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Heaterless Hollow Cathode Technology - A Critical Review

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ABSTRACT:

We present a critical review of heaterless hollow cathode technology. We list the three different configurations of this technology and explain the motives for the design of each one. We then elaborate on the different phases of heaterless hollow cathode ignition sequence: initial breakdown, when the discharge is generated; heating phase, when the emitter is heated by the discharge; steady state operation when cathode operation is self-sustained by the discharge. To support our arguments we bring examples from the relevant literature. Additionally, we discuss reported failure mechanisms during each one of the ignition phases and speculate on the causes for the leading failure modes in such devices. Lastly, we briefly present pre-heated cathode ignition technology, bring the motives for using it and list the few studies conducted on this subject.

1. INTRODUCTION

Heaterless Hollow Cathodes (HHCs) are a subclass of hollow cathodes that do not require external heating to heat up the electron emitter to its operation temperature. Instead of using external heating HHCs use a unique ignition technique. Firstly, 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 entire thruster ignition duration is usually less than 100 seconds.

Since HHCs do not use external heating for ignition they possess advantages over their heater-utilizing cousins. First, In comparison to heater-utilizing cathodes that have typical readiness time in the order of minutes, due to the required heating duration, HHCs reach steady-state operation within tens of seconds. Secondly, since no external heating is required the Power Processing Unit (PPU) does not contain the corresponding heater module, therefore lowering its mass. Lastly, since cathode heaters usually contain refractory metals and experience extreme thermal cycling they are susceptible to cycling failure. HHC combat this problem by completely removing the ignition dependence on heaters.

HHCs have been explored for over four decades in various locations around the globe. Most work was academic in nature and performed by either universities or research entities. Some work was presented by space industries or government agencies, yet little follow up literature exists from these attempts that most likely had no continuation. Nevertheless, in recent years there is a regrowing interest in HHC technology, an interest that might lead to maturation of the technology ending in space proven hardware.

In this paper we analyze HHC technology using existing literature on this subject. Initially, we present the three common configurations of HHCs and discuss the motives for using them. Subsequently, we elaborate upon the three phases of ignition and explain emitter heating mechanisms. We also present HHC failure mechanisms and suggest the sources for these failures. Lastly, particular attention is given to ignition with partially heated cathodes utilizing embedded heaters.

2. HEATERLESS CATHODE CONFIGURATIONS

In general, three configurations of HHCs appear in literature (Figure 1). These are the (a) orificed emitter, (b) open-end emitter, orificed keeper and (c) cathode with internal electrodes for ignition.

2.1. Orificed Emitter Configuration

Cathode configuration in which the tube encapsulating the emitter, also referred to as 'the insert', is capped with an orifice plate is the most common in electric propulsion applications[1,2]. In such configuration the aspect ratio between the orifice diameter and the orifice plate thickness plays an important role during steady state operation and dictates the heating mechanism of the emitter[3].

Since orificed emitter type cathodes are widely available, and physical mechanisms understood, it is only natural that many of the HHCs are of this type.

Orificed-emitter HHCs are ignited by applying high voltage between the emitter tube, or orifice plate, and the keeper. The pre-breakdown pressure is dictated by the keeper orifice diameter which is larger than the emitter tube orifice.

2.2. Open-End Emitter Orificed Keeper Configuration

The 'Open-End Emitter Orificed Keeper' configuration, that was first introduced by Aston[4,5], is unique for HHCs. In this configuration the orifice tube is either open, making it exposed to the discharge, or capped with a relatively large diameter orifice plate. On the other hand, the keeper orifice diameter is smaller than that of the emitter tube. The main driver for this feature is the possibility to reach large gas pressure between the emitter tube and keeper, in the order of up to tens of torr. By doing so initial gas breakdown may be achieved under optimal conditions, close to the minimum of the Paschen curve, as will be described in the next section.

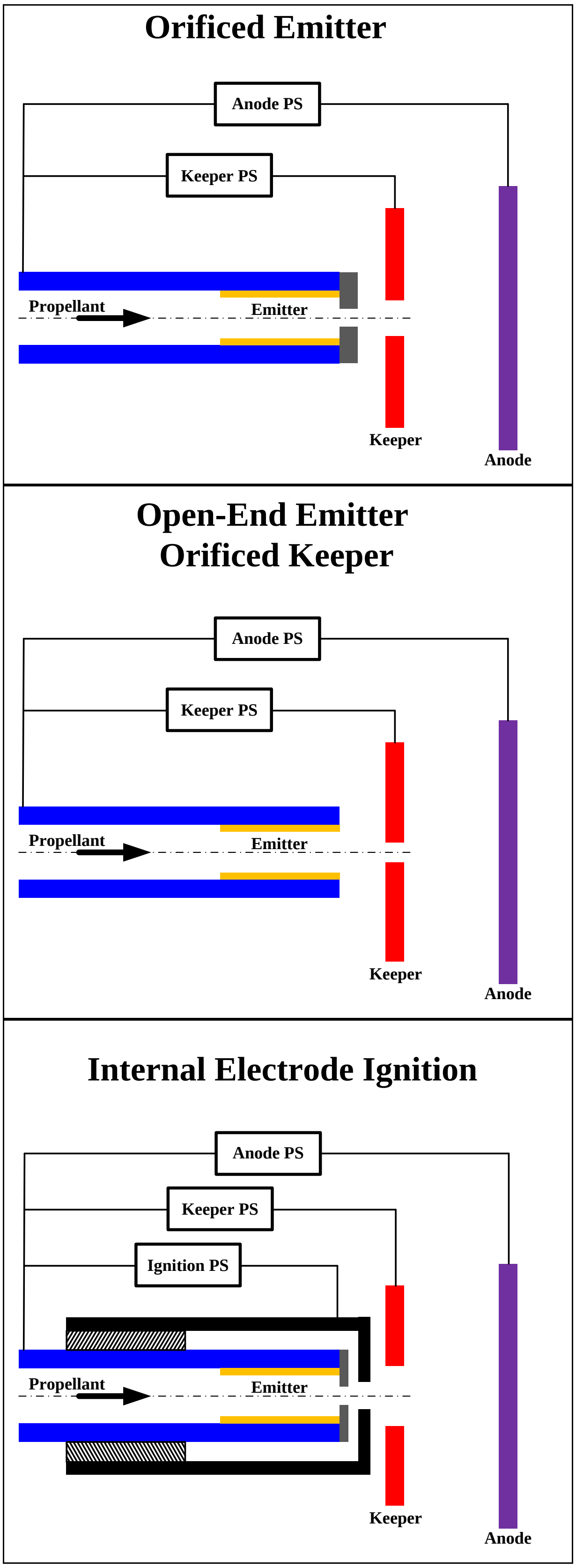

Figure 1. The three different heaterless hollow cathode configurations

2.3. Internal Electrode Ignition Configuration

Another configuration unique to HHCs is the 'Internal Electrode' configuration in which the emitter tube is in fact two electrically insulated tubes of which one contains the emitter. The tubes are usually orificed. The keeper encapsulates both ignition tubes and has an orifice diameter larger than the emitter orifice plate diameter.

The main driver for using an additional ignition electrode is to control the ignition electrodes gap for breakdown while using a larger distance between the discharge electrodes during the emitter heating phase.

Initial gas breakdown is achieved by applying high voltage between the ignition electrodes followed by a discharge sustaining feed from the keeper power supply for emitter heating. Eventually, the main anode discharge is initiated and normal steady state operation is reached.

In one exceptional case[6,7] the ignition tubes are in fact spark plugs used to generate sufficient primary electrons for discharge to initiate between the emitter tube and keeper.

The drawback of the 'Internal Electrode Ignition' HHC configuration is its mechanical and electrical complexity. Realizing such a HHC requires accurate design and manufacture to withstand shock and vibration requirements. Additionally, this configuration requires the addition of a power supply to the Power Processing Unit (PPU); this to supply the necessary heater current which is normally in the order of tens or Ampere.

3. IGNITION PHASES

A full ignition process is defined as the process in which the cathode transitions from cold state, having the same temperature as its interface to the thruster, to fully operational state with discharge current flowing between the emitter and anode. Furthermore, after the ignition sequence is complete all power supplies, except for the main (anode), may be shut down while cathode operation is self-sustained.

To complete ignition three phases are identified[8]: (a) Initial breakdown, (b) Heating phase and (c) transition to main discharge. For successful ignition all three phases must be completed in the above-mentioned order. Table 1 summarizes the initial breakdown and heating phase of past HHC studies while Table 2 summarizes the steady-state operation characteristics of these studies.

3.1. Initial Breakdown

The breakdown phase is the process in which the neutral gas becomes ionized due to sufficiently high voltage that causes ionization avalanche, as described by Paschen[9].

In general, most researchers agree that there is a stochastic nature to HHC breakdown. Additionally, breakdown voltage value variations decrease as the gas mass flow rate, hence cathode pressure, increases. In particular Fearn[10] demonstrated that breakdown voltage may vary by hundreds of percent from the minimum value at the lowest investigated mass flow rates. On the other hand Iliopoulos[11] shows that the breakdown voltage varies up to about 15% of the minimal required value. In any case, clear trends in breakdown voltage variations with mass flow rate and inner electrode gap are observed by all researchers.

Most HHC work identifies optimal breakdown as the minimum point of the Paschen curve for the relevant gas. For example, xenon may experience breakdown at about 500 volts when the product $p \cdot d$ of about 3 torr·cm is reached, where p and d are the pressure and spacing between the ignition electrodes respectively. Indeed, most studies present a Paschen-like breakdown voltage behavior as a function of $p \cdot d$. However, several researchers showed that gas breakdown may occur under voltage below the minimum predicted by the Paschen model[10,12,13,14,15], as listed in Table 1. This slight discrepancy can be reconciled by the fact that gas breakdown processes in hollow cathode geometries occur at lower voltage and lower values of $p \cdot d$ as demonstrated by Eichhorn[16]. Eichhorn explains that due to the axi-symmetry of the hollow cathode electrodes a "breakdown pendulum effect" takes place in which high energy electrons bounce between the electrode walls while enhancing the ionization avalanche effect.

To achieve efficient breakdown most researchers used electrode spacing of several millimeters. Subsequently, pre-ignition pressure values of the order of tens of torr were applied. We conclude that as a rule of thumb it is advisable to design the HHC such that the product $p \cdot d$ is roughly 1 torr·cm for xenon.

In some studies[17,18,19] the pressure between the electrodes was temporarily increased so to increase the product p·d. In a similar manner other studies[6,7,13] use a technique called 'Pulse Flow Technique' in which a "puff" of gas is created using local gas flow manipulation in the cathode cavity. This is done by injecting gas into the cathode line while maintaining the valve at the cathode inlet closed. After several seconds sufficiently high pressure builds up upstream from the valve. At that moment the valve is opened and gas is allowed to flow into the cathode cavity and in between the ignition electrodes that are already under applied voltage. The local pressure in the ignition electrodes' gap peaks within milliseconds and quickly decreases until equilibrium pressure is reached. The advantage of the 'Pulse Flow Technique' is the ability to achieve high pressure values regardless of the cathode mass flow rate or orifice diameter. In addition, the decrease in local pressure in the inner electrode gap is effectively sweeping across different values of p·d, thus enabling breakdown at relatively low voltage. The drawback of the 'Pulse Flow Technique' is the required wait duration between pulses which is in the order of several seconds at best.

Lastly, Schatz[13] and Iliopoulos[11] showed that breakdown voltage is weakly dependent on the particular ignition electrodes configuration for a given spacing between the electrodes. Iliopoulos[11] also showed that ignition electrode geometry, in particular sharp edges, may reduce breakdown voltage by about 20%.

It may be concluded that the "recipe" for desired discharge initiation is well understood.

3.2. Heating Phase

Following initial discharge generation a transition phase must take place in which the temperature of the electron emitting material increases from cold state to fully operational temperature. This phase is characterized by plasma discharge that is maintained between the emitter assembly and the keeper. During this phase in almost all studies the discharge current had to be limited to a certain value due to the low plasma impedance when operating in an arc regime.

There can be two main types of discharge between the cold electrodes following gas breakdown - glow discharge or an electric arc. Each is defined by different voltage-current characteristics[20] as depicted in Figure 2.

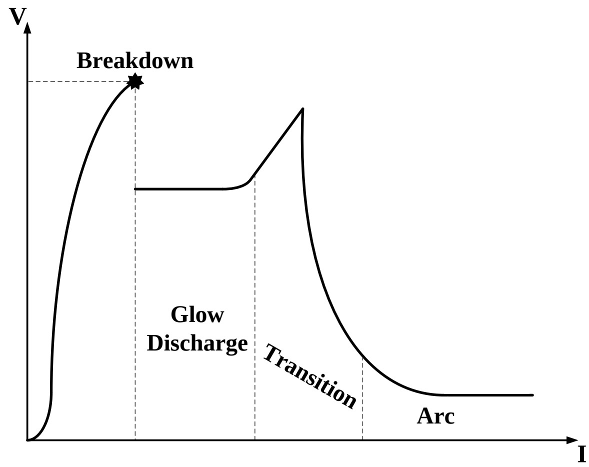

Figure 2. Typical voltage-current characteristics of hollow cathode discharge.

Glow discharge is characterized by voltage of a few hundred volts at relatively low current in the order of milliamperes. In this regime the plasma interaction with the electrodes is usually regional where any increase in the discharge current is accompanied by an increase of the discharge-electrode interaction region. Electrical arcs are characterized by voltage of tens of volts at current in the order of several to tens of amperes. In this regime the discharge is localized on a small portion of the electrode that heats up to extremely high temperatures of thousands of degrees.

When the electron emitter obtains sufficiently high temperature to emit the desired current density the discharge current may be supplied without the need for localized heating of cathode material.

In most studies the researchers aimed at reaching the arc regime within milliseconds after breakdown. This was done simply by controlling the discharge current using the emitter-keeper power supply. The reported values of discharge current, along with the type of discharge used, appear in Table 1.

The main advantage of arriving at the high current regime is quick heating of the cathode region to which the electrical arc attaches. However, it should be noted that after breakdown the emitter is still cold and its low work function does not give it any particular advantage. Therefore, the generated arc might attach to any conductive material at cathode potential. This includes arcing to the cathode structure in the vicinity of the emitter or to the emitter itself.

Although in most studies obtaining an arc between the emitter module and keeper was preferable as quick ignition was achieved, several particular studies achieved cathode heating via glow discharge generation[8,13,14,15,21]. Part of these studies reported cathode heating durations in the order of tens of seconds[8,13,21]. It can be speculated that the characteristic glow discharge heating duration depends on the characteristic thermal time of the cathode itself. In addition it is reasonable that cathodes with LaB6 emitters have a longer characteristic heating duration than tungsten-impregnated cathodes due to the higher work function of LaB6; thus higher required final emitter temperature.

At the end of the heating process, whether through arc formation or glow discharge, the emitter is hot enough for thermionic emission to take place. The emitter is able to supply the required discharge current through a relatively large area. At this point transition to main discharge generation is immediate by applying the main discharge power.

In particular, Schatz[13] reported that transition to main discharge is autonomous when the emitter is sufficiently hot if the main discharge voltage is applied prior to plasma breakdown. It is assumed that the temperature of the emitter, and the ability to generate sufficient flux of electrons from its entire surface, are the main driver for transition to main discharge operation.

3.3. Steady State Operation

After the emitter is hot and main discharge established the cathode operates under a steady state for the duration of the mission. At this state cathode operation is self-sustained by the main discharge through sufficient emitter heating.

Since the 'Orificed Emitter' configuration is the most common used for heater-utilizing cathodes its parameters and plasma heating mechanisms under steady state conditions are well understood[1,2,3]. For this reason we will focus on cathode operation under steady state conditions of the 'Open-End Emitter Orificed Keeper' cathode configuration which, to our best knowledge, is used only in HHCs.

The prime motive for using HHCs with an 'Open-End Emitter Orificed Keeper' configuration is the benefits during the ignition phase, as already specified. However, after discharge is established the physical mechanisms behind cathode operation and existing plasma parameters are not well understood.

Katz showed that the leading emitter heating mechanism of cathodes with an open-end emitter tube configuration is direct ion bombardment. This comes in contrary with orificed emitter heating that is heated through heat conduction from the orifice where the plasma is densest. In addition, plasma density within the cathode cavity is more uniform than with orificed emitters; therefore plasma resistivity in open-end emitter tubes is relatively uniform[8].

Vekselman[8], Koshelev[22] and Lev[23] showed that 'Open-End Emitter Orificed Keeper' cathodes exhibit conventional emitter-keeper voltage, which is related to cathode sheath voltage, to discharge current behavior. The voltage-current curves indicate increased voltage at low discharge current and low mass flow rate. This might be an indication of similar cathode sheath formation process and physics on the emitter surface as in orificed emitter cathodes.

At all, no experimental investigation of the physics of the plasma within the emitter-keeper gap was conducted.

The main discharge voltage, between the emitter and anode, shows large variations with mass flow rate[8,14,23,24]. In fact, Vekselman[8], Arkhipov[14] and Lev[22] reported an exceptionally sharp discharge voltage increase with a decrease in mass flow rate. This behavior may be attributed to the sharp plasma density decrease, thus pressure, at the keeper orifice; as was observed by Vekselman using spectroscopic techniques. The orificed keeper is responsible for large pressure gradients through the orifice. Additionally, it is possible that the cathode-anode distance (30 mm and 40 mm for Vekselman and Lev respectively) is sufficiently large to lead to anode starvation phenomenon - causing an exceptionally large anode sheath voltage drop at the anode surface. To test the above postulations further spatial plasma potential measurements in the cathode plume should be conducted.

Table 1. Summary of the different heaterless hollow cathode ignition characteristics.

Researcher	Name	Configuration	Gas	Emitter Material	Ignition Pressure	Minimal Breakdown Voltage	Keeper Current	Ignition Electrodes Distance	Ignition Sequence	Remarks
Koshelev et al. [8,12]	SHC-M1	Open-End Emitter - Orificed Keeper	Xe	Sc_2O_3 Impregnated W	40-60 torr	400 V	*O*(0.1) A	1.9 mm	Glow discharge formation	
Loyan et al. [24]	SHC-2A	Open-End Emitter - Orificed Keeper	Xe							
Aston [4,5,26]	FERM Cathode*	Open-End Emitter - Orificed Keeper	Ar	Ta	2 torr	300 V	1-3 A	5 mm	Arc formation	*The commercial version name is SpectraMat™
Aston [6,7]		Open-End Emitter - Orificed Keeper		Ta/W/Mo	Pulse Flow Technique**	500 V	*O*(1) A	Ignition plugs used	Arc formation	**Initial plasma "puff" propagation through the emitter tube
Lev et al. [15,23,29]	RHHC	Open-End Emitter - Orificed Keeper	Xe	BaO Impregnated W		400 V	*O*(0.1) A			
Albertoni et al. [17,18]	ALPHcA	Orificed Emitter	Xe	LaB6		950 V (not minimal†)	1.5 A	2 mm	Arc formation	†All ignitions were with the specified value of voltage
Pedrini et al. [19]		Orificed Emitter	Xe, Kr	LaB6	$\dot{m}_{Ign}$=5 mg/s	800 V (not minimal†)	2 A	2 mm		
Koroteev [27]	CNU	Orificed Emitter	Xe	BaO Impregnated W				~0.4 mm††		††Dimension extracted from figure in publication
Daykin-Iliopoulos et al. [11,28]	HHC	Orificed Emitter	Ar	LaB6	2-5 torr	300 V		1/11/21 mm	Only breakdown	
Fearn et al. [10]	T4 Cathode	Orificed Emitter	Hg Vapor	BaO Impregnated W		> 150 V‡	0.1 A	1 mm	Arc formation	‡At initial emitter temp' of 750°C
Schatz [13]		Orificed Emitter	Xe	Impregnated W	Pulse Flow Technique	450 V	0.2 A	1.52 mm		
		Internal Electrode Ignition	Xe	Impregnated W	Pulse Flow Technique	300 V	2 A	0.76 mm	Glow discharge formation	
Arkhipov [14]	HLC	Internal Electrode Ignition	Xe	Ba/K Impregnated W	15-20 torr	340 V	0.25 A		Arc formation‡‡	‡‡Multiple pulses for breakdown followed by arc formation

Table 2. Summary of the different heaterless hollow cathode steady state operation characteristics.

Researcher	Name	Configuration	Gas	Emitter Material	Emitter Ø	Mass Flow Rate	Main Discharge Current	Current Density	Total Operation Duration	Remarks
Koshelev et al. [8,12]	SHC-M1	Open-End Emitter - Orificed Keeper	Xe	Sc_2O_3 Impregnated W		0.5 sccm	0.2-0.5 A*	15-25 A/cm^2		*Operated with the SPT-20 Hall Thruster
Loyan et al. [24]	SHC-2A	Open-End Emitter - Orificed Keeper	Xe			1.3 sccm	1-2.5 A**			**Operated with the SPT-M70 Hall Thruster
Aston [4,5,26]	FERM Cathode	Open-End Emitter - Orificed Keeper	Ar	Ta	3-3.5 mm	3-5 sccm	17-35 A***	20-50 A/cm^2	*O*(10) hr	***Operated with the J series 30 cm ion thruster
Aston [6,7]		Open-End Emitter - Orificed Keeper		Ta/W/Mo						Emitter-keeper discharge sustained for stable operation
Lev et al. [15,23,29]	RHHC	Open-End Emitter - Orificed Keeper	Xe	Ba Impregnated W		1-3.5 sccm	0.4 A-1.2A		1,525 hr† 900 cold ignitions	†Operated at 0.8 A
Albertoni et al. [17,18]	ALPHcA	Orificed Emitter††	Xe	LaB6	3 mm	0.8-10 sccm	1-3 A†††	2-5 A/cm^2	50 hr 100 cold ignitions	††$\varnothing_{orifice}$≈0.33 mm, 0.44 mm †††Operated with the HET100 thruster
Pedrini et al. [19]		Orificed Emitter	Xe, Kr	LaB6	3.6 mm	1-2 sccm (Xe) 16-65 sccm (Kr)	16 A‡	1-7 A/cm^2	340 hr 100 cold ignitions	‡Operated with the J series 30 cm ion thruster
Koroteev [27]	CNU	Orificed Emitter	Xe	Ba Impregnated W	~0.65 mm‡‡	5 sccm 10 sccm (@ startup)	15 A	~1,000 A/cm^2 ‡‡		‡‡Extracted and/or calculated from figure in publication
Daykin-Iliopoulos et al. [11,28]	HHC	Orificed Emitter‡‡‡	Ar	LaB6	2 mm	1-30 sccm	20 A	20 A/cm^2		‡‡‡$\varnothing_{orifice}$=1.2 mm
Fearn et al. [10]	T4 Cathode	Orificed Emitter§	Hg Vapor	Ba Impregnated W	2 mm	0-0.9 mg/s				§$\varnothing_{orifice}$=0.15/0.25/0.3 mm
Schatz [13]		Orificed Emitter	Xe	Impregnated W	3.81 mm	30-60 sccm	1-15 A§§			§§Operated with the J series 30 cm ion thruster
		Internal Electrode Ignition	Xe	Impregnated W	3.81 mm	5-20 sccm			3,430 cold ignitions§§§	§§§11 min pause between ignitions
Arkhipov [14]	HLC	Internal Electrode Ignition	Xe	Ba+K Impregnated W		3.5-4 sccm	4.5 A@		2000 hot ignitions	@Operated with the SPT-100 Hall thruster

4. FAILURE MECHANISMS

Although HHCs do not include a heater, which is one of the main failure mechanisms in conventional hollow cathodes, they do experience other unique failure mechanisms. These failure mechanisms are either related to the heating phase, when the emitter transitions from cold state to its operational temperatures, or steady state operation in non-conventional cathode configurations.

4.1. Damage during Breakdown Phase

During ignition heaterless hollow cathodes might be eroded due to the high current “peak” induced between the two ignition electrodes. Using spectroscopic techniques Koshelev[22,30] identified barium depletion from the cathode during the ignition phase for cathodes with BaO impregnated emitters. The barium was released within the first second after gas breakdown was identified. In addition, Koshelev showed that the higher the discharge current the higher the barium erosion. Still, it is unclear whether the measured barium erosion is severe to a level that limits cathode life.

Koshelev[21] also showed insignificant damage to the keeper orifice, in cathodes with the 'Open-End Emitter, Orificed Keeper' configuration, after 840 gas breakdown cycles. He deduced that no major damage is inflicted on the keeper orifice during the initial breakdown phase.

Schatz[13] reported, after a 4,340 cycles cold ignition test, sputter marks on the exterior of the emitter tube, emitter plate and emitter surroundings – an indication of arcing between the two ignition electrodes. Still, apart for some scrubbed surface appearance the emitter and keeper orifice diameters did not change and seemed intact.

At the same time other researchers[14,17,18,19] reported little to no erosion during multiple hot startups. Therefore, it can be concluded that the actual breakdown process inflicts insignificant damage to the cathode structure even after several thousands of ignitions.

4.2. Failure during Emitter Heating Phase

Two emitter heating mechanisms were discussed. The first involves the generation of glow discharge where relatively high voltage is required to maintain low heating current of weakly ionized discharge. The second is arc mode in which low voltage highly concentrated arc heats the surface locally. It should be noted that since the heating process initiates when the entire cathode is cold any arc generation can be between any two surfaces and not necessarily the electron emitter. At the same time glow discharge tends to spread over a wide surface of the electrodes.

Schatz[13] reported significant erosion after 100 breakdowns and approximately 100 hours of arc operation. He hypothesized that the erosion is either a result of overheating or ion sputtering. Considering the fact that Schatz operated the cathode at discharge currents of about 15 times higher than the rated cathode current it may be assumed that either one of the speculations is reasonable.

In addition, Koshelev[24] maintained a glow discharge between the electrodes for cathode heating prior to full cathode ignition.

From these two studies it can be deduced that during cathode heating avoiding the arc regime should be practiced. However, one should note that glow discharge heating might be a slow process and will require heating duration of tens of seconds or even minutes as already indicated in this review.

4.3. Failure during Steady State Operation

Following cathode ignition it is self-sustained, namely, its operation is maintained through the main discharge current. At this state no heater is required for cathode operation. For this reason the expected failure modes of Heaterless hollow cathodes are the same as those of conventional heater-utilizing cathodes.

Nevertheless, most of the relevant literature covers failure mechanisms of the 'Orificed Emitter' configuration, which is also the most common configuration of heater-utilizing cathodes. There is limited coverage of failure mechanisms of cathodes with the 'Open-End Emitter, Orificed Keeper' configuration since this configuration was suggested for its advantages for Heaterless ignition. Accordingly, we present the failure mechanisms reported for cathodes with 'Open-End Emitter, Orificed Keeper' configuration.

Aston [4] reported severe cathode erosion, crystallization and localized melting of the emitter tube after 45 hours of steady state cathode operation. He concluded that a meticulous thermal design should overcome the emitter tube melting problem, allowing the cathode structure to sustain elevated temperatures. Since Aston used pure tantalum as the electron emitting material the authors believe that an adequate thermal design would be quite challenging due to the high temperatures required for sufficient electron emission, estimated above 2,500°C.

Similarly, Lev[28] reported refractory metal melting and even emitter tube plugging, after 30 hours of steady state cathode operation, due to elevated temperatures generated on the low work function emitter surface. Lev concluded that the cause for extreme temperatures was either barium depletion or emitter coating which led to a work function rise. Eventually, the high work function increased the required temperature to sustain the discharge. Lev also concluded that the root for quick barium depletion is cathode operation outside the allowed main discharge current limits.

Lastly, early experimental work by Lev[15] showed cases in which the keeper orifice became plugged due to vaporized material depositing on the orifice rim and reducing the orifice diameter during cathode operation. Nonetheless, these cases occurred only when the cathode was operated at extreme discharge current levels, higher than the allowed values. Still, it is reasonable to assume that the keeper orifice of this type of cathodes is susceptible to plugging due to its smaller size compared with conventional emitter orifice dimensions of 'Orificed Emitter' cathode configurations.

5. PRE-HEATED IGNITION

As mentioned earlier one of the leading reasons HHC technology is sought after is the fact that thermal cycling reduces heater-utilizing cathodes life expectancy. It is expected that mitigating thermal cycling by reducing the highest temperatures reached would prolong cathode lifetime. Consequently, several past studies explored the option of heating a cathode to several hundred degrees Celsius and igniting the cathode using a HHC ignition sequence. During the pre-heating phase the emitter is usually brought to temperatures above 800°C.

In addition, Uhm showed[31] that increasing the initial temperature of a cylindrical cathode configuration reduces the voltage required for initial breakdown. Therefore, pre-heated cathodes are also expected to have relaxed ignition requirements compared with HHCs.

All studies showed that emitter pre-heating aids in reducing breakdown voltage and ignition duration.

Since this review focuses on heaterless cathode ignition we will only list the studies covering pre-heating cathode ignition and bring the relevant literature references. These are Fearn[10], Sarver-Verhey[32], Rubin[33,34], Wintucky[35] and Tang[36].

6. CONCLUSIONS

We presented a critical review of HHC technology. Initially, we listed the three different configurations of HHC and explained the motives for the design of each one. We then elaborated on the different phases of HHC ignition sequence: initial breakdown, when the discharge is generated; heating phase, when the emitter is heated by the discharge; steady state operation when cathode operation is self-sustained by the discharge. To support our arguments we brought examples from the relevant literature.

Subsequently, we discussed possible failure mechanisms during each one of the ignition phases as reported by past researchers. Although limited data exists on the failure mechanisms of HHC we made speculations on the causes for the leading failure modes.

Lastly, we briefly presented pre-heated cathode technology, brought up the motives for using it and listed the few studies conducted on this subject.

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