Hollow Cathode Life Time Model

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In this paper the latest advances in the hollow cathode lifetime modeling carried out at the University of Southampton will be presented. A barium oxide insert depletion model and a surface low work function compounds deposition/depletion model have been already developed by the authors. Here a procedure to update the plasma parameters relatively to changes of the hollow cathode surface work function and an end-of-life criterion will be presented. The procedure has been validated with experimental results and then coupled with the deposition/desorption model already developed by the authors. The evolution of the surface of the cathode tested for 28,000 hours by Sarver-Verhey has been simulated and from the data obtained an end of life criterion has been developed. Then using this criterion the ELT NSTAR discharge cathode has been simulated under the throttling conditions used during the Deep Space 1 Spare Ion Engine. The lifetimes found are in agreement with the theoretical expectation.

Keywords: hollow cathode, lifetime, barium depletion

1. Introduction

Hollow cathodes (HC) are a critical technology in the field of electric propulsion and are employed to generate the relatively high electron currents required for the propellant ionisation and ion beam neutralisation processes. They are used as electron emitter and neutralizer in Kaufman thrusters and Radio frequency Ionisation Thruster (RIT).

During the lifetime of the HC due to evaporation from the hollow cathode insert the BaO contained inside the insert is gradually depleted. This depletion will causes changes in the insert impregnant chemistry that will lead to a reduction of the evaporation rates and to a consequent reduction on the deposition rate of low work function compounds on the surface resulting in a reduction of the area coverage and in an increase of the overall work function. This process leads to a reduction of the thermionic current from the emitter that, in turn, will force the cathode to operate at a higher temperature increasing the BaO depletion rate. This process will continue up to the point where the cathode is no longer able to operate.

The lifetime of the cathode is then mainly dependent on the cathode operating temperature and how this affects BaO evaporation, the chemistry of the low work function material deposition, the low work function desorption rate and on how all these effects interact with the hollow cathode plasma.

Hollow cathodes developed by NASA have to date demonstrated a lifetime of 30,000 hours in ground testing [1] and 1,600 hours in orbit, however due to the requirements of longer lifetimes for deep space mission a large amount of efforts has been spent in lifetesting, characterization and modelling of hollow cathodes to ultimately estimate their lifetime [1-12].

In this paper the latest results obtained at the University of Southampton regarding HC life time modeling will be presented.

2. BaO depletion and low work function compounds desorption modelling

In the past the authors have already developed a BaO insert depletion model [10,11] and a low work function desorption/deposition model [12].

The BaO evaporation process from hollow cathode inserts has been already studied and fully characterized by the authors [9,10]. Starting from the knowledge of the BaO-CaO-Al_2O_3 ternary diagram [13,14] the evolution of the evaporation rates of BaO with the local barium oxide content has been obtained and, using the experimental data published by Roquais [6], the diffusion coefficient relative to the BaO motion inside the insert has been derived. The depletion model so obtained has been tested with the measurements performed on the T5 cathode by QinetiQ and on the NSTAR cathode at NASA JPL finding both a qualitative and a quantitative agreement between computed and experimental data [11].

The deposition and desorption processes that take place on the insert surface has been already studied by the authors [12]. Using the measurements reported in [15,16] the main low work function compound has been identified in Ba_3WO_6 and the chemical processes leading to its deposition and desorption has been characterized and quantified [12]. It has been found that the desorption rates are strongly proportional to the insert temperature and to the plasma particle density and sheath voltage drop; the higher are these quantities the higher are the depletion rates. From the knowledge of these rates the evolution of the Ba_3WO_6 coverage on the insert surface can be obtained and from this the cathode work function can be calculated.

3. Plasma update procedure

The knowledge of the hollow cathode plasma parameters and of the insert temperatures are essential to estimate the desorption rates and hence the surface coverage of low work function compounds. To do so the ideal solution will be to have a plasma model that starting from inputs like total cathode current, mass flow rate and cathode dimension will be able to calculate the ion and electron temperature and density profiles along the insert length together with the voltage fall and insert temperature profiles. The only model that at present is able to fit these requirements is the plasma model developed at JPL [3]. Since we can not have access to this code an alternative way to obtain such plasma parameters will be developed.

We will assume quasi-neutrality ($n_i = n_e = n$), temperature equilibrium between the heavy particles and the wall ($T_i = T_w$) and that given a hollow cathode to simulate with the model described above, the plasma parameters at the beginning of life are known by measurements. We will also assume that the dependency of the plasma parameters from time and space can be divided in two separate functions so that is possible to write

$$\begin{aligned} \Delta V(t,z) &= k_{\Delta V}(t)\,\Delta V(0,z) \\ n(t,z) &= k_n(t)\,n(0,z) \\ T_e(t,z) &= k_{T_e}(t)\,T_e(0,z) \end{aligned} \tag{1}$$

meaning that the shape of the plasma parameters trend will remain the same with time whereas their values will be shifted up or down by a multiplicative factor.

We will also assume that the electron temperature will not vary sensibly due to the change in the surface coverage as its value has been shown to have small variations over a wide range of cathode operating conditions [17].

Using the assumptions made above the update of the plasma parameters has been reduced to the calculation of two time-dependent multiplicative parameters ($k_{\Delta V}$, k_n,).

To derive these parameters the power balance at the cathode surface and the total emitted current conservation will be imposed

$$\int J_{th}\left(\phi_{eff}+\frac{5kT_e}{2q}dA = \int J_e\left(\phi_{eff}+\frac{5kT_w}{2q}\right)dA\ + \right. + \int J_i\left(E_{ion}+\Delta V-\phi_{eff}\right)dA + fq_r \tag{2}$$

$$\int\left(J_{th}+J_i-J_e\right)dA = I_D \tag{3}$$

During the simulation of the hollow cathode the plasma parameters will be updated at fixed time steps. The distance between two consecutive time steps will be defined to obtain accurate simulations with reasonable computing times and will be of the order of 10 hours.

At every update Eq. (2), (3) will be solved assuming constant wall temperature deriving the values of $k_{\Delta V}$ and k_n. It might happen that a solution of these equations cannot be found. This means that the insert temperature is too low to provide enough thermionic emission to meet the total current emission requirements set by the power supply. In this case the insert temperature will be increased by 10 °C steps until a solution of Eq. (2) and (3) can be found.

4. Plasma Parameter Update Procedure Validation

In this section the procedure developed before will be tested with the data available in the literature relative to the same cathode that will be simulated later.

In [4] and [18] the data relative to NSTAR cathode electron temperature, ion/electron number density and plasma voltage have been reported relatively to discharge currents of 7.6 (TH8), 12 and 13.5 A (TH13).

Comparing the densities relative to 7.6 A, 12 A and to 13.5 A of discharge current we can see how these three trends are quite close even if from TH15 to TH8 the discharge current drops to almost half of its value. Since the ion density relative to 12 ampere of discharge current is the highest between the measured ones if we assume that the ion density is constant for all the THs and equal to the one relative to 12A we will most probably overestimate n_i hence overestimating the desorption rates finally producing conservative estimates of the surface coverage evolution and of the cathode lifetime.

In Fig. 2 a comparison between the calculated values of ΔV and T_e, and the experimental ones for TH15 and TH8 reported in [18] is presented. As it can be seen the computed data show a very good agreement with the measured one proving the goodness of the plasma parameters update procedure. Once this procedure has been validated the plasma parameters of the remaining throttle levels can be calculated. The results are reported in Fig. 3. As it can be seen the plasma voltage tends to increase as the discharge current decrease. This can be explained noting that the cathode insert always emits a thermionic current that is in excess of the desired discharge current value, this means that for every TH the interaction of electron temperature and voltage fall must produce an electron flux that counterbalance the excessive thermionic emission so that total current flowing into the cathode is equal to the value fixed by the power supply (discharge current).

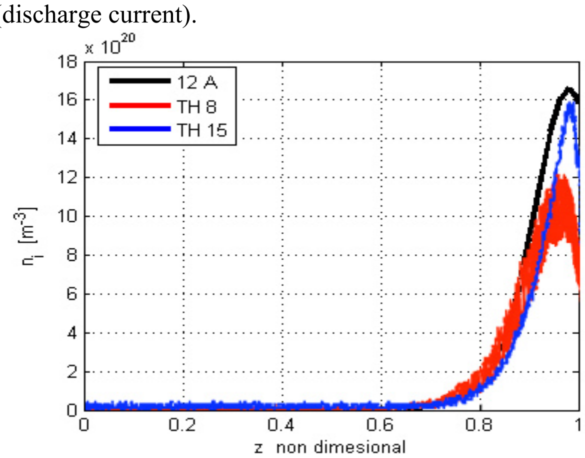

Fig.1 Ion density at TH15, TH8 and at 12 A [4], [18]

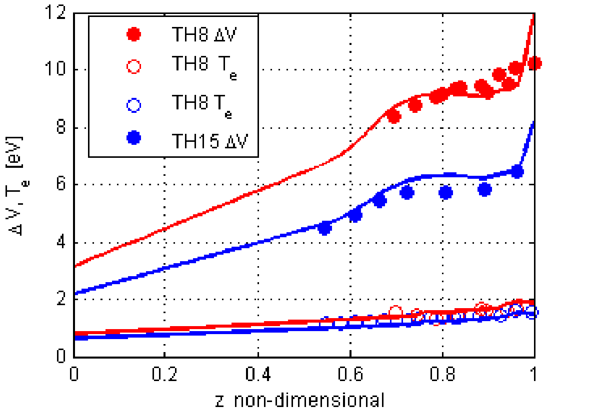

Fig.2 Comparison between calculated and measure plasma parameters for TH8 and TH15

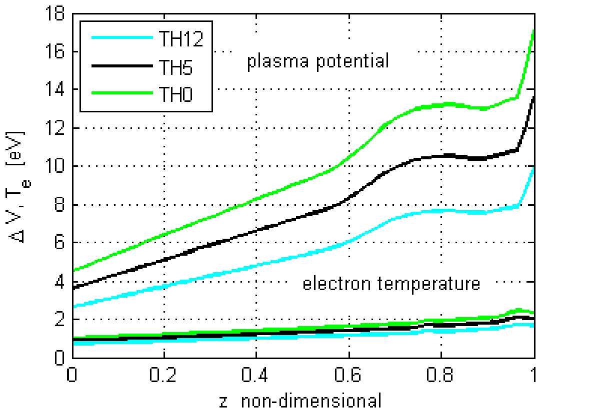

Fig.3 Calculated plasma voltage and temperature profiles for TH12, TH5 and TH0

Since the variations in electron temperature are small and the electron density is assumed to be constant, the plasma voltage will be the parameter that mainly influences the electron flux. Considering that the electron flux needed at lower discharge currents is smaller than at the higher ones and since the higher the plasma voltage the lower is the electron current, the plasma voltage must be high at low THs and low at high THs.

5. 28,000 hours cathode simulation

The cathode reported in [2] by Sarver-Verhey has been tested for 28,000 hours at 12 A of discharge current assuming that its insert temperature profile and plasma parameters are the same as those reported for the NSTAR cathode at 12A.

Using this assumption the cathode surface has been simulated for 28,000 hours. During this simulation the plasma parameters have been updated every 50 hours assuming the electron temperature to be constant during the whole simulation of the cathode. This assumption can be justified noting that the plasma temperature has shown small variations over a wide range of discharge currents and emitted currents (Fig. 2, 3) whereas the plasma voltage has shown to be strongly dependant on the emission and discharge currents.

Regarding the ion density we can note that if the thermionically emitted current drops below the discharge current value the ion flux from the plasma to the surface must become big enough to overcome the electron flux providing the additional current needed to reach the discharge value. Hence a reduction in the emitted current due to a reduction in the surface coverage will result in an increase of the ion density (to increase the ion current) and in an increase of the plasma voltage to decrease the electron current that, otherwise, since quasi-neutrality has been assumed, will increase proportionally to the ion flux.

The computed Ba_3WO_6 surface coverage and the work function evolution are reported in Fig. 4 and 5.

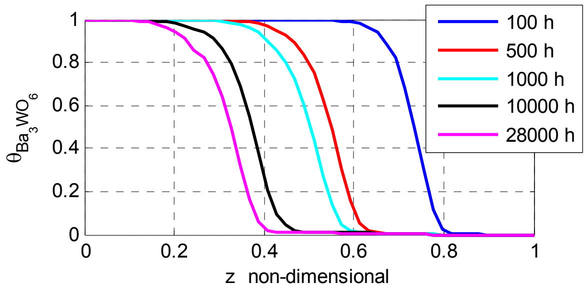

Fig.4 Ba_3WO_6 surface coverage – 12A

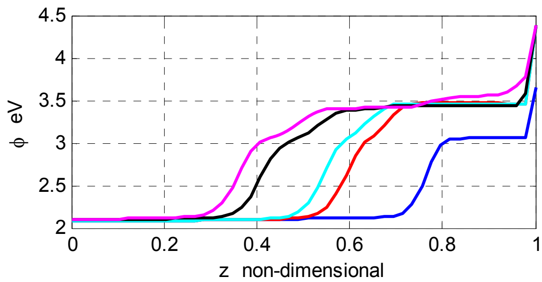

Fig.5 Surface work function – 12A

As it can be noted in the Fig. 4 and 5 the low work function compounds depletion starts at the downstream end of the cathode and then slowly moves upstream. This is due to the fact that the desorption rate is proportional to ion density and plasma voltage and that these two parameters are maximum at the downstream end of the cathode.

Looking at Fig. 5 we can see how even when all the Ba_3WO_6 has been removed from the surface the work function is still below the bare tungsten value. This is due to the presence of barium oxide in the pores that contributes to the overall emission hence lowering the average work function value of the surface.

The evolution of the plasma voltage and ion/electron density with time is represented in Fig. 6 where he values of the parameters k_n and $k_{\Delta V}$ as defined in Eq. (1) are reported.

The periodic oscillations in the values of these constants are the effect of the hypotheses made in the procedure development. In fact we have assumed the insert temperature profile to be constant with time whereas changes in the surface coverage will definitely affect its value. The insert temperature has been updated only when no solution to Eq.

(2) and (3) can be found meaning that the thermionic emission from the surface is too low to reach the required discharge current. The update procedure consists in increasing the insert temperature value by steps of 10°C until a solution can be found.

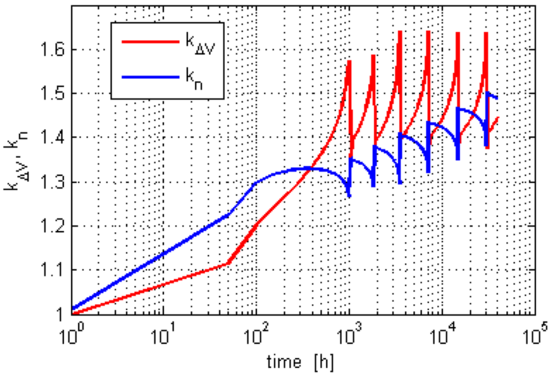

Fig.6 k_n and $k_{\Delta V}$ trend with time – 12A

In the real functioning of the cathode the insert temperature will vary gradually together with the plasma voltage and ion density. Forcing the temperature to increase only when the cathode has reached a critical condition (emitted current too low to reach the required discharge current as for example after 1000 hours in Fig. 6) will produce an overestimation of the plasma voltage since the cathode, not being able to get more current from the thermionic emission increasing the insert temperature, will try to increase the ion current and to decrease the electron one to meet the required discharge current hence increasing both the value of ΔV and n. Since the plasma voltage is overestimated this will produce conservative estimates on the surface coverage and ultimately on the cathode lifetime.

When a critical condition is going to be reached the plasma voltage will increase and the ion density will decrease reducing the value of the electron current so that the total discharge current can be obtained by the sum of the thermionic emitted current and of the ion current [19]. This explains the behaviour of $k_{\Delta V}$ and k_n just before the “steps” in Fig. 6.

When the critical condition is finally reached the insert temperature is suddenly increased increasing the thermionic emitted current hence allowing the cathode to reduce the plasma potential and to increase the particle density bringing them to a value close to the one they had before the critical condition was approached. This explains the trend of $k_{\Delta V}$ and k_n just after the “steps” in Fig. 6.

Since the ion current is directly proportional to the ion number density the electron current will be reduced mainly increasing the plasma voltage hence justifying the bigger variation in $k_{\Delta V}$ than in k_n as reported in the figure above.

6. End of Life Criterion Development

Once the evolution of the surface coverage has been derived we can now develop and end of life criterion. Commonly in hollow cathodes operation the end of life is assumed to occur when the cathode cannot be started within the power supply capabilities. This means that the cathode is sentenced to be dead when the ignition voltage goes beyond the maximum voltage that can be produced by the power supply.

A detailed modelling of the ignition process from first principle will require a full three-dimensional electrical transient simulation of the hollow cathode. In the literature the development of such a model has never been tried hence the problem will be solved in a semi-empirical way. The voltage needed to cause the break down discharge in the cathode can be assumed to be inversely proportional to the electron density inside the cathode and in the cathode – anode region.

Such electron density is certainly proportional to the emission from the cathode walls and hence from the thermionic emission from the insert.

$$\Delta V_{breakdown} \propto \frac{1}{n_e} \propto \frac{1}{J_{th}} \tag{4}$$

The thermionic emission at the start-up is proportional to the surface coverage that can be achieved at the end of the start up process. If we assume that the start up phase start at t_{start} and lasts for Δt_{start} seconds and that the insert is kept to a temperature T_{start} during the start-up phase the total barium mass evaporated from the insert and the total mass needed to reach a full coverage are respectively

$$m_{BaO\,evap} = \int_0^{\Delta t_{start}} \int_{S_{insert}} \dot{m}_{BaO}[T, \rho_{BaO}(t_{start})]\, dS\, dt \tag{5}$$

$$m_{BaO\,needed} = [\theta(t_{start}) S_{insert} \Pi + S_{OP}]\, \sigma_{BaO}$$

If we assumed that the start up time is 10 minutes and that the temperature is 1100 °C the trend of $m_{BaO\,evap}$ and $m_{BaO\,needed}$ with time is reported in Fig. 7.

Once the needed and deposited mass are know the average coverage can be calculated as

$$\theta_{startup} = \theta(t_{start}) + \frac{m_{BaO\,evap}}{m_{BaO\,needed}} \tag{6}$$

From this value of the coverage the average work function can be calculated [8] and so the thermionically emitted current.

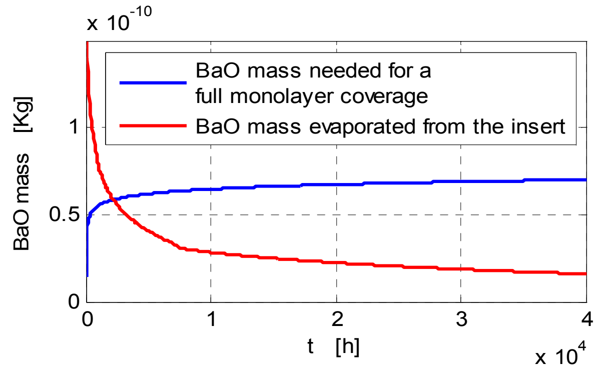

Fig.7 BaO mass needed for a full coverage at startup and evaporated mass during startup T_{start}=1100 °C– 12A

Since from Eq. (4) we only know that the voltage is proportional to $1/J_{th}$ we can define a voltage breakdown amplification factor as

$$\beta = \frac{J_{th0}}{J_{th}(\theta)} \quad (7)$$

where J_{th0} is the emission current relative to the temperature T_{start} and to a full surface low work function coverage. The calculated trend of the amplification factor for the cathode tested by Saver- Verhey [2] is reported in Fig. 8, whereas the one derived from the experimental measurements is in Fig. 9.

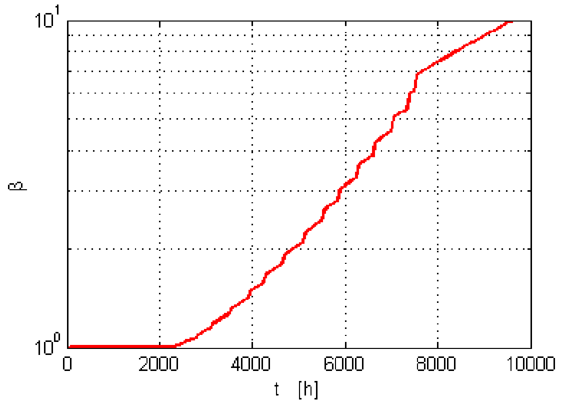

Fig.8 Calculated voltage amplification factor

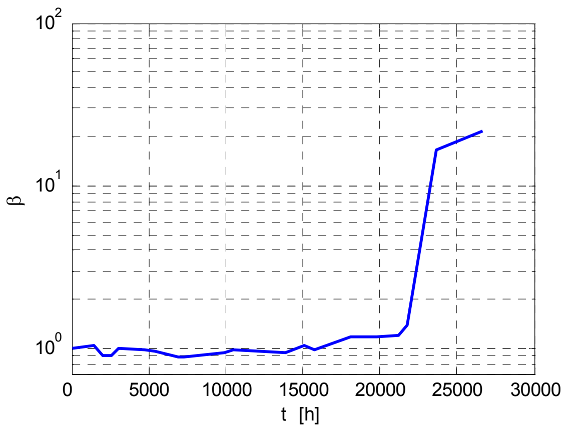

Fig.9 Experimental voltage amplification factor [3]

Comparing the data in Fig. 8 and Fig. 9 it can be seen how both the time values and the amplification values are out of scale. In spite of this the shape of the experimental and numerical β curves are quite close showing a phase were the start up voltage stays constant, a phase of quick increase of the voltage, and then a phase of slower constant rate increase.

The shift in the timescale can be explained noting that in the model a lot of conservative hypotheses have been done resulting in a voltage increase (cathode death) that for 1100 °C happens much before than in reality. The difference in the amplification values can be explained noting that Eq. (4) represents only a very easy interpretation of the relation between surface coverage and start up voltage.

The qualitative similarities found between these two trends give us an evidence of the goodness of the model stressing its conservative nature and give us also a clear end of life criterion.

Comparing Fig. 7 and Fig. 8 we can note how the voltage increase happens when the evaporated barium oxide mass becomes less than the needed one hence and end of life criterion can be state as:

"Given the temperature and the duration of the start up procedure the end of life of a cathode is reached when the barium oxide mass evaporated from the insert during the start up phase is not enough to provide a full monolayer coverage over all the internal cathode surfaces".

Using this criterion we will now change T_{start} until the end of life of the cathode reported in [3] matches the experimental value of 28,000 hours. The experimental value is matched when the start up temperature is 1150 °C, the relative graph of the evaporated and needed mass is reported below

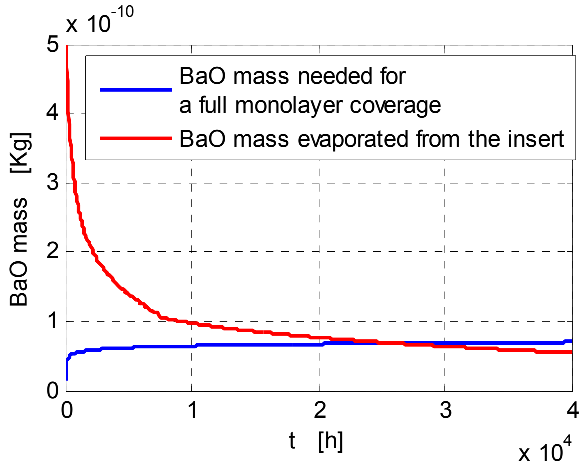

Fig.10 BaO mass needed for a full coverage at startup and evaporated mass during startup T=1150 °C– 12A

8. NSTAR Discharge Cathode Life Time Prediction

The ELT discharge cathode has been simulated for the using the throttle level history relative to the Deep Space 1 flight spare ion engine test reported in Table 1.

The data relative to Ba_3WO_6 coverage and work function are very similar to the one reported in Fig. 4, 5 and hence will not be presented.

Table 1 ELT discharge cathode throttle settings

TH level	Accumulated hours	Discharge Current
12	500	9.9
15	4800	13.5
8	10500	7.6
15	15500	13.5
0	21500	4.9
15	25500	13.5
5	30000	6.9

Looking at Fig. 11 we can note how after 30,000 hours the cathode has still not reached the end of life. This is in agreement with the real test of the cathode that has been voluntary stopped after 30,000 hours. The estimate of the lifetime of the cathode of course depends on the throttle level the cathode will be run at from 30,000 hours on.

As it can be seen in Fig. 11 during the time when the cathode is run at TH15 we have a net reduction of the evaporated mass while during the other TH levels we have even an increase in the evaporated mass.

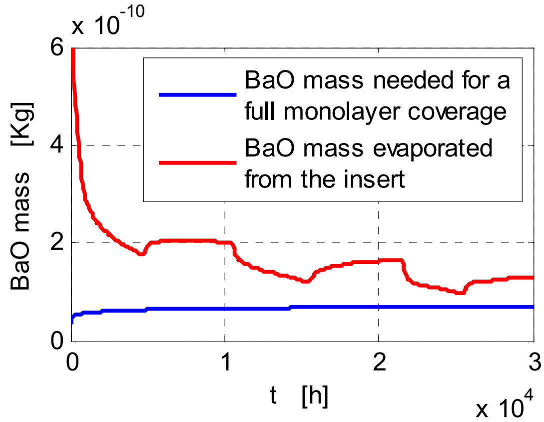

Fig.11 BaO mass needed for a full coverage at startup and evaporated mass during startup T=1150 °C–NSTAR

This increase can be explained noting that the evaporation is proportional not only to the temperature but also on the local BaO concentration as demonstrated in [11].

When the cathode moves from TH15 to a lower throttle level the insert temperature will decrease. A lower temperature means a lower evaporation rate hence a higher possibility that by diffusion the BaO depletion at the surface can be replenished.

This at the beginning will result in a local increase in the BaO concentration that will lead to an higher evaporation rate explaining while at the beginning of TH8 (4,800h), TH5(15,500h) and TH0 (21,000h) the total deposited BaO mass increase with time.

After some time this higher evaporation rate will bring the system to an equilibrium between diffusion and evaporation (TH8 7,500 h) and then to a gradual reduction of the surface BaO density with a subsequent decrease in the evaporation rate (TH8 7,500-10,000 h).

It can be useful to estimate the lifetime of the cathode assuming that the operating conditions from 30,000 hours on will reflect those used until 30,000 hours. To do so the trends in Fig. 11 have been extrapolated up to 100 thousands hours.

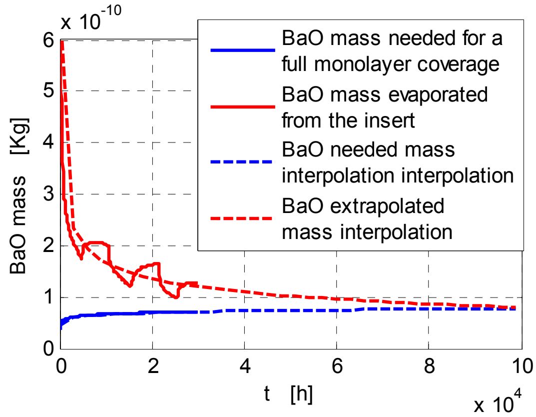

Fig.12 Extrapolation of the deposited and needed BaO mass T=1150 – NSTAR

From this extrapolation a life time of 100,000 hours can be predicted. The lifetime so predicted might seem too long considering that the lifetime of the cathode in [2] was 28,000 hours and that this cathode was run at 12 A. This can be explained calculating the average discharge current of the cathode using the nominal current of each TH level weighted with the time that each TH level has been used for. The value so obtained is 8 A (very close to the current of TH8) and so definitely lower than 12 amperes. The lifetime of 100,000 hours is then valid if the cathode is run at TH8 from 30,000 hours onward or if the throttle history reported in Table 1 is repeated for other 70,000 hours keeping the same ratio between the various throttle levels but using smaller time intervals so that the overall trend will get closer to the average one.

If the cathode is run at TH15 the lifetime is going to be around 35,000 hours (hence compatible with the measurements in [4]) whereas if the throttle level used is lower than TH8 the lifetime will be in excess of 100,000 hours.

9. Conclusions

In this paper the hollow cathode lifetime modeling research carried out at the University of Southampton has been presented. The developed lifetime model is composed by a barium oxide insert depletion model, a deposition/desorption model for low work function compounds on the insert surface, a plasma parameters update procedure and by an end-of-life criterion.

The BaO depletion model is the first model that takes into account both the dependence of the BaO evaporation rate on the insert chemistry and the BaO diffusion process form the insert core to the surface. This model has been validated by comparison with experimental results showing both qualitative and quantitative agreement.

The plasma update procedure has been tested with experimental values showing a good agreement and coupled with the deposition/desorption model.

The use of these models together with the developed end-of-life criterion results in the one of the most advanced hollow cathode life time model present in the literature.

This model has been tuned using the lifetime data in [2] and then used to predict the lifetime of the NSTAR discharge cathode. The computed lifetimes are in agreement with the expectations and with the measurements confirming the validity of the model.

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