Life Model for Lanthanum Hexaboride Hollow Cathodes for High-Power Hall Thrusters

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Lanthanum hexaboride (LaB_6) hollow cathodes have been in development for space applications for many years. The life of the LaB_6 insert in these hollow cathodes has previously been evaluated using a simple constant-temperature insert-evaporation calculation. A detailed investigation of the life of a 1.5-cm outside-diameter LaB_6 hollow cathode operating at 25 A of discharge current has been made. In-situ insert temperature measurements are used in a 1-D disk evaporation model that accommodates the insert axial temperature profiles found at different discharge currents and flow rates to predict the insert evaporation rate and life. The evaporation rate is compared to date from a 4000-h discharge wear-test of a laboratory model cathode, where insert weight loss measurements were made at the start, middle and end of the test. The results suggest that there is significant insert outgassing early in life, but redeposition of the evaporated lanthanum inside the hollow insert reduces the net evaporation rate, extending the cathode life. This 1.5 cm cathode is projected to exceed 50,000 hours of operation at the nominal 20-25 A of discharge current used in high power Hall thrusters such as the HERMeS 12.5-kW thruster.

Nomenclature

A	=	coefficient in Richardson-Dushman equation [A/cm^2K^2]
B	=	constant in Lafferty evaporation model = 36,850 K
C	=	constant in Lafferty evaporation model = 13
e	=	electron charge [Coulombs]
k	=	Boltzman's constant [J/°K]
J	=	thermionic emission current density [A/cm^2]
T	=	temperature [K]
W	=	evaporation rate [$gm/cm^2/s$]
ϕ	=	insert work function [eV]

I. Introduction

Electric thrusters are being developed by NASA for primary propulsion for a wide range of for robotic and human exploration deep space missions. Lanthanum hexaboride (LaB_6) hollow cathodes have been in development for several years at JPL for high-power Hall thruster applications[1,2]. LaB_6 hollow cathodes have demonstrated discharge current capabilities from 5 to 300 A, and different versions have successfully operated in Russian and American Hall thrusters for many years. A large reason for the application of these cathodes in flight systems is the high current capability and extreme robustness of this cathode material against poisoning from impurities in the flight-system propellant system or from air exposures during testing. In

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addition, lanthanum hexaboride hollow cathodes have calculated lifetimes from tens to hundreds of thousands of hours depending on the size of the cathode and the discharge parameters.

The LaB_6 hollow cathode described in this paper[3,4] is being investigated for the HERMeS Hall thruster[5,6] in development by NASA Glenn Research Center and Jet Propulsion Laboratory. This Hall thruster is magnetically shielded[7] to provide sufficient life and throughput for the mission, and has been tested at over 12.5 kW at voltages between 300 and 700 V. A large throttle range is also required by the mission, which places a requirement on the cathode to produce nominally 9 to 32 A of discharge current for durations exceeding 50 kh (including margin). The LaB_6 cathode in development for this application runs nominally at 7.5 to 100 A, and the calculated life shown below exceeds 50 kh over the full range of discharge currents needed for the thruster.

The first life predictions published[4] for the HERMeS LaB_6 cathode were based on an emitter evaporation model that assumed a uniform insert temperature. Recent insert temperature tests by Polk[8] at JPL showed that the insert temperature is relatively uniform when using a 5-mm dia. cathode orifice, but the present 3-mm cathode orifice installed to extend the throttle range of the hollow cathode causes a significant temperature and internal plasma density gradient to exist along the length of the insert. The life model was modified to a 1-D disk model, where the measured temperature profile was used to calculate the electron emission per disk and the absolute temperature was then adjusted so that the integrated emission current for all the disks matched the total discharge current. The model was iterated to produce the correct total discharge current and provide emitter evaporation rates for each disk based on the original evaporation data of Lafferty[10]. The evaporation profile and total evaporated material from this model is then used to predict the cathode life.

Two wear tests were also performed on this cathode to verify the insert life model. The first was a 4000 hour test in a laboratory simulator of the thruster[8] using propellant grade (99.995% purity) xenon. This test was stopped at 2 kh to measure the insert erosion, and then restarted and run to 4000 h. The second test was an 1800-hour test of an identical cathode using a propellant grade xenon that contained 10 ppm oxygen, intended to simulate worse case flight system impurity levels. The cathodes ran normally for the full duration of these tests, and were then disassembled and the inserts weighed and measured to determine the evaporation rate for the life model. The results of these two tests were previously reported[7].

In this paper, we present a description of the new insert life model for the 1.5-cm LaB_6 cathode and the test measurements used to establish the temperature of the insert and benchmark the model predictions of insert evaporation. The measurements and model results are then used to predict cathode lifetime and demonstrate its applicability for use in high power Hall thrusters.

II. Cathode Configuration, Setup and Characterization

A. LaB_6 Cathode Configuration

Lanthanum hexaboride was first developed as an electron emitter by Lafferty[9] in the 1950's and its characteristics extensively described in our previous publications. Lanthanum hexaboride is a crystalline material made by press-sintering LaB_6 powder into rods or plates and then electron-discharge machining the material to the desired shape. Polycrystalline LaB_6 cathodes have a work function of about 2.67 eV depending on the surface stoichiometry[10], and will emit over 10 A/cm^2 at a temperature of 1650 ˚C. Since the bulk material is emitting, there is no chemistry involved in establishing the low work function surface and LaB_6 cathodes are insensitive to propellant impurities[11] and air exposures that would normally destroy a BaO dispenser cathode. In addition, the cathode life is determined primarily by the evaporation rate of the bulk LaB_6 material at typical operating temperatures[12]. The higher operating temperature of LaB_6 and the need to make contact with LaB_6 with compatible materials has perhaps unjustly limited their use in the US space program.

The major reason for using LaB_6 cathodes, as compared to conventional impregnated dispenser cathodes, is the incredible robustness, high current density and long life exhibited by LaB_6 electron emitters[13]. Lanthanum hexaboride cathodes are routinely used in all noble gases from helium to xenon, reactive gases including hydrogen and oxygen, and various other materials including liquid metals such as bismuth. LaB_6 cathodes have even been successfully used in oxygen and nitrogen plasma discharges at emission current densities exceeding 20 A/cm^2, and vented to water vapor (from cooling lines breaking) and air during operation without damaging the cathode. Lanthanum hexaboride cathodes are ideally suited for high current operation in hollow cathodes because they operate at sufficiently high temperatures (>1600 ˚C) to radiate excessive heating from the high density insert plasma generated during high current operation. LaB_6 hollow cathodes have been successfully operated at over 800 A[14]. The space heritage of LaB_6 cathodes in Russian and US spacecraft is considerable, and the university and industrial experience in dealing with the higher operating temperatures and materials compatibility issues is extensive.

LaB_6 hollow cathodes intended for space applications have been described in many previous publications[1-4, 12-14]. A cross section of the laboratory-model cathode used in this work is shown in Fig 1. The hollow cathode consists of a LaB_6 thermionic emitter inside a molybdenum hollow tube terminated by a tungsten orifice plate. The insert is held in place against the tungsten orifice plate by a thin carbon pusher tube and a tungsten spring. To avoid diffusion of boron into the refractory metals, the insert is held in thin graphite cups that slip fit into the molybdenum tube. An alumina-insulated tantalum coaxial heater, which is capable of providing up to 300 W of heater power, is wrapped around the cathode tube and is used to preheat the insert to the emission temperature. The heater is thermally shielded by multi-layer tantalum foil and enclosed by a 3.3-cm-dia. graphite keeper used to initiate the discharge and as protection against erosion of the orifice plate from back-ion bombardment.

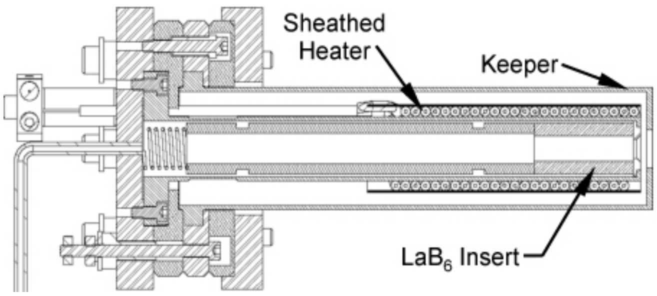

Figure 1. Schematic drawing of the 1.5-cm-dia. LaB_6 hollow cathode. The keeper O.D. is 3 cm in this version.

The 1.5-cm-dia.-insert laboratory model hollow cathode is shown in Fig 2. The cathode was previously tested[4] with cathode orifice diameters of 3 mm and 5 mm. The smaller orifice diameter was selected for wear testing because this also provides stable lower current operation down to 5 A of discharge without the need for additional keeper current to keep the cathode hot. The insert used for the experiment has an internal diameter of 0.63 cm and length of 2.54 cm, which provides an active emission area in contact with plasma at beginning of life of 5 cm^2. At a uniform temperature of 1700˚C, this cathode is capable of emitting up to 100 A of discharge current. If the temperature is not uniform, which is the case for the 3-mm orifice version, the cathode can still provide 100 A of discharge current, but regions of the insert will be hotter and evaporate faster.

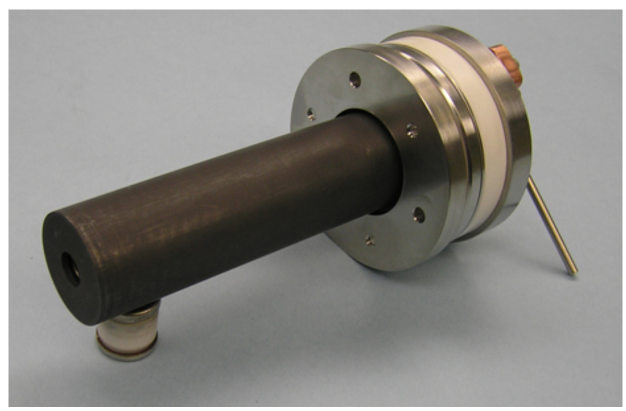
Figure 2. The prototype LaB_6 1.5-cm-dia. hollow cathode.

B. Experimental Setup

The LaB_6 cathode was tested in one of the JPL cathode-test facilities[15]. The facility has a 1-m diameter by 2-m long vacuum system that has 1250 l/s xenon pumping speed from 2 cryo-pumps that produce a base pressure of 1x10^{-7} torr. The cathode was tested in the wear-testing assembly shown in Fig. 3, which consists of a water-cooled anode with an integral solenoid designed to simulate the local magnetic field for a center-mounted cathode in this class of 5 to 20 kW thruster[4]. All of the discharge current and voltage characterization was performed in this setup. Separate experiments with a pneumatic probe mechanism that drives an internal scanning Langmuir probe[15] were made to determine the internal plasma density and temperature profiles, but will not be described here.

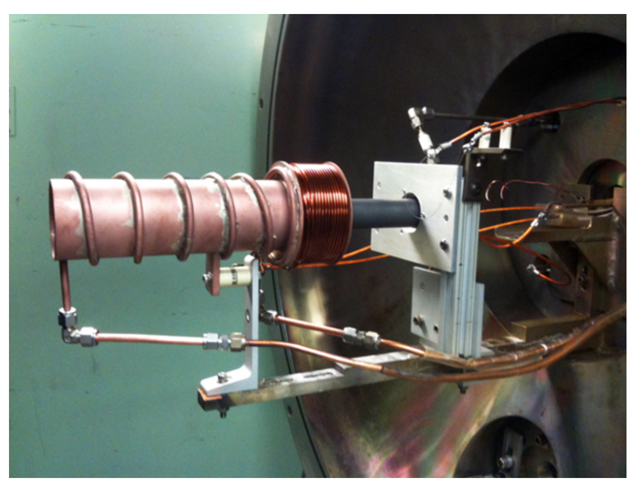
Figure 3. Cathode wear test configuration with anode on the left and cathode assembly on the right.

The cathode is normally installed in the facility and pumped down into the 10^{-6} torr range prior to testing. The heater is then turned on at typically 13 A for 18 to 20 minutes. The discharge is initiated by starting the gas flow rate, applying 150-V to the keeper, and regulating the keeper current to 2 A. Once the discharge begins, the heater is turned off and the anode power supply is turned on to the desired discharge current in the range of 5 to 35A. The anode voltage usually varies in the 15-25V range depending on the xenon flow rate. As soon as the anode current reaches the nominal value, the keeper power supply is turned off and the keeper allowed to float at a potential that varies between 5-20V. At this point the discharge current can be regulated and the cathode reaches a steady state in few seconds.

C. Insert Temperature Profiles

Of critical importance is the temperature profile along the insert length. Insert temperature measurements were previously taken by Polk[8] using three tantalum-sheathed thermocouples insert into holes drilled to different axial depths in the LaB_6 emitter wall. Since the insert wall is thin compared to the distance between the thermocouple end points, the temperature reading is an indication of the local surface temperature. Examples of the steady state temperature profiles inferred from these three thermocouples are shown in Fig. 4 at fixed mass flow rate and variable discharge current for the cathode configured with two different orifice sizes. The polynomial fits to the data in the figure are intended for visual interpretation of the data.

The absolute magnitude of the temperature in each profile is affected by sheathed thermocouple contact inside the insert wall and conduction along the sheathed thermocouple to the mounting feedthough at the back of the setup. This caused the measured temperatures in the first setup tested with the 5-mm dia. orifice cathode to be 50 to 100 ˚C lower than expected from the measured emitted currents. In addition, the magnitude of the temperatures tended to change with insert operation history (on-time duration and discharge operating condition). This is likely due to stoichiometry changes on the insert surface from preferential sputtering or redeposition of evaporated material causing changes in the work function with time. The work function is known to change depending on the stoichiometry[10] from LaB_9 (boron rich), LaB_6 (nominal surface state in vacuum), and LaB_4 (lanthanum rich). However, the temperature profiles didn't vary significantly during these changes at a given discharge current and flow, but simply shifted up or down in temperature.

Figure 4 (top) shows the insert temperature profile measured for the cathode with the 5-mm orifice. While the temperature between the two end thermocouple locations varied over 100˚C for the 10A case, and about 60˚C for the 35A case, it is very uniform (within 10˚C) for the 25A case. Insert temperature measurements of the cathode with the 3mm orifice are shown in Fig. 4 (bottom). In this case, the temperatures are lower than the actual values required to produce the measured emission current by about 200˚C, which was found to be due to a change in the mounting of the thermocouples. Subsequent tests with another mounting scheme caused the indicated temperature to increase to levels similar to the 5-mm orifice cathode case. However, the relative error between the thermocouple measurements is <5˚C and the temperature profiles were insensitive to these magnitude changes, so the profile information at a given discharge condition (current and flow) for each cathode orifice size can be used in the life model (below) for evaluation of the emission current and emitter evaporation rates.

A comparison of the temperature profiles and plasma density profiles[16] (not shown here) between the two orifice plate cases shows that as the discharge current decreases, the peak location both of the plasma density and wall temperature moves downstream, suggesting that the discharge moves deeper into the cathode. This behavior is generally true for cathode with lower internal pressures corresponding to larger orifice diameters[12]. With the smaller orifice, even at lower discharge current, the wall temperature tends to peak close to the orifice

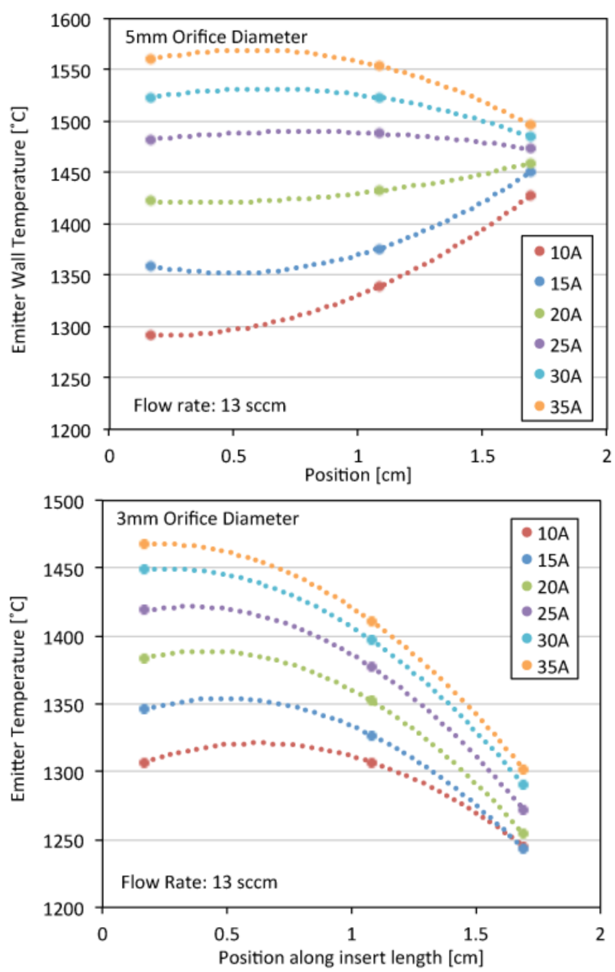

Figure 4. LaB_6 insert temperatures at three points for the two cathodes at constant xenon flow rate.

plate and decrease with distance from the orifice entrance. Using a smaller orifice then results in higher insert temperatures near the orifice plate at a given discharge current compared to the larger orifice size, but the additional orifice heating in the smaller orifice allowed stable operation to be obtained at lower discharge currents (down to 5-7 A) then with the larger cathode orifice.

III. Life Model

The life of LaB_6 cathodes is determined primarily by evaporation of the insert surface at the temperatures required for thermionic emission. Keeper erosion is another potential life-limiting factor, but is not discussed in this paper. The thermionic emission current density from the insert is given by the Richardson-Dushman[17] equation:

$$J = AT^2 \exp(-e\phi/kT)\ [A/cm^2]\ , \tag{1}$$

where T is the surface temperature in Kelvin. Lafferty[9] determined that for a LaB_6 surface in vacuum, A = 29 A/cm^{2}K^2, and the work function of LaB_6 is ϕ = 2.67 eV. Previously published lifetime models[4] of the LaB_6 cathode assumed a constant insert wall temperature due to the high thermal conductivity of LaB_6 and the use of a large cathode orifice diameter (as in Fig. 4 (top) at 20-30 A of discharge current) that produces a flat density profile inside the insert and relatively uniform heating. The old life model calculated the temperature of the entire insert inner surface area required to produce the discharge current, and used that temperature to calculate an evaporation rate using Lafferty's measured evaporation rate for polycrystalline lanthanum hexaboride in vacuum. Lafferty published[9] a model for the evaporation rate of LaB_6 that fit his data and is given by:

$$W = \frac{10^{(C-B/T)}}{\sqrt{T}}\ [gm/cm^2/s]\ , \tag{2}$$

where B and C are constants, which according to Lafferty are B=36,850 K and C=13. The old hollow cathode life model assumed (conservatively) that all the evaporated material left the insert region without any redeposition, and followed the change in the emission surface area as the inner diameter increased with time all along the length of the insert due to evaporation of the inner surface. As the insert ID increases, the required emission *current density* reduces with time, which lowers the temperature and evaporation rate. The model tracked the insert change with time, and the cathode life was considered over when there is no insert material was left or a pre-set minimum wall thickness resulted.

The temperature data[8] presented above showed that for the 3mm-orifice case, the assumption of uniform plasma density and heating is incorrect. Therefore, the life model was revised to incorporate the measured surface temperature profile by discretizing the emitter into a series of disks, as illustrated in Fig. 5, and uses the polynomial fit of the temperature data shown in Fig. 4 to assign a temperature for each disk along the emitter length. The model then evaluates the emitted current density from each disk using the Richardson-Dushman equation in Eq.1, integrates the emission and compares the integral of the current emitted from the entire insert length with the discharge current. If the total emission current does not match the discharge current, the code then shifts the magnitude of the temperature in the polynomial fit up or down until the emitted current reaches the discharge current used in the experiment. Note that this technique ignores Schottky effects and back-flowing electron current to the emitter surface from the tail of the Maxwellian distribution overcoming the cathode-sheath. The Schottky term is found to be small, and ignoring backflowing electron current is actually a good assumption[12] for low-pressure hollow cathodes like this because the sheath voltage is typically 3-5 times the electron temperature and the backflow electron current is negligible.

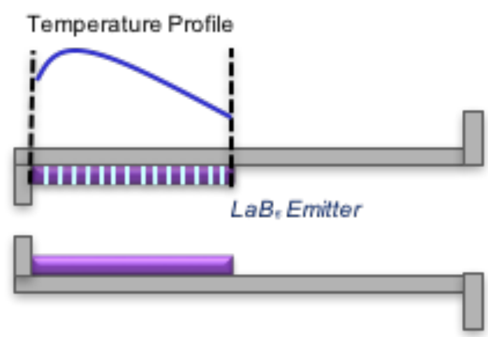

Figure 5. 1-D insert disk model.

The new life model's iterative approach to determining the surface temperature is necessary in order to use the Lafferty published[9] work function and evaporate rates. Once the temperature of each disk is established, the model calculates the evaporation rate at every position using Eq. 2 and determines the mass loss along the emitter length for a preset time step. The model increments the time and re-evaluates the total emitter material loss until the surface reaches a minimum defined thickness or all the material is evaporated to determine the lifetime of the cathode. If redeposition is to be considered, the model reduces the evaporation rate by a given value (either uniformly along the insert length or with some axial profile matching the plasma density profile) to match the measured net evaporation rate from the wear test data.

To validate the cathode life model, a wear test of the 3-mm-orifice hollow cathode operating at 25 A of discharge current at 14.8 sccm of cathode flow was performed for 4000 hours. The insert was first outgassed by inserting it into a heated graphite tube at 1500˚C for one hour in vacuum, weighing the insert, and repeating the vacuum-heating and weight loss measurements until the weight loss became negligible. Figure 6 shows the measured weight loss for each of these steps, where the final outgassing steps represented on a few mg of material lost. The total mass loss from outgassing process was 126 mg, which was about 1.4% of the insert mass. The LaB_6 insert material from the vendor is specified as 99% pure with no carbon present, but surface analysis of the inserts shows additional carbon material in the near surface region exists, likely left over from the press sintering fabrication procedure performed in a graphite boat. So this amount of outgassing of impurities and carbon is not unreasonable.

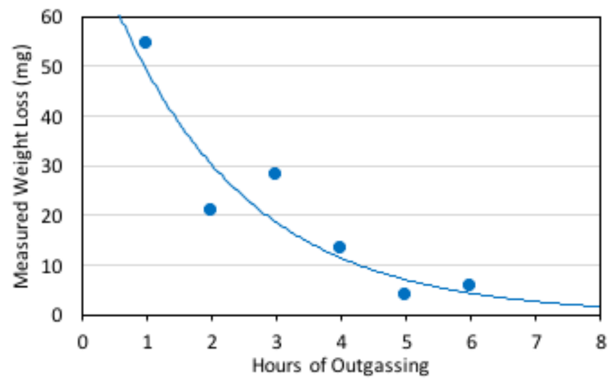

Figure 6. Insert mass loss per hour from outgassing in vacuum at 1500˚C.

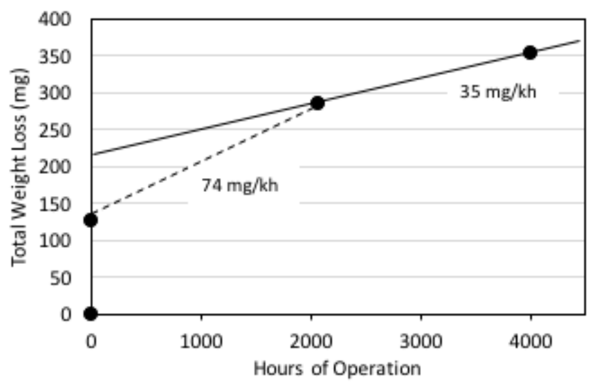

Figure 7. Insert mass loss per hour of operation during the wear test at 25 A of discharge current.

Figure 7 shows the insert mass loss as a function of time during the wear test. The outgassing weight loss of 126 mg is shown at the start. The additional measured mass loss from evaporation of the insert inner-diameter material at the completion of the first wear test phase (at exactly 2065 hours of operation) was found to be 152 mg. However, the mass loss in the second 2000 hr of operation was only 68.5 mg, so the apparent or net evaporation rate had decreased by over a factor of two in the second 2000-h test period. This suggests that additional outgassing was occurring early in the test, likely due to the higher insert temperatures (>1600˚C) required to achieve the required electron emission during plasma discharge operation. Since the plasma conditions were held constant during the entire 4000 h wear test, it is unlikely that the rate of any redeposition of the evaporated insert material back to the insert surface changed.

The life model prediction of the mass loss using Lafferty's evaporation rate model (Eq. 2) is shown by the red line in Fig. 8, and specifically is 165.5 mg at 2065 h in reasonably good agreement with the wear test result. The small reduction in the measured weight loss at 2065 h compared to the value predicted using the Lafferty evaporation rate is likely due to a balance between the outgassing and redeposition of some fraction of the evaporated insert material back onto the insert surface. After 4000 hours of operation, the total measured mass loss during the plasma operation was found to be 226 mg. The incremental mass loss between 2000 and 4000 h was measured to be only 68.5 mg, less than half the mass loss in the first phase of the test. Using Lafferty's evaporation rate from Eq. 2 and assuming all the evaporated material leaves the insert, the life model predicts a total of 302 mg of evaporated mass, which is significantly higher than the total wear test result.

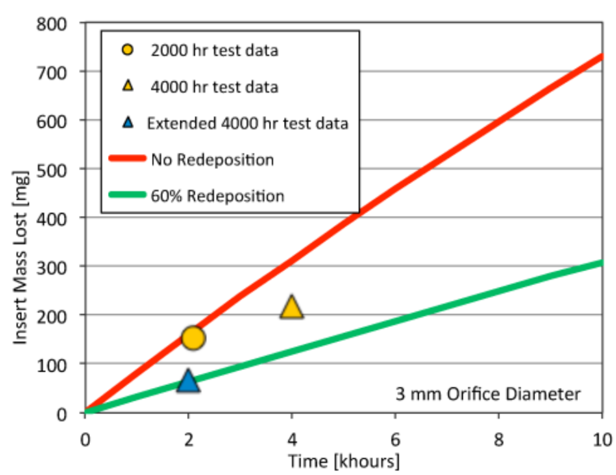

Figure 8. Insert mass loss from the long duration 4000 h wear test.

The lower mass loss in the second phase of the test is likely due to the actual net loss from the competing effects of evaporation and redeposition. The hollow insert geometry allows evaporated lanthanum neutrals to simply deposit on the opposite side of the insert ID, and the electric field in the insert plasma pushes any ionized lanthanum back onto the surface. Redeposition of lanthanum on the insert surface tends to form a layer of LaB_4, which has been reported to slightly decrease the work function of the emitting surface. Neglecting any work function changes, the life model predicts the observed 68.5 mg of mass loss of at the end of 2nd phase 2000 hours (blue point in Fig. 8) if 60% of the evaporated material is redeposited (green line).

Figure 9 shows the evolution of the diameter of the insert as a function of time predicted by the life model using the original Lafferty evaporation rate (top) and the wear test results with 60% of the evaporated material redeposited (bottom). If redeposition is neglected, the non-uniform temperature profile with the 3mm orifice causes the insert to evaporate rapidly at the downstream end to the full outside diameter at the front edge of the insert in 50 kh. This does not represent the end of life because experiments by Siegfried[18] showed that hollow cathodes can run with the insert spaced up to 1 cm back from the orifice plate, which is predicted to occur at about 60 kh in this cathode. Since this analysis does not take into account redeposition and the life model is only account for evaporation loss related to the measured temperature profile, this is a very conservative prediction for the minimum life of this cathode. With redeposition the insert surface evolves much more slowly and wall material remains even after 100 kh of operation.

The minimum wall thickness as a function of time predicted by the life model with and without redeposition is shown in Fig. 10. The minimum wall thickness using the Lafferty evaporation rates is zero at 50 kh associated with the downstream tip of the insert. With the observed 60% reposition from the 2nd phase of the wear test, the insert has over ¼-mm minimum wall thickness (again at the downstream tip of the insert) remaining at 100 kh, and the life is expected to significantly exceed this time.

It is interesting to evaluate the life of the LaB_6 cathode with a 5-mm orifice size running at 25 A. Due to the flatter temperature profile produced by the lower internal pressure, nearly half the insert thickness is predicted by the life model (with redeposition) to remain after 120 kh. Even if redeposition is complete neglected in this 5-mm orifice cathode operation, the minimum wall thickness is still found to be about 1 mm at 120 kh. The life of the cathode with the larger orifice and a more uniform temperature insert then greatly exceeds 100 kh.

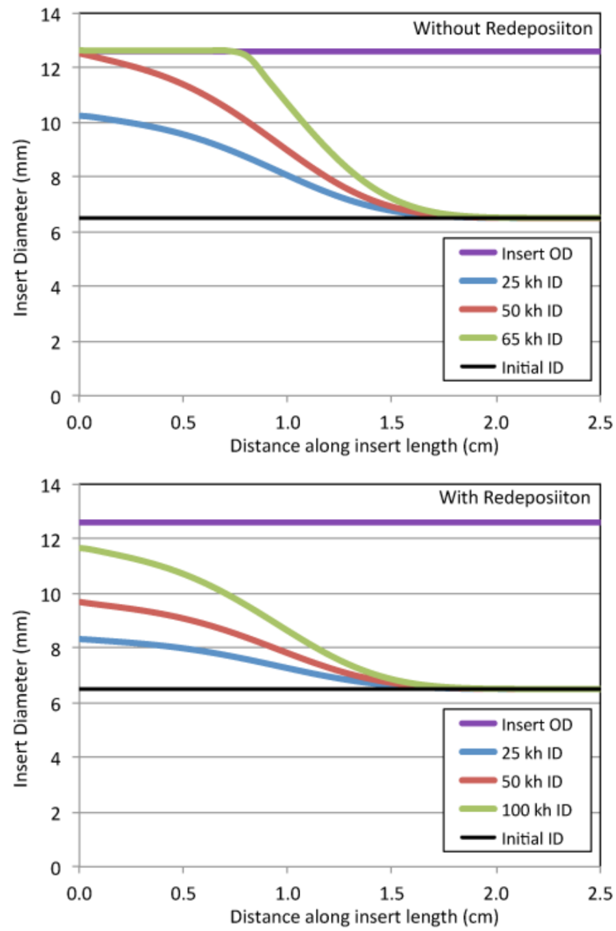

Figure 9. Predicted evolution of the insert diameter at 25 A using the Lafferty rate (top) and wear test data (bottom).

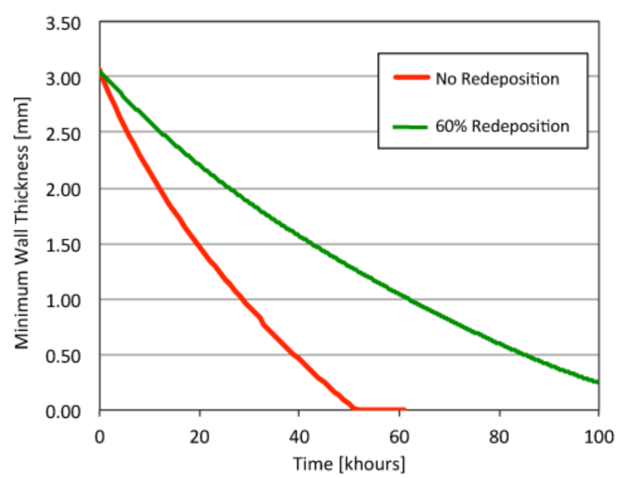

Figure 10. Comparison of the predicted minimum wall thickness with time at 25 A.

IV. Discussion

The life model described here uses measured temperature profiles, the measured work function of LaB_6, and measured evaporation rates as a function of temperature to calculate the insert temperature profile required to produce the measured discharge current, and to calculate an evaporation rate profile along the insert length. The lower mass loss than predicted by Lafferty during the second 2000 hours of the wear test is attributed to redeposition of evaporated lanthanum, and the model used Lafferty's work function (2.67 eV) and evaporation rate reduced by the wear test result in predicting the >100 kh insert life. The life of the cathode is reduced with a smaller cathode-orifice diameter due to the non-uniform insert temperature profile, and this disadvantage is traded against moving the throttle range of the cathode to lower current levels than achievable with the larger cathode orifice size.

One recent observation made while the taking new temperature profile measurements is that with a new insert that has not been operated previously in the plasma discharge, the temperature is >100˚C higher when first turned on (in good agreement with the temperatures expected from the Lafferty work function at the operating discharge current), and decreases over 20 to 50 hours to approximately the values shown in Fig. 4. It is possible that at the start of testing this is due to real LaB_6 on the surface, and after some ten's of hours the redeposition causes a lanthanum enriched surface (LaB_4) with a lower work function and a lower temperature. The lower mass loss in the wear test is then potentially the result of both redeposition and a lower surface temperature. Experiments are on-going now to observe this stoichiometry change and to characterize the LaB_4 surface and determine its parameters.

V. Conclusion

The laboratory model 1.5-cm LaB_6 hollow cathode has been developed and tested to evaluate cathode performance required by Hall thrusters that operate in the 5-20 kW range of power. This hollow cathode has a LaB_6 emitter with a total initial internal active emission surface of 5 cm^2, which provides stable discharge currents in the range 5-100 A. The cathode was tested with two different cathode orifice diameters over a large range in discharge currents and gas flows, and a life model based on measured temperature profiles and a 4000-h wear test with the smaller orifice size a discharge current of 25 A provides cathode insert life predictions. Using the most conservative evaporation rate based on data from Lafferty in the literature and assuming that all the evaporated material leaves the system with redepositing on the insert, the cathode with 3-mm orifice diameter has a projected life at 25 A of discharge current in excess of 50 kh. Weight loss data from the second half of the 4000-h wear test suggested significant redeposition of the evaporated insert material occurs and reduces the net evaporation rate by about 60%. In this case, the cathode life is predicted to exceed 100 kh. The same hollow cathode geometry with larger 5-mm orifice easily achieves more than 100kh of operation for both evaporation and redeposition cases. Work is on-going to further validate the characteristics of the redeposited surface insert temperature profiles and insert evaporation rates used in the life model.

VI. Acknowledgments

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