

Lifetime assessment of Hall thruster

IEPC-2013-172

*Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013*

Hu Yanlin¹. Chen Jian². Mao Wei. Shen Yan. Chen Jun.
Business or Academic Affiliation 1, City, State, Zip Code, Country

Beijing Institute of Control Engineering, Beijing, 100190 China

Abstract: Hall thruster is one of the most world-wide used electric thruster. With the trends of long life and high power of spacecraft, the Hall thruster should meet high requirements, especially the long lifetime requirements. This paper presents the research progress in lifetime prediction of Hall thruster. The discussion started from the essential factors that affect the lifetime of Hall thruster, by analysis of progress in the relative models. At the end, a summary of lifetime prediction model is given in this paper.

Nomenclature

E	=	energy of ion
n	=	normal direction of channel wall surface
n'	=	ion incidence direction.
$\dot{\xi}$	=	sputtering erosion rate
θ	=	angle between of incidence ion and the normal direction of the wall surface

I. Introduction

As one kind of electric thruster, Hall thruster is the most world-wide used and have the most mature technology. From SPT-60 has been launched successfully in 1972, there are totally 240 Hall thrusters have done the flight in orbit. The typical characters of Hall thruster are high specific, low thrust and long life. For example, the most widely used Hall thruster, SPT-100, which has been flown in Russia, USA and Europe. The specific impulse of this thruster is about 1600s with thrust 80mN and lifetime over 7000h. Because of its high specific, efficiency and reliability, Hall thruster can be applied in attitude control, orbit manoeuvres, deep space exploration and some other mission. For instance, deep exploration satellite, Smart-1, which has been launched in 2003 was used PPS-1350 as the primary thruster. With the trends of long life and high power of spacecraft, the Hall thruster should meet high requirements especially the long lifetime requirements. Every thruster used in orbit need to be verified by ground test, but the full time test costs lots of time and money, consequently, the stable and reliable lifetime prediction method has been became one of the research focus recently. The lifetime limit factor of Hall thruster include cathode failed, material aging caused by radiation in space environment, thermal shock caused by repeat turn on and off. But the most obviously factor that can effect the lifetime of Hall thruster is the erosion of channel wall bombarded by the energetic ion flux^[1,2,3]. The erosion of channel wall can make the mass loss and when the magnetic pole is exposed in ion flux, the magnetic topology will be destroyed. And this is the sign of end life of Hall thruster. Therefore, many institutes and universities have put great efforts at this field and lots of lifetime prediction methods have been proposed, included some theoretical method and semi-empirical methods, and the comparison between the results of prediction methods and experimental have been done. This paper begin from erosion model of channel wall, and mainly discussed the lifetime assessment methods, focus on the currently and tendency of lifetime prediction methods.

¹ Electric Thruster Designer, Propulsion Department huyanlin502@163.com.

² Electric Propulsion Engineer, Propulsion Department, chen5051@sina.com.

II. Status of Hall thruster's lifetime prediction

A. Experimental investigation

Because of the incomparable reliability of life time verification, full time test of Hall thruster has been done both in Russia and USA although its cost is huge, and many valuable data were obtained, the summary was list below:

Tab 1 Summary of Hall thruster full lifetime test

SPT type

Thruster	Time (h)	Organization	Power (W)	Current (A)	Voltage (V)
SPT-100	5730	JPL	1350	4.46~4.48	300
SPT-100	7008	Fakel	1350	4.5 ± 0.1	300 ± 2
T100	2000	KeRc	1300	4.5 ± 0.05	300 ± 5
T220	1000	GRC	10000	20	500
pps-1350	7506	Snecma	1500	4.28	350
BPT-4000	5800	Aerojet	3000-4500	7.5~15	300~400

TAL type

Thruster	Time (h)	Organization	Power (W)	Current (A)	Voltage (V)
D55	636	JPL	1350	4.47	300
TAL-110	1018	TsNIMASH	3000	8.6 ± 0.1	350 ± 10
TAL-110	1000	JPL	3100~3400	9.0~9.5	350 ± 10
D80	2000	GRC	2800	4	700

Full lifetime test of Hall thruster cost huge., For example SPT-100, if adopt the full time test method to verify the life. it will spent 7000 hours and about 1.26 million dollars. Except that it will cost lots power to maintain the vacuum environment. But the lifetime test can not grasp and determine the erosion character of channel wall when operate at other modes. Except full life time test, there are some other short term test method has been proposed by the researchers. For example, NASA has investigated erosion character of five kinds channel wall based on NASA-120M.

B. Model of lifetime prediction

a Definition of lifetime

In Hall thruster, the energy of ion flux is enlarged from anode to the outlet because of the distribution of voltage. So, the outlet corner of channel wall is easily to be corroded, This is the usually explanation of the phenomena that why erosion depth is enlarged along the axis direction^[4].

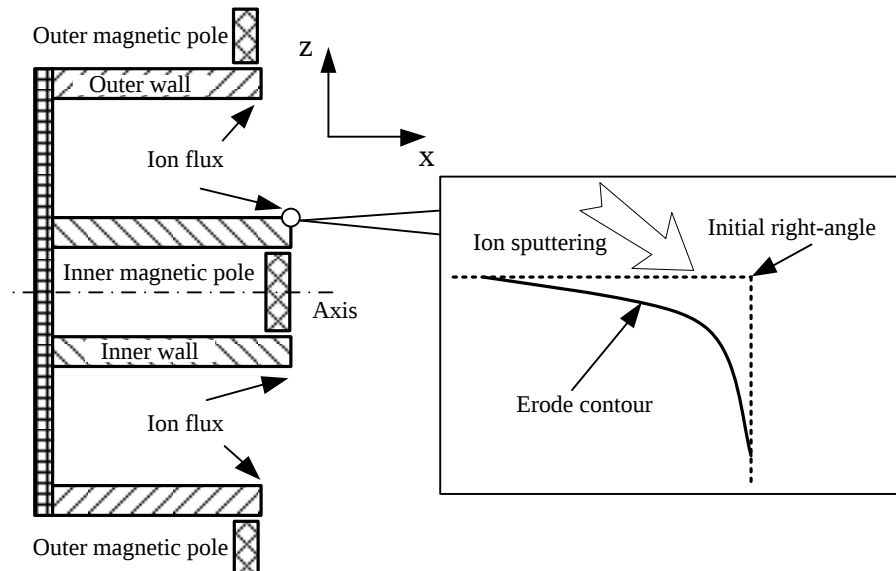


Figure 1 Erosion of Hall thruster wall corner by energetic ion sputtering

As shown in fig 1, the magnetic pole will expose to the energetic ion flux when the channel wall was eroded

entirety, then, the erosion of magnetic pole will make the magnetic topology departure from design aim, and this will effect the performance of the thruster until the thruster can't work normally. This is why the moment of the magnetic pole exposed to the ion flux is usually considered to be the life terminal moment of Hall thruster. Therefore, the key of lifetime prediction accurately is to forecast the contour evolvment with time. And the issue of Hall thruster lifetime prediction transit to investigate the erosion rate of the channel wall in the environment of energetic ion flux.

The depth of channel wall in Hall thruster will reduce at the bombardment of ion, as shown in Fig. 2. $\theta = \arccos(n \cdot n')$ θ is the angle of ion incidence and the surface normal, and n is the normal direction of channel wall surface, n' is the ion incidence direction.

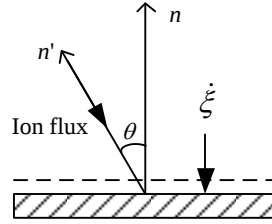


Figure 2 Erosion rate of channel wall by ion sputtering

$\xi̇$ is sputtering erosion rate, can be expressed as ^[5]

$$\xi̇ \approx j_{iw} S_v(E, \theta) \quad (1)$$

In above formula, j_{iw} is the density of ion flux, $S_v(E, \theta)$ is the volume sputter production. E is the energy of ion. θ is the incidence angle of ion flux. according to the formula, there are two model should be establish to predict the evolvment of channel wall contour. One is the model of ion flux that bombarded the channel wall, the other model is the volume sputtering erosion srate of the channel wall.

b ion flux in channel

Because of the effects of many kinds physiccil factors, the ion flux in the channel of Hall thruster will deviation, and the reason for this phenomenon is that the electric field direction can't parallel to the axial because of the interaction of magnetic field and thermal electrons. Except that, the sheath, pre-sheath formed by the interaction of ion flux and channel wall and collision of particles can also make the ion flux deviation. The actual movement of ion flux in channel is like Fig 3.

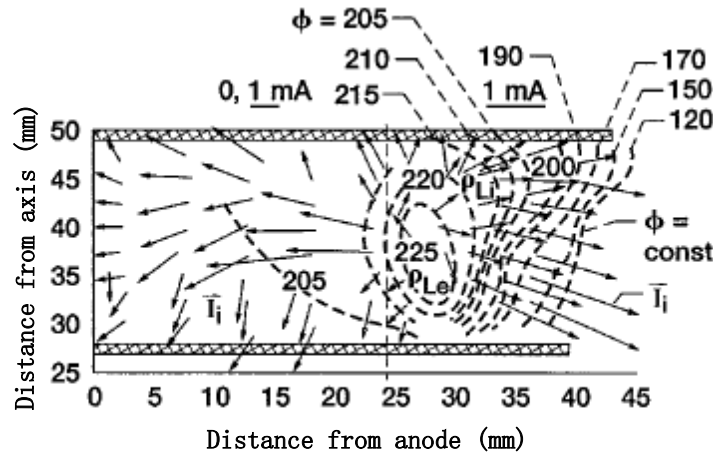


Figure 3 Ion flux in the channel wall

In order to deeply understand the physical process in the channel of Hall thruster, the method of 2D hybrid particle-in-cell is adopted by Fife^[6] graduated from MIT in his doctoral thesis, and then Allis^[7] and Femandez^[8] from Stanford University improved the model and dissertate detailed. The model make the hypothesis that plasma is quasi-neutral, and the electrons are treated as liquid, the flow is quasi-one dimension and obey the ohm law. The ions and atoms are treated as scatter particles. and adopt the PIC method to solve the movement. Detail of ion flux flow can consult the papers^{6,7,8}.

Hybrid particle-in-cell model is the normal method to compute the movement of ion channel currently, many

institutes and universities in USA, Europe and Japan have adopt this method and this method belong to theoretical prediction method. Except that , the Russia researchers proposed some experiential model, such as ion resource model adopted by KIM^[9] at MAI. This model consider the ions emitted from equivalent ion resource . and this ion resource located at the interface between the ionization and acceleration zone. Along with the operation time, the width of channel wall is largened and the density of ion and atom, the collision probability and the length of acceleration zone will reduce, so the position of ion resource is changed continually, and move toward the outlet direction. This model is also applied in Kelydesh research center. Vladimir Baranov^[10]from Kelydesh research center solve the density of ion flux that bombardment to the channel wall by the method analysis the difference between experimental and theoretical results.

c Sputtering model

Sputtering is one physical phenomenon that the solid surface corrode by the bombardment of energetic particles. and this phenomenon is discovered by Grove in 1852 at the experiment of gas discharge. Sputtering production is a quality to measure the atoms' number of channel wall that sputtered by the incidence of energetic ion. This physics parameters is dependent on the composition of the base material , microstructure, profile of channel wall, energy of incidence ion, incidence angle, temperature of target material and so on. When the material is fitted, the mainly factor considered is energy of incidence ion and incidence angle.

$$Y = Y(E, \theta) \quad (2)$$

E presents the energy of ions, θ is the angle between of incidence ion and the normal direction of the wall surface

Sputtering arose by the bombardment of energetic ions. According to the above analysis, in order to predict the lifetime of Hall thruster, the sputter production at varied by the different energy and different incidence angle should be known exactly. BN is the normal materials used for channel wall of Hall thruster currently. $Y(E, \theta)$ is varied at different sputter mechanism. the discharge voltage of Hall thruster is below 1kV, additionally some voltages are loss, so the sputter mechanism of channel wall belong to linearity cascade sputering. This model is established in 1969 by Sigmund based of lots of experimental results and his some improvement of the theory. ^[11,12]:

$$Y(E_0, \theta_0) = \Lambda F_D(0, E_0, \theta_0) \quad (3)$$

Λ is shown as material factor, and is just related to the material characteristic. F_D is energy deposit function, the sputter production can be written as :

$$Y(E, \theta) \approx 0.042 \frac{\alpha(M_2/M_1, \theta) \cdot S_n(E)}{U_0} \quad (4)$$

U_0 is the bond energy of surface, $S_n(E)$ is cross area of prevent α is the corrective factor related to the incidence angle. this formula showed that the two factors E and θ affect the Y is independent. so the formula can be rewritten

$$Y(E, \theta) = S(E) \cdot Y'(\theta) \quad (5)$$

$S(E)$ is identified as energy sputter production, with $Y'(\theta)$ is normalized angle sputtering production.

a) Energy sputtering production

Because of the different material adopted by different Hall thruster. the energy sputtering production is different. And the semi-experimental expressions of $S(E)$ is used aboard. this expression considered the effectiveness of material sputter yield and the electron excited to the sputtering. the expression is shown as ^[13,14] :

$$S(E) = \frac{0.042 \cdot \alpha(M_2/M_1)}{U_0} \frac{S_n(E)}{1 + A s_e(\varepsilon)} \left[1 - \left(\frac{E_{th}}{E} \right)^{\frac{1}{2}} \right]^5 \quad (6)$$

E is the energy of incidence ion. E_{th} is sputtering yield. when the ion and channel wall material are fitted, α, U_0 are constant. $S_n(E)$ and $s_e(\varepsilon)$ are related to the ion energy. In 1996, Yamamura^[13] pointed that s should be 2.5, and few sometimes can be 2.8.

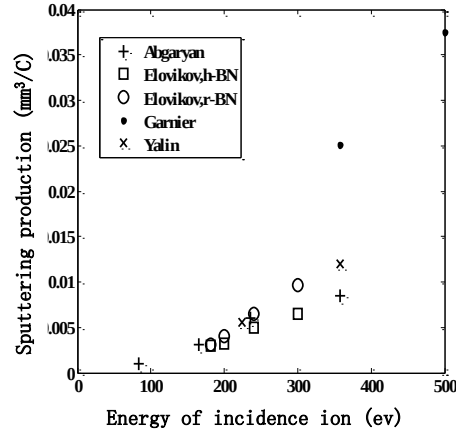


Figure 4 Energy sputtering production of BN when the ion incidence at the direction normal to the surface [5,15,16,17]

In the lifetime prediction model, the formula (6) often simplified according to the experimental data, Shannon Yun-Ming adopted the formula below to compute the sputtering production according to the experimental results as shown in Fig 4 in his doctoral thesis.

$$S(E) = \frac{AE^{0.5}}{1 + BE^{0.3}} \left[1 - \left(\frac{E_{th}}{E} \right)^{\frac{1}{2}} \right]^{2.5} \quad (7)$$

The values of A and B are related to the sputtering yield. because of the uncertain of the yield, the below relationship between E and S(e) is existed.

The similar formula is also used by Hofer^[18] and Ahedo^[19] in their computation.

$$S(E) = AE^{0.5} \left[1 - \left(\frac{E_{th}}{E} \right)^{\frac{1}{2}} \right]^{2.5} \quad (8)$$

In this expressions the value of A is fitted experimental data.

b) Angular sputtering production

For the sputtering production of BN, many experiments have been done by the researchers. Garnier^[16] and Yalin^[17] did the investigation of the relationship between sputtering production and incidence angle while the incidence ion energy is low. Elovikov did the research when the ion energy is high and angle is 45°. Briton^[20] investigated the variety of production with the difference voltage, when the incidence angle is 30°, 50° and 75° independently. the variety characteristic of $Y'(\theta)$ with θ can be explained as below:

Based on lots of material sputter experimental results, Yamamura summarized that the experimental expression of $Y'(\theta)$ can be written as:

$$Y'(\theta) = x^f \exp[-\Sigma(x-1)] \quad (9)$$

In the above formula, $x = 1/\cos\theta$ and f fulfilled the expression $\frac{\Sigma}{f} = \cos\theta_{opt}$. currently this fitted formula is used the most widely. and at the condition $f = 2.23$ and $\theta_{opt} = 67.9^\circ$, the fitted curve and the experimental data are shown as below.

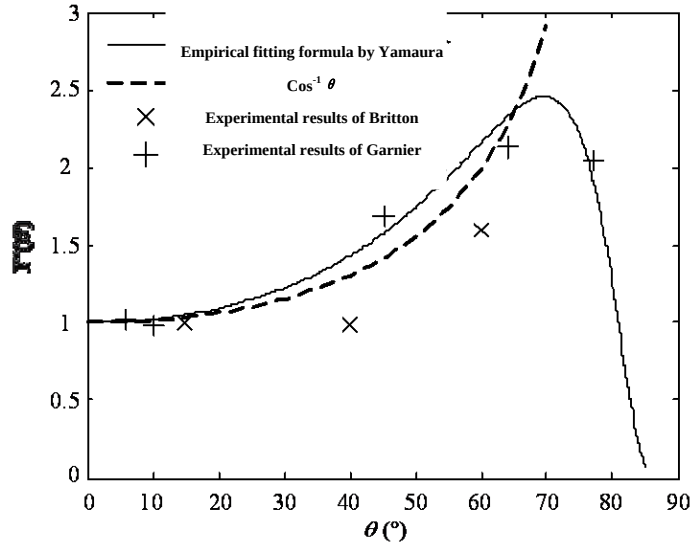


Figure 5 normalized angular sputtering production ^[15,20]

Doctor Liu Hui^[21] do the simulation in channel wall, at the same time the Dr. Li Yuquan who came from the same laboratory do a lot of basis theoretical investigation, and brought the lifetime prediction model based on Huygens wavelet method. except that Dr. Li Yuquan also deeply investigated the micro sputter mechanism of channel wall. From both micro and macro point discussed the erosion progress^[22].

In conclusion, the practically lifetime prediction model is very important for the engineering application, this tendency can also be seen from the papers published in IEPC.

d Research of accelerate test

According to the above analysis, the full lifetime test cost huge. And can not predict the profile of channel wall varied with erosion time. so through short time lifetime test and in combination with prediction model to assess the lifetime of Hall thruster. This method can save time compared to full time test and is also more reliable. Kim from MAI brought a kind of accelerate test method. This method can assess the lifetime of Hall thruster in a very short time. maybe can save about 80%~90% time in compare with full time test^[23]. This method composed by steps below: 1) Deduce the parameters of incidence ion flux based on the prediction model according to a few times erosion experiment results 2) Predict the contour of channel wall a few times later, according to the results of step 1 and the prediction model 3) mechanical process the channel wall to achieve the profile predicted at step 2. 4) make the profile of channel wall achieve to the appearance predicted in step3, and then repeat the above steps from step 2.

III. Conclusion

In conclusion, Many scientists have done the research about Hall thruster's lifetime prediction. And have got lots of achievement. but the lifetime prediction model is not perfect.

Experiments about sputtering yield and production. Currently, the material for Hall thruster's channel wall is BN. For this material, the sputtering yield is unknown, and the production near the sputtering yield is lack of experimental data. Unfortunately, many research results showed that the production at sputtering yield and near that energy precisely has a great impact to the erosion rate.

Temperature sputtering production. In the lifetime prediction model, the factor of temperature did not have been considered. But the experiment research in MAI showed that, the sputtering production increased with the temperature, for the channel wall material used in SPT100, the relationship between temperature and the production as is shown in Fig 6, it can be seen that, when the temperature is higher than 600°, sputtering production increased sharply with temperature. For this characteristic the literature 24,25 have give a simple interpretation, but the analysis object is not the usually used material for Hall thruster.

Anomalous erosion model. The prediction model is mainly considered the erosion caused by the ion bombardment. This is often known as classical erosion, but the analysis in combination with the erosion profile showed that, the electrons can also effect the profile, this phenomenon is called anomalous erosion, and now this model is not clear.

Except that the ion flux model is also a limit factor restrict the accuracy of the prediction model.²⁶

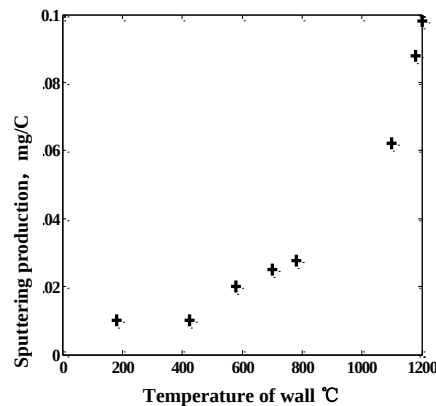


Figure 6 Relationship between production and wall temperature in SPT-100^[27]

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