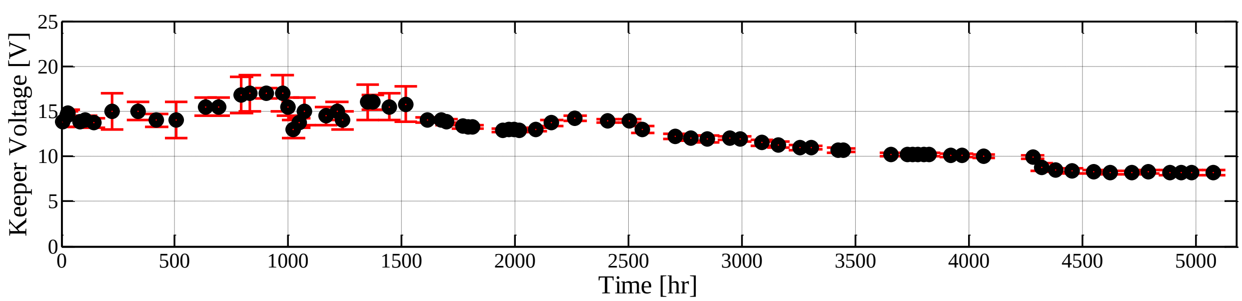

Figure 11. Floating keeper voltage throughout the 5,000 hour cathode endurance test.

To measure the required cathode ignition breakdown voltage it was ignited multiple times during the endurance test, and at least twice in every 1,000 hours of operation. It was found that all ignition voltages were under 400 V regardless of cathode operation history. This encouraging finding demonstrates the robust design that assures low and repeatable ignition voltage values. It was also shown in a past study that a sharp increase in ignition voltage, although for a heated hollow cathode, is one of the symptoms for reaching the cathode's end of life[29]. For this reason it is speculated that the cathode internal structure experienced negligible wear or deformation, as was also confirmed in the post wear test analysis.

The above results reassure that the emitter has yet to reach its end of life and no indication for excessive BaO depletion was observed. It can therefore be assumed that the cathode is able to continue normal operation if necessary.

I. Manufacture Repeatability Test

To examine the ability to produce identical cathodes six additional RHHC pieces were manufactured and assembled. All six cathodes, denoted AC-04 to AC-09, are identical and manufactured in three different batches. The assessment of performance consistency was conducted by running each cathode through the same acceptance test in which three main parameters were monitored – ignition breakdown voltage, floating keeper voltage and external keeper surface temperature 10 mm from cathode tip. Cathode parameters were recorded specifically under nominal conditions at anode current of 0.8 A and mass flow rate of 0.25 mg/s. Each measurement was taken multiple times to assure measurement accuracy.

Table 2. Ignition breakdown voltage, floating keeper voltage (I_A=0.8 A, ṁ=0.25 mg/s) and keeper temperature 10mm from cathode tip for RHHC cathodes AC-4 to AC-9.

Cathode	V_{BD} [V]	V_k [V]	Temp'
AC-4	340±20	10.8±0.5	229°C
AC-5	355±10	11.3±0.5	258°C
AC-6	320±50	10.8±0.5	244°C
AC-7	360±20	10.5±0.5	272°C
AC-8	340±10	10.3±0.5	237°C
AC-9	330±10	9.9±0.5	258°C

The measured parameters for each of the cathodes are presented in Table 2. It can be seen in the table that for all cathodes ignition breakdown voltage is between 320 V and 360 V. This value is in line with cathode characteristics observed in the cathode ignition and endurance tests. It is also clear from the table that keeper voltage values range from 9.9 V to 11.3 V. These values assure a fairly consistent cathode mode of operation. Lastly, cathode keeper temperatures were measured to be in the range 229-272°C. The variance in the temperature most likely stems from small divergences in the positioning of the thermocouple on the cathode body, which may definitely lead to variations of ±21°C as observed in the measurements.

In conclusion, cathode manufacturability is consistent and each RHHC produced is identical, in terms of performance, to other cathodes, even from different production batches.

J. Performance at Very Low Current Levels

To assess the RHHC ability to operate with low power thrusters, less than 100 W, cathode operation at discharge current levels of 0.2-0.5 A was explored. To do so RHHC low discharge current operation was explored with two cathodes: (1) a new cathode, with less than 100 hours of operation and (2) the used cathode that finished over 5,000 hours of operation. The cathodes were operated in diode mode against plate-shaped and cylindrical-shaped anodes. The main purpose of the test was to examine the RHHC capability to operate in self-sustained mode without the need to maintain keeper power in steady state. For this the cathodes were left to operate, at each operation point, for at least one continuous hour while the electrical and thermal parameters are monitored. In very low discharge current operation points, in cases when the cathode has spontaneously shut down, the keeper power supply was turned on and experiment at that particular operational point re-initiated. This, however, occurred only for discharge current cases of 0.3 A or less, as presented hereafter.

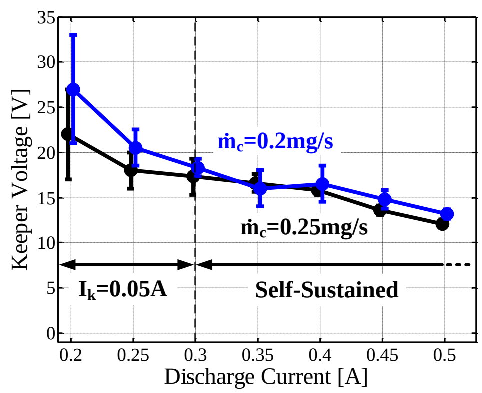

Figure 12. Floating keeper voltage measurements as a function of the discharge current from 0.2 A to 0.5 A, for mass flow rate values of 0.2 mg/s and 0.25 mg/s.

Floating keeper voltage measurements at discharge current levels of 0.2-0.5 A, for two mass flow rates, are shown in Figure 12. Both cathodes operated successfully in self-sustained mode at discharge current levels down to 0.3 A. This finding is a proof for the robust thermal design of the cathode that allows sustainable and energy-efficient operation even at the lowest discharge current levels. At discharge current levels less than 0.3 A an additional keeper current of 50 mA, corresponding to approximately 1 W, is sufficient to sustain cathode operation.

K. Coupling with Hall Thrusters

Since the RHHC is dedicated for Hall thruster operation it was coupled with two separate low power Hall thrusters – CAM200 and HT-100D. The CAM200[30] and HT-100D[31] are low power Hall thrusters developed and produced by Rafael (Israel) and Sitael (Italy) respectively. Both thrusters operate in the 100-300 W power range; therefore require discharge current of 0.5-1.1 A.

Several RHHCs were successfully operated with both Hall thrusters, in two separate vacuum facilities, for cummulative steady state operation duration of several hundred hours[10]. During its operation with both Hall thrusters the cathode generated discharge current levels in the required range from 0.5 A to 1 A.

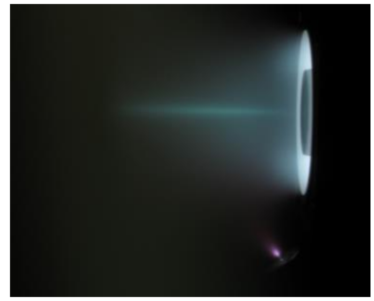

Figure 13. Picture of the RHHC coupled with the CAM200 low power Hall thruster.

Additionally, the RHHC was coupled in an ignition test with the CAM200 thruster (Figure 13) where the cathode ignited the Hall thruster with reduced current to the magnetic coils at the thruster's nominal operation point. On the other hand, low power Hall thruster ignition with full magnetic field strength is challenging due to the low electron cross field mobility[32]; therefore such an ignition should be treated by employing non-conventional means. To eanble thruster ignition with maximum magnetic field strength a dedicated augmented ignition unit was designed and tested at Rafael. The ignition unit enabled immediate thruster ignition during all attempts in all cases tested. This important improvement to the ignition process allows for RHHC operation with Hall thrusters that incorporate permanent magnets; thus do not possess the ability to reduced the magnetic field strength before ignition.

III. Conclusions and Future Work

The paper described the development process of the RHHC, a heaterless hollow cathode, as was conducted at Rafael. The various development activities were presented, from early technology study, through prototype unit production and to full scale operation with Hall thrusters. The cathode development process culminated with two major experiments - a 5,000 hour endurance test and a 3,500 cold ignition cycles test. During these experiments cathode ignition and steady state operation were proved successful and compatible with expected low power electric propulsion system requirements. It is concluded that the RHHC is a high-end beam neutralizer solution for low power Hall and ion thrusters. In particular, the simple design of the cathode, along with available material composition, permits for mass-production and makes the RHHC an ideal cost-effective solution for satellite constellations.

Future work on the RHHC will include the design and production of a Qualification Model (QM) of the cathode, shock and vibration test and a lifetime experiment with a low power Hall thruster.

References

[1] D. Lev and L. Appel. "Heaterless Hollow Cathode Technology - A Critical Review". *The 5th Space Propulsion Conference (SP)*, 2-6 May, 2016, Rome, Italy, SP2016_3125366.

[2] Dan M. Goebel & Ira Katz. *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*. JPL Space Science and Technology Series, Jet Propulsion Laboratory & California Institute of Technology, 2006.

[3] Dennis L. Tilley, Gary F. Willmes, Roger M. Myers and Richard D. Smith. "Flight Hollow Cathode for Hall Thruster Applications". *Proceedings of the 34th Joint Propulsion Conference (JPC)*, 12-15 July, 1998, AIAA-98-3339.

[4] William G. Tighe, Kuei-Ru Chien, Dan M. Goebel and Robert T. Longo. "Hollow Cathode Ignition Studies and Model Development". *Proceedings of the 29th International Electric Propulsion Conference (IEPC)*, October 31 - November 4, 2005, Princeton, NJ, USA, IEPC-2005-314.

[5] W.G. Tighe, K. Freick and K.R. Chien, "Performance Evaluation and Life Test of the XIPS Hollow Cathode Heater", AIAA_2005-4066, *Proceedings of the 41st Joint Propulsion Conference (JPC)*, Tucson, AZ, July 10-13, 2005.

[6] G.C. Soulas, "Status of Hollow Cathode Heater Development for the Space Station Plasma Contactor", *Proceedings of the 30th Joint Propulsion Conference (JPC)*, Indianapolis, IN, June 27-29, 1994.

[7] J. Herscovitz, Z. Zuckerman and D. Lev. "Electric Propulsion Development at Rafael". *Proceedings of the 34th International Electric Propulsion Conference (IEPC)*, July 4-10, 2015, Hyogo-Kobe, Japan, IEPC-2015-30.

[8] Tommaso Misuri, Riccardo Albertoni, Cosimo Ducci, Barak Waldvogel, Leonid Appel, Raanan Eytan, Dan Lev, Kathe Dannenmayer and Davina Di Cara. "MEPS: A Low Power Electric Propulsion System for Small Satellites". *Proceedings of the 10th IAA Symposium on Small Satellites for Earth Observation*, Berlin, Germany, April 20 - 24, 2015, IAA-B10-1103.

[9] T. Misuri, C. Ducci, M. Andrenucci, B. Waldvogel, D. Lev, G. Alon and K. Dannenmayer. "MEPS Engineering Model Development and Test". *The 5th Space Propulsion Conference (SP)*, 2-6 May, 2016, Rome, Italy, SP2016_3124638.

[10] Dan Lev, Leonid Appel, Amoz Davidson, Barak Waldvogel and Jacob Herscovitz, Tommaso Misuri, Cosimo Ducci, Daniela Pedrini and Mariano Andrenucci and Kathe Dannemayer, "MEPS Project - Engineering Model Development and Testing Status," Presented in *the 35th International Electric Propulsion Conference (IEPC)*, 8-12 October, 2017, Atlanta, GA, USA, IEPC-2017-246.

[11] Mizrahi, J., et al. "Simulation of Plasma Parameters during Hollow Cathodes Operation." *Journal of Propulsion and Power*, vol. 28, no. 5, 2012, pp. 113.7

[12] V. Vekselman, D. Levko, Ya. E. Krasik and I. Haber. "A Comparative Study of Heaterless Hollow Cathode: 2D PIC Modeling vs. Experimentation". *Proceedings of the 33rd International Electric Propulsion Conference (IEPC)*, 6-17 October, 2013, Washington D.C., USA, IEPC-2013-380.

[13] Vekselman, Vlad, et al. "Particle-in-Cell modeling of the heaterless hollow cathode operation: Keeper region." *2014 IEEE 41st International Conference on Plasma Sciences (ICOPS)* held with 2014 IEEE International Conference on High-Power Particle Beams (BEAMS), 2014.

[14] Vekselman, V., Krasik, Ya. E., Gleizer, S., Gurovich, V. Tz., Warshavsky, A. and Rabinovich, L., "Characterization of a Heaterless Hollow Cathode," *Journal of Propulsion and Power*, Vol. 29, No. 2, pp. 475-486, 2013.

[15] J. L. Cronin. "Modern Dispenser Cathodes," *IEEE Proc.*, Vol.128, Pt. I, No. 1, February 1981.

[16] Dan Lev, Gal Alon, Dmytry Mykytchuk and Leonid Appel. "Development of a Low Current Heaterless Hollow Cathode for Hall Thrusters". *Proceedings of the 34th International Electric Propulsion Conference (IEPC)*, July 4-10, 2015, Hyogo-Kobe, Japan, IEPC-2015-163.

[17] D. Lev, G. Alon, S. Fisher and L. Appel. "Cathode Test Facility at Rafael". *The 5th Space Propulsion Conference (SP)*, 2-6 May, 2016, Rome, Italy, SP2016_3125365.

[18] D. Lev, G. Alon, A. Warshavsky and L. Appel. "Low Current Heaterless Hollow Cathode R&D at Rafael". *The 18th Israeli Conference on Plasma Science and its Applications (IPSTA)*, 3 March, 2016, Beer-Sheva, Israel, Poster.

[19] D. Lev, G. Alon, D. Mykytchuk and L. Appel, "Heaterless Hollow Cathode Characterization and 1,500 hr Wear Test", *Presented at the 52nd Joint Propulsion Conference (JPC)*, 25-27 July, 2016, Salt Lake City, UT, USA. AIAA-2016-4732.

[20] James E. Polk, Dan M. Goebel, Ron Watkins, Kristina Jameson, Lance Yoneshige, JoHanna Przybylowski and Lauren Cho, "Characterization of Hollow Cathode Performance and Thermal Behavior", AIAA_2005-4066, *Proceedings of the 42nd Joint Propulsion Conference (JPC)*, July 9-12, 2006, Sacramento, CA, USA.

[21] Matthew T. Domonkos, Alec D. Gallimore, George J. Williams Jr. and Michael J. Patterson. "Low-Current Hollow Cathode Evaluation". *Proceedings of the 35th Joint Propulsion Conference (JPC)*, June, 1999, Los Angeles, CA, USA, AIAA-99-2575.

[22] Matthew T. Domonkos, Alec D. Gallimore and Michael J. Patterson. "An Evaluation of Hollow Cathode Scaling to Very Low Power and Flow Rate," *Proceedings of the 25th International Electric Propulsion Conference (IEPC)*, 24-28 August, 1997, Cleaveland, OH, USA, IEPC-97-189.

[23] William G. Tighe, Kuei-Ru Chien, Dan M. Goebel and Robert T. Longo. "Hollow Cathode Ignition Studies and Model Development". *Proceedings of the 29th International Electric Propulsion Conference (IEPC)*, October 31 - November 4, 2005, Princeton, NJ, USA, IEPC-2005-314.

[24] Brophy,, J.R., Brinza, D.E., Polk, J.E. and Henry, M.D., "The DS1 Hyper-Extended Mission", AIAA-2002-3673, *Proceedings of the 38th Joint Propulsion Conference (JPC)*, July, 2002.

[25] Michael Schatz. "Heaterless Ignition of Inert Gas Ion Thruster Hollow Cathodes ". *Proceedings of the 18th International Electric Propulsion Conference (IEPC)*, 30 September - 2 October, 1985, Alexandria, VA, USA.

[26] D. G. Fearn, "An Investigation of Physical Processes in a Hollow Cathode Discharge," *AIAA Journal*. Vol. 11, No. 2, pp. 131-132, 1973.

[27] G. F. Cirri, A. Cipriani, G. Matticari, A. Severi, C. Bartoli, G. Saccoccia and H. Von Rohden. "Review of Qualification Activities on the Neutralizer for the RIT10 Ion Thruster". *Proceedings of the 23rd International Electric Propulsion Conference (IEPC)*, September, 1993, Seattle, WA, USA, IEPC-93-109.

[28] James E. Polk, Ioannis G. Mikellides, Angela M. Capece and Ira Katz. "Barium Depletion in Hollow Cathode Emitters". *Proceedings of the 45th Joint Propulsion Conference (JPC)*, 2-5 August, 2009, Denver, CO, USA, AIAA-2009-5197.

[29] Timothy R. Sarver-Verhey. "28,000 Hour Xenon Hollow Cathode Life Test Results". *Proceedings of the 26th International Electric Propulsion Conference (IEPC)*, 24-28 August, 1997, Cleveland, OH, USA, IEPC-97-168.

[30] D. Lev, R. Eytan, G. Alon, A. Warshavsky, L. Appel, A. Kapulkin and M. Rubanovych. "The Development of CAM200 - Low Power Hall Thruster". *Trans. JSASS, Aerospace Tech. Japan*, 14(ists30), pp. Pb_217- Pb_223, 2016.

[31] T. Misuri, et al. "Sitael Low Power Hall Effect Thrusters for Small Satellites," *Proceedings of the 34th International Electric Propulsion Conference (IEPC)*, July 4-10, 2015, Hyogo-Kobe, Japan, IEPC-2015-102, Kobe, Japan, July 2015.

[32] Azziz, Y., "*Experimental and Theoretical Characterization of a Hall Thruster Plume*," Doctoral Dissertation, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 2007.