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Scenario for Hollow Cathode End-of-Life

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SCENARIO FOR HOLLOW CATHODE END-OF-LIFE

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Abstract

Recent successful hollow cathode life tests have demonstrated that lifetimes can meet the requirements of several space applications. However, there are no methods for assessing cathode lifetime short of demonstrating the requirement. Previous attempts to estimate or predict cathode lifetime were based on relatively simple chemical depletion models derived from the dispenser cathode community. To address this lack of predicative capability, a scenario for hollow cathode lifetime under steady-state operating conditions is proposed. This scenario has been derived primarily from the operating behavior and post-test condition of a hollow cathode that was operated for 28,000 hours. In this scenario, the insert chemistry evolves through three relatively distinct phases over the course of the cathode lifetime. These phases are believed to correspond to demonstrable changes in cathode operation. The implications for cathode lifetime limits resulting from this scenario are examined, including methods to assess cathode lifetime without operating to End-of-Life and methods to extend the cathode lifetime.

Introduction

Hollow cathode lifetime has long been a critical issue for the implementation of several space-based technologies; primarily electric propulsion thrusters and spacecraft charge control systems. These applications require hollow cathodes with lifetimes on the order of thousands of hours. In recent years, cathodes operating with inert gases, primarily xenon, have been able to demonstrate these lifetimes.[1-7]

The hollow cathode employed for a majority of these applications typically consists of a refractory metal tube with a refractory metal orificed plate welded to the end. The insert or electron emitter is located at end of the tube with the orifice plate and consisted of a refractory metal cylinder impregnated with a barium oxide-calcium oxide-aluminum oxide mixture. On the outside of the cathode tube, a heater is affixed over the region occupied by the insert.

There is presently no methodology for determination of cathode life status (i.e. how much operational time and cycles remain for the device). Zuccaro[8] and Mirtich & Kerslake[9] attempted to predict hollow cathode lifetime as a function of electron emitter or insert temperature based on estimating the barium depletion rates. This approach was never verified with microscopic examination of a tested impregnated insert. Much of their work was an extension of cathode insert depletions models employed with vacuum tube cathodes, where these mechanisms have been validated.[10,11] The many discrepancies between vacuum tube cathodes and the hollow cathode presently employed result in significantly different operating environments. These differences are believed to have significant impact on cathode lifetime.

This paper will present a scenario for hollow cathode End-of-Life (EOL), based on the post-test evaluation of the 28,000 hour life tested hollow cathode,[12] and on results from other cathode life tests.[13,14] This scenario describes the suspected evolution of insert surface chemistry and its impact on the electron emission process within the cathode. As a consequence of this scenario, the assumptions about hollow cathode operation and lifetime held by the propulsion and plasma contactor community need to be updated. In the new paradigm, hollow cathode evolution must be viewed as a series of complex chemical reactions, driven by the operating conditions, that both creates the low work function surface necessary for electron emission and ultimately the poison compounds that will prevent the work function lowering process. The implications of such a view will be discussed herein. Several methods for the qualitative assessment of cathode lifetime are postulated and evaluated. While relatively gross, these techniques have the potential to provide in situ lifetime assessment or extrapolation of remaining lifetime from the current microscopic condition of an operated cathode insert, thereby mitigating the requirement for lifetime demonstrations.

This report is comprised of three sections. The first section will summarize the results of the 28,000 hours life test and the post-test condition of the hollow cathode. The second section will describe the mechanisms proposed to be responsible for the hollow cathode reaching its End-of-Life. Finally, a scenario for cathode surface chemistry evolution and End-of-Life will be presented and applications of this scenario to hollow cathode lifetime determinations will be discussed.

28,000 hour Hollow Cathode Life Test

Life Test Performance

Extensive details of the 28,000 hour hollow cathode life test have been previously presented.[1,12] Consequently, only a brief description will be provided herein. This hollow cathode life test was undertaken as part of the Hollow Cathode Assembly (HCA) development program for the International Space Station (ISS) Plasma Contactor system to demonstrate the required life time of 18,000 hours. The cathode was tested in a diode configuration with a planar anode mounted downstream of the orifice plate. The test was performed at 12.0 A emission current and 4.5 ± 0.3 sccm xenon flow rate.

While the performance of the hollow cathode during the life testing has been documented elsewhere, the behavior of three parameters during the life test were of particular interest. The discharge voltage, cathode tip temperature, and ignition voltage as functions of time are shown in Figs. 1-3, respectively. Both voltages were measured between the cathode and anode. While the discharge voltage was relatively stable during the life test, the cathode tip temperature and ignition voltage showed significant changes over time. These changes are believed to be significant indicators of cathode condition. Their behavior will be discussed later in this report.

Life testing of the hollow cathode was stopped when the cathode failed repeatedly to ignite at hour 27,800. Rather than attempt to ignite by further increasing ignition conditions (ignitor voltage, heater power), the life test was voluntarily discontinued because the cathode behavior[1] suggested that the insert characteristics had changed. Additionally, ending the life test preserved the cathode insert and orifice plate conditions, which could experience rapid changes during operation at off-normal conditions.

Post-Test Analyses

The critical features of the hollow cathode were the cathode orifice and the insert. These were examined extensively with various microscope techniques. The final conditions of the orifice and insert are summarized graphically in Figure 4.

While changes in orifice geometry occurred, these were believed to effect operating performance primarily[12] and have only a limited impact on hollow cathode lifetime. The insert condition will determine cathode lifetime because it is responsible for the electron emission process within the cathode and therefore plasma generation for the required device. Consequently, the final state of the insert contains information about the chemical processes leading up to a cathode EOL or failure. The final state of the insert was examined extensively to map physical and chemical changes. There were three critical physiochemical reactions observed which are believed to be responsible for the cathode EOL. These reactions are tungsten deposition, barium-containing layer formation, and tungstate formation.

Tungsten Deposition

Deposits of metallic tungsten are observed at the downstream end of a life-tested cathode. For the 28,000 hour life test hollow cathode, this formation extended approximately 0.3 cm upstream of the orifice plate, and was composed of tungsten grains of approximately constant size.

The deposit is believed to result from the condensation of free metallic tungsten onto these surfaces. This phenomenon has been observed previously,[13] and a process for free metallic tungsten formation and deposition has been hypothesized.[12] While the free tungsten is expected to be present throughout the hollow cathode cavity, the final formation will be location-dependent.

At the orifice plate and downstream end of the insert, the deposit is expected to occur after work function lowering capability of the downstream end has degraded due to impregnate chemistry evolution. The electron emission zone in the hollow cathode cavity is expected to move upstream where the insert surface is still readily providing low work function material. Consequently, the downstream surface temperature is expected to be lower than the emission zone and therefore serve as a condensation area for tungsten which collects into stable crystalline formations of varying sizes, from whiskers to larger crystals. The degraded surface of the downstream end results in reduced impregnate decomposition thereby allowing the metallic tungsten deposits to form, which would not have occurred with free Ba or Ba-O in the area. Tungsten deposition is not expected to affect cathode operation unless it becomes sufficient to obstruct the orifice or reduce the insert cavity size.

At the upstream end, the deposited tungsten is believed to react with elements on the insert surface. The effects of these reactions on electron emission are discussed below. Because of the reactions with other elements, the tungsten is unlikely to form into crystalline deposits, which have not been observed in this region.

Ba-Containing Layer Formation

Ba-containing layers are amorphous layer formations that cover portions of the insert surface, primarily at the upstream end.[12-14] Elemental examination of these layers indicated that they were comprised primarily of Ba and W, with varying amounts of Ca, Al, and O. Layer thickness varies from relatively thin coatings on the matrix tungsten grains to relatively thick solid layers. The chemical composition of these layers has not been completely determined, but they are believed to be comprised of various barium oxides, including aluminates and tungstates. For the purpose of this paper, the Ba-containing layer will refer to the amorphous forma-

tions on the insert surface, including both usable and poison compounds.[12,13,14]

For the 28,000 hour cathode, these layers covered approximately 70% of the upstream end.[12] The layers are believed to be formed when Ba and other elements released from the impregnate in the emission region collect at cooler locations on the insert surface. Since these collection regions are believed to be outside the emission zone, there is no significant mechanism for permanent removal of the material. Additionally, free tungsten is also expected to be deposited in these regions and contribute to the chemical evolution of these layers.

The configuration of the hollow cathode and the presence of a relatively high pressure atmosphere in the region of the insert will enhance the insert surface chemistry processes. In traditional dispenser cathodes, any material released from the surface will migrate quickly away from the insert and condense on the much cooler surfaces surrounding the insert.[15] Little or none of the evolved material will remain on the surface long enough to react there. In the hollow cathode, the cylindrical geometry and the large area fraction of the insert relative to the total surface area in the cathode will result in the collection of free materials onto other regions of the insert rather than on other surfaces. Additionally, the high local pressure resulting from the xenon flow and restricting orifice will keep much of the evolved material in place. Reactions with local elements and subsequent oxide formations are to be expected.

The Ba-containing layer can be deleterious to cathode operation for two reasons. First, the layers can act as reaction zones for the formation of compounds that lock up the elements necessary for work function lowering process (i.e. Ba, O). This includes the formation of poison compounds. Second, these layers can also impede the normal impregnate decomposition process within the insert by preventing the migration of Ba and Ba-O from the interior of the insert to the surface for the work function lowering process.

Tungstate Formation

The Ba and other deposited components (including tungsten) will react with elements in the Ba-containing layer and the underlying insert surface. At the elevated temperatures of the insert, the elements will eventually evolve into barium tungstates and aluminates, of which $BaWO_4$ is the most stable form at the typical hollow cathode operating conditions. The formation of these tungstates are expected under normal insert operation.[16] In the case of the 28,000 hour life test cathode, X-Ray microanalysis of the insert surface detected the extensive presence of tungstates on the insert surface, with primarily Ba_2CaWO_6 near the downstream end and $BaWO_4$ dominant at the upstream end. While $BaWO_4$ will be completely inert at the cathode operating temperature, it is not clear if the Ba_2CaWO_6 will continue to react and assist the work function lowering process.[17]

The barium tungstate composition of the surface layers indicated that a substantial portion of the insert was not able to support the work function lowering process at the selected operating conditions, thereby appearing to be depleted of barium. It is estimated that the size of the surface area that remained available for electron emission at the end of the life test was approximately 0.5 cm ± 50 % along the axis of the insert.

Barium Content in Insert Past hollow cathode lifetime models have suggested that the amount of barium in the insert has been depleted, thereby accounting for the cathode ceasing operation.[8,9] However, this was not the case here. Elemental analysis of the insert interior for the 28,000 hour life test cathode indicated that there was an ample amount of Ba within the insert.[12] Since chemical composition information was not available and extremely difficult to acquire, the amount of Ba available for further insert operation is presently unknown.

It is expected that some of the Ba will be in tungstate or aluminate compounds as part of the normal insert chemistry.[10,16] Excessive formation of these compounds inside the insert, particularly in a reaction layer that forms the interface between the impregnated interior and the open pores near the surface, inhibits Ba release from the impregnate material, thereby preventing reduction of the surface work function in that region. It is suspected that significant formations of these compounds are present in the downstream end of the insert, where the crystalline tungsten depositions were observed. Additionally, usable Ba may not be available because it is trapped within the insert by the Ba-containing layers formed on the upstream surface. Therefore, while ample Ba can be present in an insert, its form and access to insert surface may be inadequate to maintain the work function lowering-processing. Consequently, Ba depletion can appear to have occurred because the Ba is no longer usable under present operating conditions. Barium is expected to become available if the insert temperature is increased sufficiently to drive the decomposition of the existing compounds thereby releasing Ba and Ba-O to the surface.

Hollow Cathode End-of-Life

For the 28,000 hour life test, the hollow cathode stopped functioning because an ignition voltage in excess of 1000 V or increased cathode heater power were required to operate.[12] Additionally, the cathode temperature had exceeded its maximum allowable value. Therefore, further life of this hollow cathode could only be obtained by increasing the range of operating conditions.

Under any testing conditions, the mechanisms responsible for the surface and bulk insert chemistry necessary for insert operation are the interrelated

factors of barium and oxygen availability and insert temperature.

Barium Availability

The barium supply is determined primarily by the insert temperature and indirectly by oxygen availability because these factors drive the thermochemistry that releases the Ba from the impregnate. Because of this dependency and the fact that the amount of Ba, in either elemental or compound forms, had not been significantly reduced in the 28,000 hour cathode insert, barium availability appears to be a consequence of hollow cathode operation.

Oxygen Availability

Oxygen is a significant component in the impregnate material and is necessary for the formation of the Ba-O dipole structures responsible for the lowered work-function[16] as well as for the formation of tungstates and aluminates, which are the main end products of the impregnate chemistry. The tungstates and aluminates are also considered to be insert poisons at typical operating conditions.

There are two possible sources for oxygen that can react at the insert surface. These are contamination of the xenon gas upstream of the cathode and oxygen release from the insert (impregnate and sintered tungsten matrix).

Oxygen contamination can come from impure xenon or gas feed system leaks or outgassing, which result in high oxygen content reaching the insert. This contamination has resulted in cathode failure and degradation.[18,19] During the 28,000 hour life test, no direct evidence was found that any oxygen contamination had occurred (i.e. no feed system failures or no rapid changes in cathode operation). Post-test point-of-use purity measurements showed the xenon gas to be within the defined purity limits. Since no abnormal chemical or physical changes or unique phenomena were observed, the total amount of oxygen at the surface likely did not significantly exceed that expected to be released by the insert. Therefore, oxygen contamination was not believed to limit cathode lifetime.

The second source of oxygen is the significant amount available within the impregnate.[15,20] This oxygen includes that released during the normal decomposition of the impregnate at high temperature. Additionally, it has been estimated that 200-300 ppm of oxygen is trapped in the sintered tungsten of the insert during fabrication.[15] The oxygen will be released within the insert during operation and thereby contribute to the insert chemistry. Besides being a relatively significant oxygen source, oxygen release from within the bulk material and reaction at the insert surface is an inherent part of the impregnate decomposition that enables the work function-lowering process.

While these sources of oxygen are an issue for all types of dispenser cathodes, in a hollow cathode the oxygen will be contained to the insert region for a relatively long time as discussed previously. This containment enhances the surface chemistry in a fashion that is unique to the hollow cathode.

Temperature

While oxygen is necessary for insert chemistry, it is the temperature that drives the chemistry at the insert.[10,16] This includes both the Ba and Ba-O release to lower the work function as well as the formation of barium tungstates. For a hollow cathode, the temperature is determined primarily by the operating emission current, which, in conjunction with xenon flow rate, determines the total power deposited on the cathode. Secondary parameters which can effect the operating temperature including the cathode and orifice configuration (i.e. diameter and thickness, size), energy loss processes (i.e. radiation losses), and anode coupling area.

The recommended operating temperature range for long life of the impregnate material is 950-1,150 °C,[21] with 1,050 °C as the nominal target. For the 28,000 hour cathode, the nominal orifice plate temperature was approximately 1,150 °C up to hour 22,000, after which the temperature stabilized again at 1,220 °C for approximately 4,000 hours before exceeding 1250 °C at test's end.[1] In reference 9, the insert temperature was determined to be lower than the cathode tip temperature by as much as 200 °C at a discharge current of 10.6 A. Therefore, it is possible that the 28,000 hour cathode test was operated in the recommended insert temperature range.

The temperature sensitivity of the insert material lifetime is significant. It is estimated that there is a factor of two reduction in lifetime for every 40 °C increase in temperature.[15] Consequently, at 1,150 °C, the expected lifetime for a vacuum tube cathode with identical insert material is estimated to be approximately 200-400 hours.[15] The shortened lifetime estimate is attributed to rapid formation of barium tungstates and aluminates which can stop insert operation.

For the 28,000 hour life test cathode, either the insert was significantly cooler than the measured orifice plate temperature or different chemical reactions were occurring. The lack of quantification of the chemical reactions taking place on and in the insert prevents determination at this time of the actual mechanisms. Regardless, the final result was that this cathode was operated at conditions that likely resulted in an insert temperature that limited the lifetime to 27,800 hours.

The initial conclusion is that operating a cathode at a lower temperature should inhibit the formation of poisoning compounds, thereby extending cathode lifetime. However, lowering the operating temperature would also slow the work function lowering process, which might make the cathode more difficult to operate. The deleterious effects of cooler operation are discussed below.

End-of-Life Condition

It can be concluded from the above discussion that the hollow cathode lifetime is determined wholly by the cathode operating conditions (assuming no external contamination occurs). These conditions determine the insert temperature, which establishes the chemical reaction rates in the insert. Based on temperature and cathode geometry factors, and using the 28,000 hour life test cathode as representative of a hollow cathode's final stage, a scenario for cathode operation and its EOL was developed.

End-of-Life Scenario

The following three-stage scenario for insert chemistry evolution is proposed for operation under steady state conditions.

The first stage, illustrated in Figure 5, occurs during the initial operation of the cathode when the insert surface stabilizes for steady-state electron emission. Electron emission will start at the downstream end of the insert and the orifice plate interior.[22] Morphological changes to the insert will occur during this time as the insert surface is modified by barium release (as either Ba or Ba-O gas), which reacts with the matrix tungsten. As the surface condition (emission zone) stabilizes, cathode operation also stabilizes, which may be indicated by decreasing operating temperature. The stabilization time required by the cathode may vary from 10s of hours to more than 1,000 hours, depending on the operating conditions. For the 28,000 hour life test cathode, this stage probably lasted until at least 500 hours, and may have lasted up to 3,000 hours, as estimated from Fig. 2.

The second stage begins once the insert surface has stabilized for operation on the test conditions. During operation, the electron emission is believed to occur at a region of the insert surface whose size is determined by the operating conditions but which is smaller than the insert surface area,[22] as illustrated in Figure 6. This emission zone will move further upstream during the life test because the downstream region can no longer maintain the low work function surface as well as the upstream regions. The emission zone is expected to maintain a relatively stable size as it shifts upstream because of the steady-state operating conditions. The downstream region degrades because the operating temperature can no longer drive the decomposition of the impregnate material in this region sufficiently to produce the barium needed to maintain the low work function surface. Because barium release to the surface is reduced, if not stopped, the tungsten can collect on the now cooler surfaces and form metallic crystalline structures, as has been observed. This stage two behavior will be maintained as long as the emission zone can move upstream to regions that can maintain a low work function surface.

The third stage begins when the emission zone shifts to surface regions that cannot provide the barium needed to maintain the low work function at the operating conditions. Barium production is inhibited in this region because of the Ba-containing layer formation, which prevents the low work function surface from forming on upstream insert surface.

Because the upstream surface has been degraded, the size of the emission zone will decrease, as illustrated in Figure 7. Consequently, the current density will increase to satisfy the operating requirements, which results in an increased temperature at the emission zone. At higher temperatures, barium release mechanisms will resume again on some of the insert surfaces, in particular the upstream layers. However, these higher temperatures also accelerate impregnate decomposition and tungstate and aluminate formation, resulting in more rapid consumption of available barium. Therefore, the hollow cathode is not expected to be able to maintain stable operation for extended periods, once the third stage has been reached.

For the 28,000 hour life test cathode, the third stage appears to have begun at hour 22,000 and stabilized at hour 23,800 where it subsequently operated stably for approximately 4,000 hours. The ignition voltage increased significantly by hour 23,800, which would be expected if the insert could no longer produce the nominal low work function surface. The insert surface degradation appeared to continue, as suggested in the continually increasing ignition voltage, while the cathode operating parameters (i.e. voltage) are relatively stable. By the end of this 4,000 hour period, the device was no longer able to operate at the specified conditions. While it is expected that further operation would have been possible if the operating conditions were extended, the life test was stopped.

Another change observed with the 28,000 hour life test cathode was that the minimum operating current that the device could support had increased from approximately 2.5 A to approximately 5.0 A by the end of the test. This increase indicated that the insert work function was degraded and required the higher temperature achieved at 5.0 A emission current to establish a stable emission surface, which is consistent with the cathode behavior and post-test insert examination.

Impact on Hollow Cathodes

There are three consequences of this proposed scenario that will be addressed now. The first of these are methods to extend hollow cathode lifetime based on the findings presented herein.

Lifetime Extension

Because of the first-order dependency of the insert chemistry on temperature, the operating temperature must be decreased to slow the life-limiting insert

chemistry, and thereby maximize lifetime at steady-state conditions. While the magnitude that the temperature must be decreased cannot be quantified, in the vacuum tube experience, a reduction of 50 °C in insert temperature could result in a significant increase in operating lifetime.[15] There are several possible ways to reduce the operating temperature. These include:

- Lower operating current.
- Modify cathode geometry.
- Decrease the xenon flow rate.

There are two negative factors associated with a lowered operating temperature that should be considered. First, this change can cause a degradation of the cathode performance at a fixed set of conditions. This occurs because the work-function lowering process will also be slowed at the lowered temperature. Consequently, a hollow cathode may encounter instabilities in the operating parameters (voltage, current) which may be unacceptable for mission requirements. Besides single point operation, the throttlable range of a hollow cathode might be reduced. Cathode performance must be characterized over the throttling range to ensure that the insert temperature remains in the recommended range of 950 to 1150 °C.

Second, the insert chemistry may be too complex for lifetimes to scale directly with temperature. While lower temperatures should slow the formation of life-limiting compounds on an insert, too low (< 950 °C) an operating temperature will inhibit the barium release mechanisms and result in shortened usable lifetimes. The optimum temperature for maximizing insert lifetime is unknown for hollow cathode applications although many extended tests have been very successful by ensuring the insert temperature is in the 950 °C to 1150 °C range.

Lifetime Assessment

Another consequence of the proposed scenario for cathode EOL is that several qualitative methods for determination of cathode lifetime present themselves. These will be separated into in situ and post-test approaches. While these approaches presently provide only crude and qualitative determination of the remaining cathode lifetime, they should be viewed as starting points to the development of accurate, in situ lifetime assessment techniques.

In Situ Techniques

In situ monitoring of cathode operating parameters may be used to determine in which of the three stages of cathode evolution a hollow cathode is presently operating. In particular, cathode temperature and ignition behavior appear to be strong indicators of cathode operating status. This is demonstrated with the 28,000 hour life test cathode where the temperature and ignition voltage started rising after approximately hour 22,000. Cathode voltage was not a strong indicator of changing cathode conditions for this configuration. In general application, increasing temperature and ignition requirements may be taken to mean that the hollow cathode has reached the third stage of operation, as defined above. A cathode is expected to be able to operate at the required conditions after reaching this stage, but the remaining lifetime is presently unknown.

Post-Test Evaluation

During post-test physical examination of the insert, its surface condition can be used to assess the potential lifetime capability for a wear test cathode (that has not been tested to End-of-Life). The first feature to examine is the amount of available insert surface area that can still produce or can be expected to produce a low work function surface. This could be done microscopic examination to determine if the insert surface has been coated with Ba-containing layers or by direct work function measurements on the surface. In addition, the condition and composition of any features on the insert surface should be investigated. Features to look for would include the size and degree of metallic tungsten deposited at the downstream surface of the insert and orifice plate as well as identification of the composition of Ba-containing layers at the upstream end. Also, microscope elemental and compound analysis can be performed to determine composition of Ba-containing layers, and in particular, one should look for barium tungstates. If a large portion of the insert surface is relatively free from deposits, then it may be expected that there is relatively long life remaining in the insert. Conversely, if large areas of the insert are covered with amorphous layers containing barium tungstates, then the insert could be near the end of its usable lifetime.

Effect of Operating Conditions

The scenario presented in this paper is derived from primarily from the results of a cathode life tested at steady state conditions. In this test, the emission current was fixed at 12.0 A for the duration. Because most applications require that the hollow cathode operate at two or more emission current settings during its life because of changing mission profiles or power availability, the effects on changing operation will be addressed briefly. Because of the temperature dependence of the insert chemistry, it is apparent that an operating profile where the emission current increases with time, thereby resulting in increasing operating temperatures over time, would be the simplest way to obtain the longest lifetime from a cathode. In this application, the cathode would be operated at a steady-state condition until it reached EOL, at which time the emission current would be raised. With the increased current, and subsequently temperature, the insert chemistry could be extended beyond the point where it would have been limited at a fixed set of conditions. This extension may include temperatures exceeding 1250 °C, the maximum temperature of the 28,000 life test, because higher temperatures would drive decomposition of impregnate

products that are nominally inert (i.e. barium tungstates) at typical hollow cathode conditions. While increasing temperature is not expected to continually increase operating life because life-limiting chemistry will also be driven at increased rates, it is likely to be the most expedient way to achieve the maximum insert lifetime.

Conversely, applications that require decreasing emission current over time(i.e. planetary spacecraft) or two or more emission currents that change cyclically with time(i.e. plasma contactor for orbital spacecraft) should consider the temperature dependence of the insert chemistry because decreasing temperature resulting from the lower current(s) will be unable to drive the impregnate chemical reactions at the same rates of the higher temperature condition. Further, emission capability at lower temperatures could change with time and would have a direct impact on cathode lifetime. Such a change is believed to be responsible for the increased minimum emission current limit of the 28,000 hour life test hollow cathode discussed above. For that device, operation became unacceptably unstable at emission current less than 5.0 A. Consequently, the operating profile of any hollow cathode must be considered when assessing lifetime capabilities.

To mitigate any detrimental effects on cathode lifetime, a thorough thermal characterization of a hollow cathode should be undertaken to accurately determine its limits of operation over the required conditions.

Concluding Remarks

While there is an increasing body of evidence that hollow cathodes have the lifetime necessary for present applications, this evidence had to be obtained empirically. There is no method presently available that has been demonstrated to be able to predict the hollow cathode End-of-Life. Previous attempts to model cathode lifetime relied on projections of barium depletion rates within the insert, which were never validated with a life-tested hollow cathode using an impregnated insert.

To address this limitation, a scenario for the chemical evolution of the insert under steady-state operating conditions is proposed. This scenario postulates hollow cathode evolution based on probable physiochemical reactions at the insert surface and within the insert body. Extensive examination of several wear and life tested hollow cathodes revealed similar physiochemical phenomena occurring inside the cathode. These phenomena included tungsten deposition, Ba-containing layer formation, and tungstate formation. Using the condition of a hollow cathode operated until its End-of-Life after 28,000 hours as a guide, the evolution of the insert chemistry is proposed to have occurred in three distinct phases. These phases are shown to be responsible for observed changes in cathode operation.

Using the observed changes as indicators of cathode evolution, assessing the remaining lifetime may be possible for operating hollow cathodes. While the techniques for lifetime assessment proposed in this report are presently qualitative, further refinements are expected to enable better fidelity lifetime assessments.

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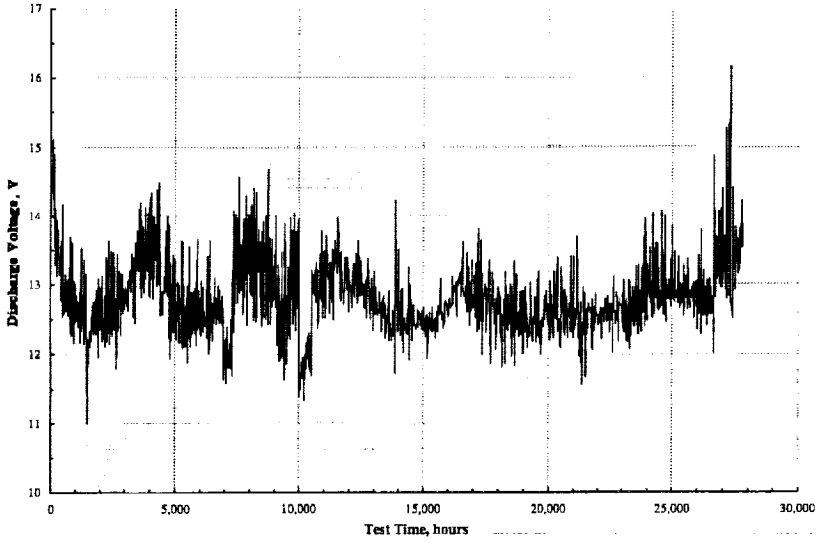

Figure 1. Discharge voltage during the 28,000 hour cathode life test. Voltage was measured at vacuum facility flange with digital voltmeter.

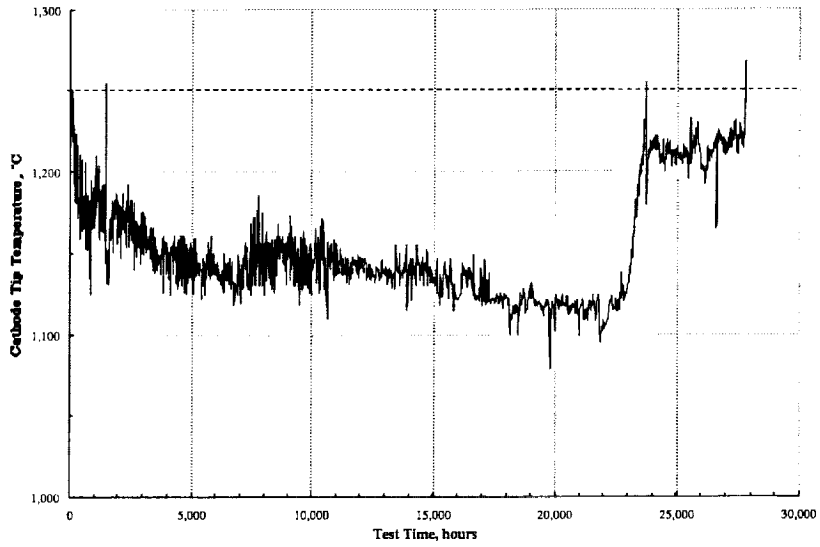

Figure 2. Cathode tip temperature during the 28,000 hour cathode life test. Temperatures were measured with a disappearing filament pyrometer. Indicated temperatures were corrected via calibrations with thermocouple measurements at cathode tip. The dashed line indicates the maximum temperature limit for the life test.

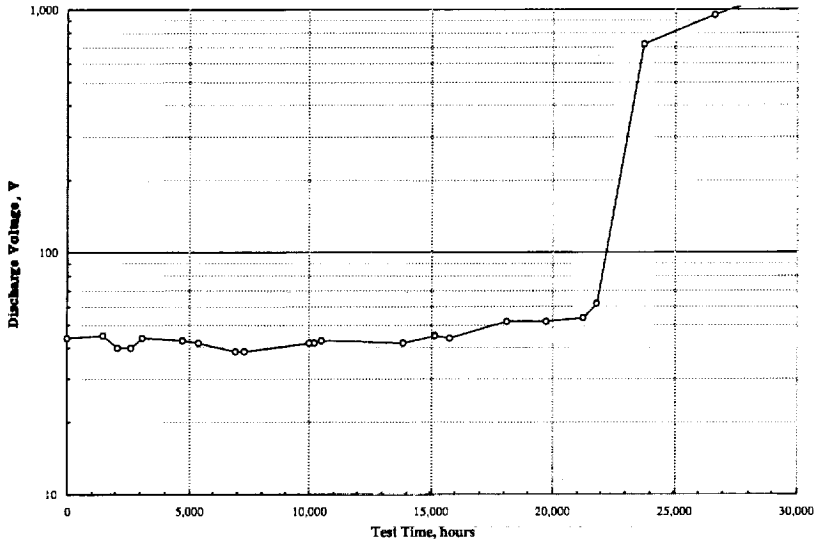

Figure 3. Ignition voltage at breakdown during the 28,000 hour cathode life test. For ignition, a DC voltage was ramped while the cathode was heated until the discharge lit. Voltage was measured at vacuum facility flange with digital voltmeter

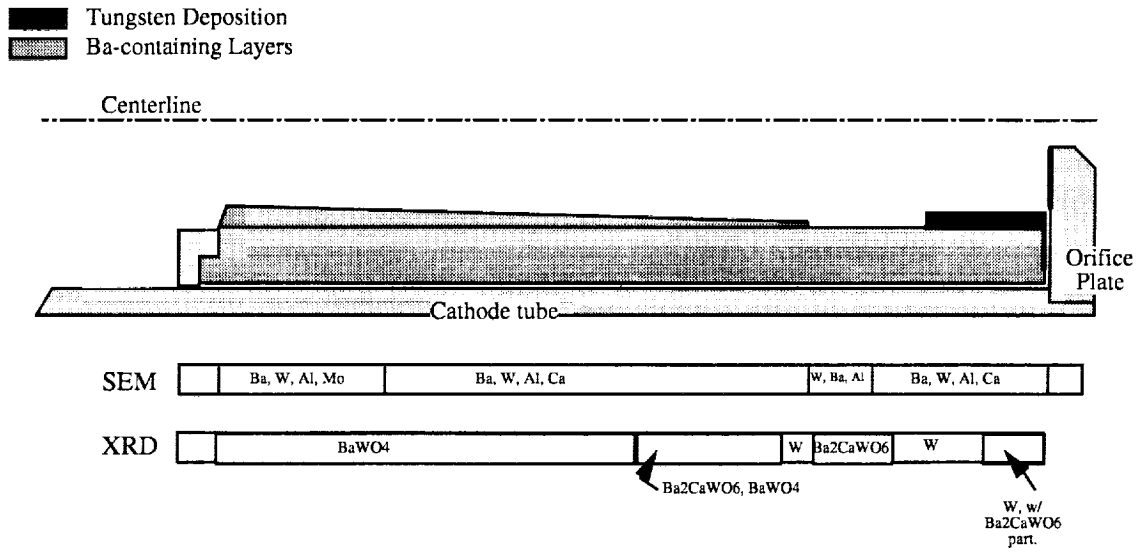

Figure 4. Schematic of observed phenomena on the post-test 28,00 hour life test cathode insert. The insert, orifice plate, and deposition geometry are not to scale. Azimuthal symmetry is assumed.

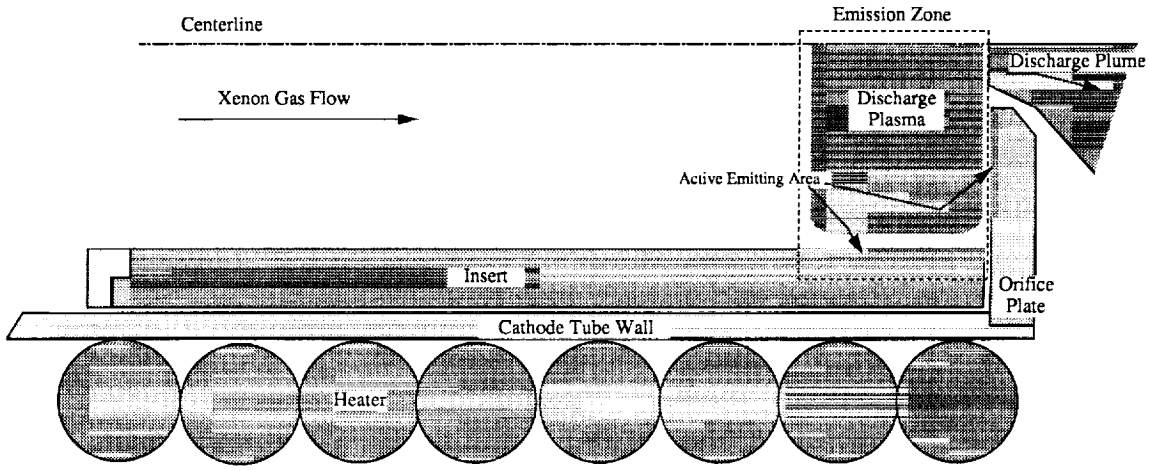

Figure 5. Stage 1 of End-of-Life Scenario: Initial operation of the cathode where insert chemical processes are being established as the discharge stabilizes. The features of the cathode are not to scale. Azimuthal symmetry is assumed.

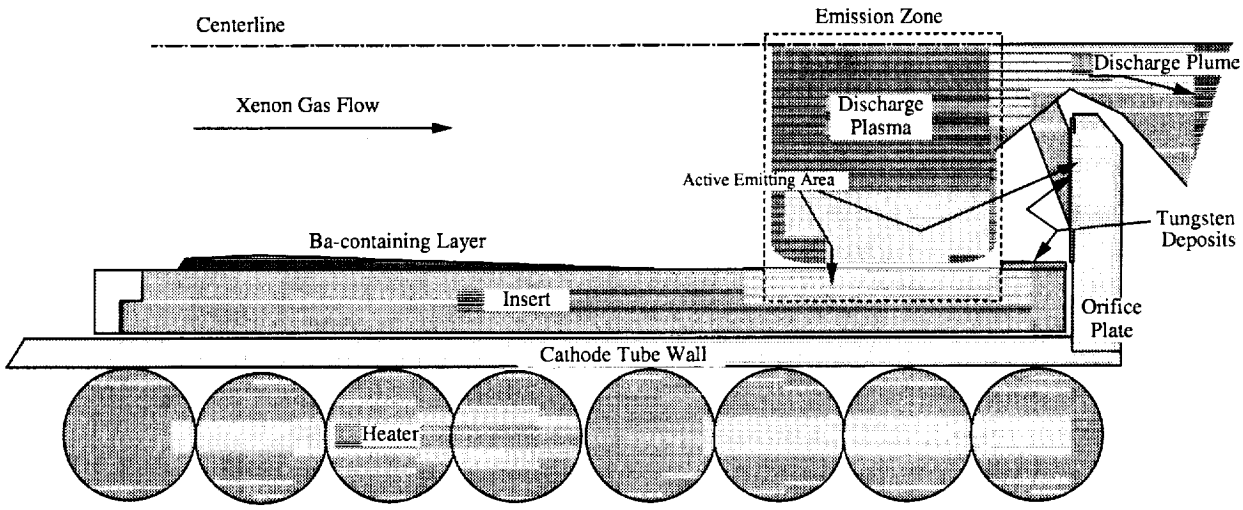

Figure 6. Stage 2 of End-of-Life Scenario: Primary operating mode of cathode where the discharge occurs over emission zone with nominally constant size. The emission zone is expected to shift upstream over the course of the life test. The features of the cathode are not to scale. Azimuthal symmetry is assumed.

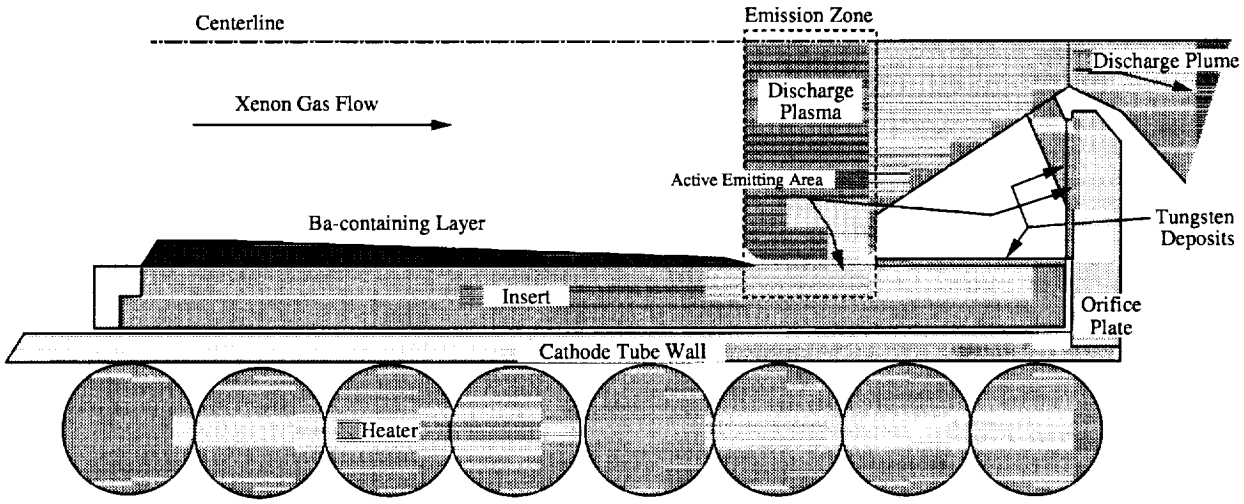

Figure 7. Stage 3 of End-of-Life Scenario: Final stage of stable operation at fixed conditions, where the emission zone is shrinking because of surface degradation due to Ba-containing layer formation. The features of the cathode are not to scale. Azimuthal symmetry is assumed.

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13. ABSTRACT ***(Maximum 200 words)***

Recent successful hollow cathode life tests have demonstrated that lifetimes can meet the requirements of several space applications. However, there are no methods for assessing cathode lifetime short of demonstrating the requirement. Previous attempts to estimate or predict cathode lifetime were based on relatively simple chemical depletion models derived from the dispenser cathode community. To address this lack of predicative capability, a scenario for hollow cathode lifetime under steady-state operating conditions is proposed. This scenario has been derived primarily from the operating behavior and post-test condition of a hollow cathode that was operated for 28,000 hours. In this scenario, the insert chemistry evolves through three relatively distinct phases over the course of the cathode lifetime. These phases are believed to correspond to demonstrable changes in cathode operation. The implications for cathode lifetime limits resulting from this scenario are examined, including methods to assess cathode lifetime without operating to End-of-Life and methods to extend the cathode lifetime.

14. SUBJECT TERMS

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