SPT's high lifetime – some problems of solution

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Abstract: One of the factors limiting an SPT lifetime is a process of ceramic isolator sputtering. For the future long time space missions it is necessary to choose a ceramic with sputtering resistance at least in 1.5 – 2.0 times higher that traditional BN base ceramic has. For this purpose it is necessary to know in details what is happening with ceramic in the SPT channel. In this paper the conditions of ceramic operation in the SPT channel are just examined. Experimental results and the procedure of calculation are represented in the paper.

Nomenclature

a	= ions incidental angle
δ_w	= typical size of the near wall area
∇p	= electron pressure gradient
Δl_k	= length of a wall segment
E	= vector of electric field density
φ_0	= potential value on the wall's surface
Φ	= potential distribution depending on electron pressure gradient (∇p_e)
J_c	= discharge current value
Λ_I	= length of ionisation
m	= ion mass
N_i	= ion birth frequency in the SPT discharge chamber
N_w	= number of examined particles hitting onto discharge chamber wall
ρ	= mass density of wall material
q	= ion charge
r	= vector of ion disposition
r_0, V_0	= initial coordinates and ion velocity
S_m	= $\Delta m/I\tau$ mass coefficient of sputtering
S_a	= $\Delta N_a/I\tau$ - atomic coefficient of sputtering
S_a	= relative coefficient of sputtering
$S(E_i, \beta)$	= wall material sputtering coefficient under energy of falling down ion E_i and incidental angle β
σ_e	= coefficient of secondary emission for electron component
T_e	= electron temperature
τ_M	= time of simulation

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I. Introduction

The electro – rocket thrusters (ERT) are widely used onboard the spacecrafts of different applications. Among different types of the ERT's the prevailing one is the stationary plasma thruster (SPT). This type of the thruster has relatively high performances optimal to existing missions and is considered as the main one for perspective missions and programs including flights to the planets and asteroids.

In spite of high success in SPT application, there are lots of problems still necessary to solve. Among them the most interesting is a problem concerning the long time wearing tests.

Mainly a process of ion – plasma erosion, destructing the discharge chamber walls, limits SPT's life – time. Isolator's erosion causes thrust decreasing and spacecraft contamination by sputtered products, which in its term can change physical properties of functional surfaces under thruster long time operation (for example, to loose solar sell cover glass transparency). The thrust decreases as far as magnetic system pole pieces begin to sputter after ceramic disappearing. As a result magnetic field topology changes and though electron current increases and ion beam de-focuses.

The space technique development requires to create SPT models with a lifetime about 10 – 15 thousand hours and more. One of the evident way permitting to overcome this problem – to use materials with increased resistance ability against ion sputtering. But it was found out that if we use well-known materials, either thruster's performances drop or walls' erosion increases. The most suitable performances were obtained if ceramic materials, bases on boron nitride, were used. Nowadays 9000 hours life - time of the SPT is demonstrated during on ground test. But it is very problematically to increase it sufficiently in future. It is impossible to choose properly a material with increased resistance ability against ion sputtering without detailed analyses of sputtering process occurs under specific conditions of SPT operation.

The SPT erosion processes are examined weakly. Nowadays there are two mechanisms permitting to explain the character of main isolator wearing: ion (cathode) sputtering and electron stimulated desorption. The last mechanism is practically uninvestigated for ceramics materials, but with its help it is possible to explain the character of "abnormal erosion".

In this paper the authors represent the first results concerning complicated study of erosion process in SPT channel.

II. Discharge chamber walls erosion simulation

The schema of the processes, which occur in the SPT channel and influence onto isolator's erosion and sputtered particles dispersion, is represented in Fig.1.
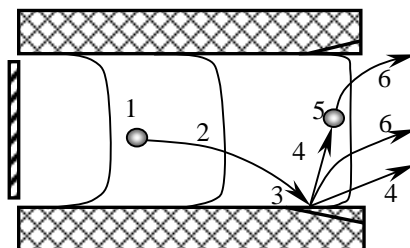
1 - ion birth process; 2 - prime ions motion in the electrical field; 3 - ions interaction with isolator's surface; 4 - neutral sputtered particles escaping; 5 - ionization of neutral sputtered particles; 6 – ionized particles accelerating in the channel

Figure 1

The prime process, responsible for ions dynamic in the channel, discharge chamber isolator erosion and parameters of sputtered particles in the SPT jet, is the process of propellant ionisation. This process is characterised by ionisation rate in every point of the discharge chamber volume. The main reliable information about ionisation rate can be obtained by probe's[1] and optic spectrum[2] measurements. The typical picture of ionisation rate distribution in the SPT channel is represented in Fig.2.
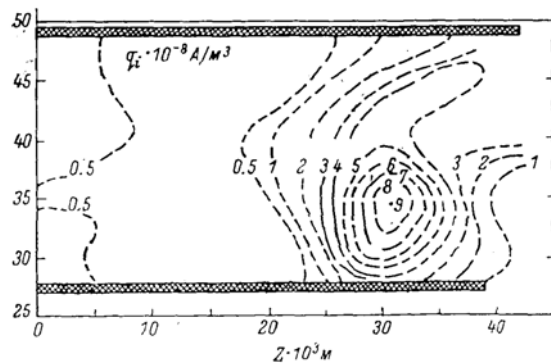

After its birth, ions begin to accelerate in the electric field. Part of them freely comes out of the channel and other part – moves in the wall direction. If we have information about ions initial velocity in the point of ionisation and about plasma potential distribution in the SPT channel, there are no difficulties to determine ions trajectory in the SPT channel. But in the main cases it is very difficult to obtain these data

Figure 2

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One can use data of probes' measurements if it is necessary to obtain data about plasma potential on the wall and in the central part of the channel (not closer than 1-2 mm from the wall)[3]. Unfortunately it is practically impossible to obtain information about near wall potential drop in the SPT by probe's method as far as boundary layer's thickness is commensurable with probes' sizes (~1-2 mm). Therefore, if one likes to determine plasma potential distribution in this zone it is necessary to use different numerical models.

Nowadays when near wall layer is calculated sometimes it is assumed that along the magnetic line potential distribution Φ depends on electron pressure gradient (∇p_e). But for SPT plasma where the electrons' length of free motion between electron-electron collision is significantly greater than channel's size it is not very correct to use ∇p_e concept[4]. Under these conditions Φ potential distribution can be formed by the account of plasma interaction with channel walls. In the work[5] it was shown that the best agreement with the experiment has the model of transition layer, suggested by Self[6]. This model is the result of Poisson equation solution for plate transition layer under quasi-neutrality parameters $\alpha = 0 \ldots 10^{-3}$ in the case of Maxwell distribution of electrons over energies. But it is well known that under typical for SPT values of plasma parameters the group of fast electrons can form the significant share. Besides, ions containing in the sputtered isolator particles' flow, influence onto parameters of near wall potential drop. Therefore, it is not correct to use known numerical methods for near wall potential drop profile creation. In this case it is more reasonable to use quasi-empirical or combined models, using existing experimental data about potential distribution in the SPT channel.

In this work we used one of such models[7]. This model is similar to work[6] and is the result of Poisson equation solution for one-dimensional stationary case under the assumption of Maxwell distribution functions for electrons and ions. According to this model plasma potential in the boundary layer changes according to the following law:

$$\varphi = \varphi_0 \exp(-\frac{y}{\delta_w}) \tag{1}$$

$$\varphi_0 = \frac{kT_e}{e} \ln \left[(1-\sigma_e)\sqrt{\frac{m_i T_e}{m_e T_i}} \right] \tag{2}$$

It is necessary to know data about plasma potential on the discharge chamber's wall and in the area closed to it in order to approximate near wall potential drop with the help of Eq.(1). In this case typical size of near wall area δ_w is an adjustment coefficient, securing the best quality of the approximation. If there is no information about potential on the wall, it can be obtained using Eq.(2).

More complicated problem is the problem connected with plasma potential determination in the area of isolator erosion. The reason is the following: with channel geometry variation, plasma potential distribution changes too. The simplest analysis shows that inclination angle between isopotensials and channel wall surface should be positive during the erosion (in opposite case ions will not reach the surface). Due to this we may assume that field structure in the erosion area is more complicated than that we obtained under field extrapolation from central part of the channel. Besides, as far as just electric field determines dynamic of isolator's erosion, the accuracy of its determination will define the accuracy of erosion prediction. Due to this field model creation is very difficult and crucial problem.

The central process, responsible for isolator erosion and sputtered particles parameters in the jet is the process of ion interaction with the channel wall. In order to describe this process, such performances as sputtering coefficient dependence on energy, incidental angle and ion fluence; mass and charge composition of sputtered particles and also particles distribution over energies and angles of effusion are used. As a rule all these performances are determined experimentally. In practice the mass coefficient of sputtering ($S_m = \Delta m/I\tau$) is mainly used. Atomic coefficient of sputtering ($S_a = \Delta N_a/I\tau$) is used much random due to great uncertainty in composition and relatively in average atomic weight of ceramics (for the majority of ceramics we have only qualitative information about their composition).

The investigations [8] show that coefficients of sputtering for different types of the ceramics depended practically linearly on the energy of falling down ions (Fig.3). Sputtering coefficient dependence on ion incidental angle is characterized by relative coefficient of sputtering $S_a = S(a)/S(a=0)$. The value S_a has maximum under ions incidental angles $a = 50\ldots60°$ for the most numbers of ceramics. Under the energy range $100\ldots400$ eV the position of maximum can be assumed as stable (Fig.4).
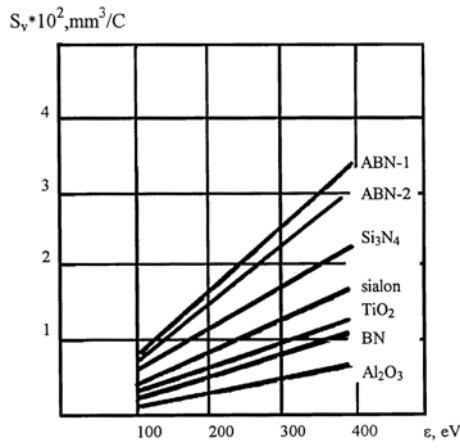
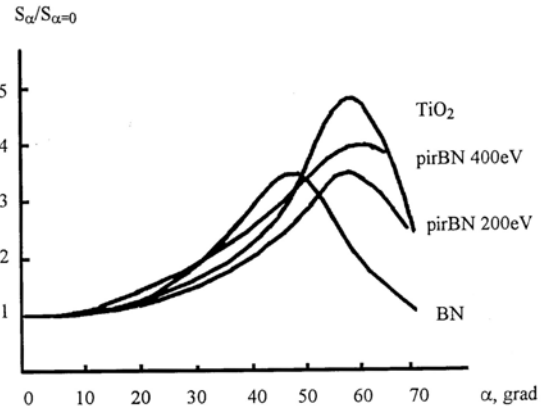**Figure 3**   **Figure 4**

Neutral particle dispersion is determined mainly by the conditions of their start. It is so due to the fact that neutral particles motion in the channel and out of it is a collision free. But some part of neutral particles can be ionised and after that SPT electric field begins to influence onto their motion. Under typical for SPT values of mentioned parameters (V_a = 300 m/s, V_e = 2.6·10^6 m/s, n_e = 10^{17} m^{-3}, σ_i = 10^{-19} m^2) the length of ionisation is Λ_i = 1 cm that is commensurable with the size of ionisation zone. So, it is very probable that sputtered particles will be ionised. Therefore carried out estimation shows that the main part of sputtered particles can be charged. In this case angular and energetic distribution of these particles in the jet will be determined not only by parameters of start but and by SPT electric field.

Taking into account all mentioned above, the model of sputtered particles dispersion should take into account the following: composition, charge and energetic distribution of sputtered particles over escaping angles, distribution of electron density in the channel, near wall drop of the potential, electric field in the channel and out of it. Besides the model should consider stochastic character of particles ionisation process in the channel and particles escaping off the ceramics. The wall surface relief can be very important. For practical calculation it is necessary to have the information about ionisation cross section of sputtered substance.

It is very difficult to create such model. And if all mentioned factors are taken into account the absence of necessary initial information (especially about performances of sputtering and ionisation cross sections of sputtered substances) does not permit to obtain good results.

Therefore at this stage of the investigation we decided to develop the model of neutral component effusion. For ionized component it was assumed that it is distributed like ions in the jet. As for relation between flows of ionized and neutral components, they should be determined experimentally.

For ion birth process simulation in the SPT discharge chamber it is suggested to use Monte-Carlo method. The coordinates for the point of ion birth are played randomly according to ion birth frequencies $\nu(z,r)$. Ion birth frequencies are set on 2D mesh.

The ion motion in the SPT channel can be described by:

$$\frac{d^2 r}{dt^2} = \frac{q}{m} E \qquad (3)$$

Under *E=const* ion position and its velocity after time Δt from the beginning of motion are calculated as:

$$r = r_0 + V_0 \Delta t + \frac{q}{m} E \frac{\Delta t^2}{2}$$

$$V = V_0 + \frac{q}{m} E \Delta t \qquad (4)$$

Electric field in the channel is set at the orthogonal 2D mesh, overlapping all area of the channel and isolator. The mesh overlapping isolator's area is necessary in order to take into account electric field distortion caused by channel wall erosion. In every point of the mesh the electrical field potential is set. The field intensity in the intermediate points of the mesh is calculated with a method of linear interpolation.

The wall length is divided onto K segments. For this purpose, using data about ion collisions with walls, we create empirical function for distribution of ion hitting points. Using this function, channel walls are divided onto segments in which equal numbers of points are hit. Obtained separation is adaptive

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relatively to density of particle flow to the channel wall: as greater flow density is - the smaller step of separation is. Then, on every segment the average erosion rate is calculated. In this case every examined particle hitting into the K segment is taken into account.

Ion flow density bringing onto the wall by examined particle is:

$$nv_i = \frac{1}{2\pi R_i \Delta l_k \tau_M} \tag{5}$$

$$N_i = 2\pi \iint_{r,z} v(r,z) R dr dz \tag{6}$$

If SPT discharge current value J_c is set, time of simulation can be calculated as:

$$\tau_M = \frac{(M - N_w) \cdot e}{J_c} \tag{7}$$

Flow of sputtered material from one examined particle is calculated by the following way:

$$nv_i^- = nv_i^+ \cdot S(E_i, \beta) \tag{8}$$

In this case total wall erosion rate on the wall segment Δl_k is:

$$\delta_k = \frac{1}{2\pi\rho\Delta l_k \tau_M} \sum_i \frac{S(E_i, \beta)}{R_i} \tag{9}$$

In Fig.5 it is represented the results of simulation for *SPT-100* (experimental wall profile – dotted line - according to data[9]).
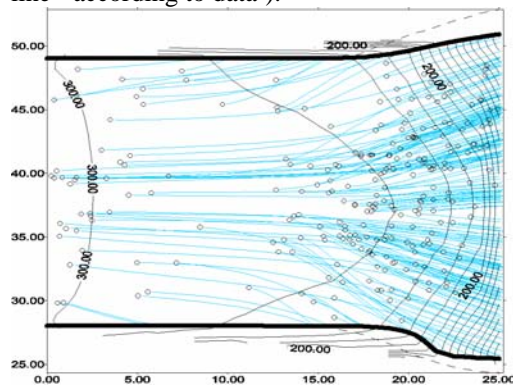

Figure 5

It is necessary to point out that there is great disagreement between calculated and experimental profiles. Analyzing this phenomenon we found out that the error causes due to the fact that the values of ceramic sputtering coefficients are understated. The problem is the following: the procedure of sputtering coefficient determination is usually carried out at the surface temperature 500K. The real temperature of the SPT walls is 1000K[10,11]. The investigation carried out in MAI[12] showed that with surface temperature growth the sputtering rate of BOROSIL type (BN+SiO$_2$) ceramics increases (Fig.6).
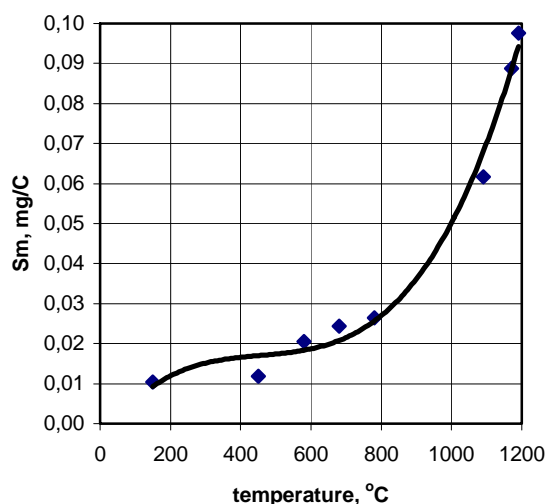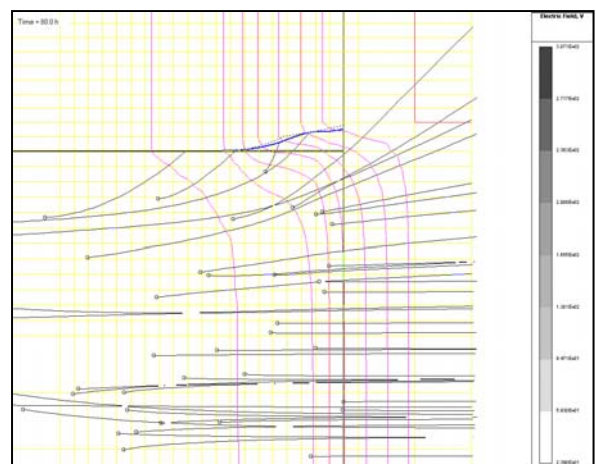

Figure 6

Figure 7

After sputtering rate correction the results of calculation became more realistic (Fig.7).

III. Simulation of the SPT ceramic isolator sputtering process

It is known that one of the ways permitting to increase SPT lifetime is to increase ceramic resistance-ability. But it is necessary to investigate in details sputtering process occurring in the SPT in order to choose ceramic materials in a proper way. The fact that not only accelerated ions of the jet act to ceramic, but also and electrons do and also there is oscillation process in plasma and the temperature of ceramic's thin near-surfaced layers is closed to melting temperature complicate the task. Mentioned phenomena complicate greatly the process of investigation of sputtering process and materials choosing.

3.1. Test procedure description

The experiment was carried out in the vacuum chamber with a volume 2.5 m^3. Chamber pumping is done with two turbo-molecular pumps TMN-2500 and cryo-pump NVC-400 with a capacity 6500 liters per sec. (over air). Chamber pressure during thruster operation was not more than $5 \cdot 10^{-5}$ mm Hg. During the test a stationary plasma thruster SPT-70 was used. Thruster's isolator was made of a ceramic BGP-10 – type (BOROSIL).

Figure 8

Analysis of ceramic elemental composition was done with Rutherford Back Scattering method (RBS)[13,14]. Due to test equipment limitation (insert sizes should not be more than 10x10 mm), it was impossible to examine the whole isolator. So, the thruster was modified as it is shown in Fig. 8. In the inner isolator the four slots (diametrically located) were done. The inserts made of BOROSIL were put in these slots (insert # 1 – under cathode, ## 2, 3, 4 – clockwise). In order to prevent spurious discharges and gas leaking, the inserts and slots had a trapeze form. The inserts were fixed in the slots with the help of spring-supported split ring made of a tungsten wire.
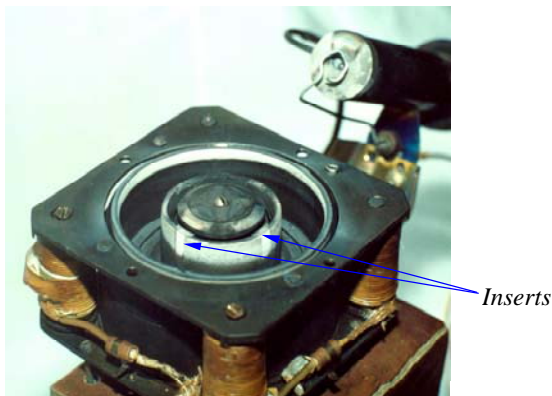
In the first group of experiments the following procedure was used. Before first ignition elemental composition of the insert's material were analyzed; inserts' profiles were measured; inserts were weighted. After that, the inserts were placed to the selected position and the SPT was ignited (discharge current 2.3 A and accelerated potential 290 V). Then when SPT operation cycle was finished, the inserts were taken out, their profiles were measured, inserts were weighted and insert #1 elemental composition was analyzed. Then the inserts were put to their places again and the next cycle of SPT operation was carried out. It was carried out four cycles with duration 8 – 12 hours. In this case total lifetime of the SPT was 44 hours. In the second experiment the two new inserts were used, the two other ones were taken from the previous experiment (after 44 hours of operation using Xe). The chosen working point was: voltage - 300V and current not more than 4 A with maximal portion of nitrogen. But there is appeared a problem with thruster operation during experiment due to ignition problems and discharge instability. The solution was: to decrease discharge potential down to 185 V. In this case average discharge current was about 1.88 A. Xe and nitrogen content in the jet was 56% and 44% (over current), Xe mass flow rate – 1.65 mg/s, N_2 – 0.28 mg/s. Time of thruster operation reached 28 hours.

3.2. Ceramic inserts examination

The main aim of this part of the work is to obtain information how compositions of surfaced layers are changing during its exploitation. For composition determination the Rutherford Back Scattering method was used (for hydrogen ions with energy $E_0=1MeV$).

This method was used as far as it is absolute one, i.e. it is not necessary to use standards (calibration over etalons). Besides, this method is single non-destructive one, permitting to determine multi-elemental concentration profiles over depth for the thickness range from several nanometers up to dozens micrometers.

The disadvantage of this method is: it is impossible to identify the elements directly, if their atom masses are closed (for example, it is impossible to identify an alloy $Fe_{1-x}Ni_x$). Such disadvantage can be compensated by roentgen fluorescent analysis under ion, electron or roentgen excitation.
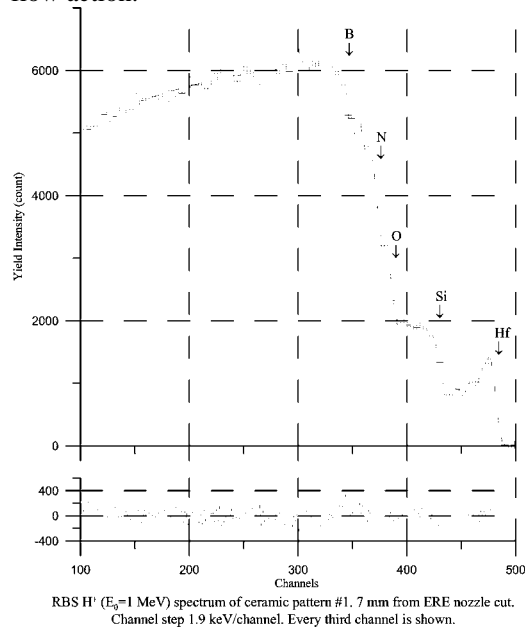
Hydrogenous ions were chosen as a probe due to the fact that they are very effective for examination of element concentration for the targets consisting mainly of atoms with low atom mass (B, C, N and so on). Energy choice is a compromise decision. On one hand, if one decreases ion beam energy, method resolution

over mass increases. But on the other hand, if ion beam energy increases, a cross-section of non-Rutherford ion scattering on nuclease of some elements (first of all on boron, carbon and oxygen nuclease) increases. Besides, with this energy increase, the nuclear reaction $^{11}B(p;\alpha)^8Be \rightarrow 2\alpha$ yield increases. Both factors complicate RBS spectrum processing, causing non-control errors in determining elemental concentrative profile of the tested target. As a whole, RBS parameters correspond to the accuracy 3-4% and resolution over depth is characterized by a value 20 – 30 nm.

Rutherford examination showed that initial composition of ceramic material is the following: $B_{0.31}N_{0.31}O_{0.15}C_{0.16}Si_{0.06}X_{0.01}$. Besides the main structure-forming elements of a ceramic, in the material there are Al, Ca and Fe (0.7%, 0.2% and 0.1% respectively), as roentgen fluorescent measurements showed. As special additions in the material there are atoms of Zr and Hf in micro-quantity. It is significant that these elements are distributed over material volume not uniformly, in the form of separate micro-granules with typical composition ZrO_2 and HfO_2.

Isolator surfaces after the experiment was examined in two points – 3 and 7 mm from the thruster cut. The four ceramic segments of ring - form isolators, contacted with Xe plasma cloud during different periods of time, were investigated. Theoretical and measured spectrums (with RBS method) for insert 1 are represented in the Fig. 9.

Analyzing data obtained with RBS method one can see that a concentration of atoms B, C and also micro-admixtures of Fe, Ca, Zr and Hf changes sufficiently in isolator's near-surface zone exposed to plasma flow action.

RBS H^1 (E$_0$=1 MeV) spectrum of ceramic pattern #1. 7 mm from ERE nozzle cut. Channel step 1.9 keV/channel. Every third channel is shown.

Concentration of atoms Si, Al in this zone is practically invariable, if it is compared with ceramic composition without plasma exposition. Oxygen atoms concentration in modified surface is insufficiently higher than it is in a pure ceramic. Comparing the concentration profiles for two points on surface of isolator (l=3mm and 7 mm) one can see that a thickness of a modified layer and micro-admixtures content increases with coming down to thruster's cut. Exception is Hf atoms content in upper layer of the surface for the insert 4 (evidently characterized by maximum fluence of plasma action) for the point l=7 mm. It can be due to the fact that in initial ceramic Hf atoms distribution is not uniform or due to Hf atoms re-deposition.

Element concentration change in surfaced layer of isolator depends on the fact that different components of the material have different sputtering coefficients under chosen service conditions.

Figure 9

Carbon atoms are taken away from the isolator most intensively under plasma flow action. In this case one can see that carry-out rate is greater for the point l=7mm than for the point l=3mm. Carry-out rate for nitrogen, Si and Al atoms can be assumed as equilibrium for chosen sputtering conditions as far as their concentrations in the surfaced area are the same as it is in the volume.

The concentration of heavy admixed atoms (Ca, Fe, Zr, Hf) in the modified surfaced area increases as far as theirs sputtering coefficients are small. At the same time, if one compares concentration profiles corresponding to different periods of time and different intensity of plasma action, it is possible to see, that such accumulation is not unlimited. May be it is possible to assume that there is some critical value of plasma flow fluence, which is determined by average energy of plasma particles and time of plasma action onto isolator's surface. As a result of such action an equilibrium elemental distribution is set in for given elements distribution over ceramic thickness. From the standpoint of such assumption it is necessary to pay attention to the fact, that boron atoms concentration increases greatly in the near-surfaced layer of a material subjected to plasma action. On the one hand it is pointed to the decreased sputtering rate of the mentioned element (boron) relatively other structure-forming atoms. At the same time one can see that boron maximum content is taken place not in the upper layer of the near-surfaced zone, but is in the area on 100 nm deeper. It permits us to assume that a ceramic with a composition corresponding to this area of concentration profile is the most resistant against plasma action for the chosen elemental composition and plasma flow parameters.

3.3. Data analyses

In the Fig.10 it is represented a dependence of ceramic composition on the thickness at different moments of time. As one can see from this figure, composition stabilization is happened already for the first hours of thruster operation, after that profile of concentration is changing insufficiently. The great thickness of changed layer can be explained by micro-relief presence on ceramic surface (micro-relief is formed under ion bombardment). According to RBS, typical size of the micro-relief is 3-5 µm and is increasing with thruster time of operation. Visual examination gives the same result.

In Fig.11 a) it is represented the angular variation of ceramic composition. The variation of heavy fraction is significantly lager than light ones. The extreme value for both is insert 4. This data is in good correlation with sputtering rate.

In Fig.11 b) it is represented the angular sputtering rate divergence obtained with weight measuring method. One can see that for insert 4 the wearing is significantly greater. We could not explain this phenomenon identically. But in any case the maximal sputtering rate was achieved for the insert with minimum light component concentration.

After 44 hours of thruster operation one could see that there was a sufficient "washing out" of nitrogen (Fig. 10 b, 12a)[15]. It could be happened due to sharp increase in ceramic sputtering coefficient. Therefore it is interesting to examine concentration profile of nitrogen and other ceramic components, if a nitrogen and Xe mixture is used as a thruster's propellant (Fig. 12 b-d).
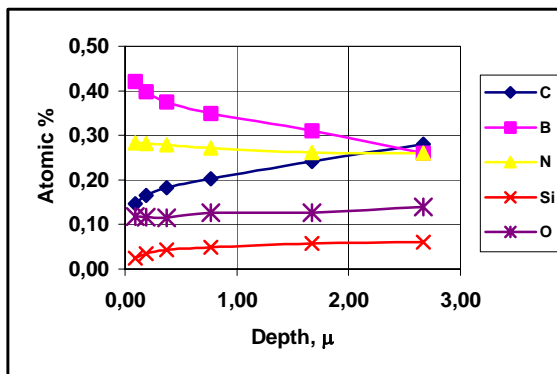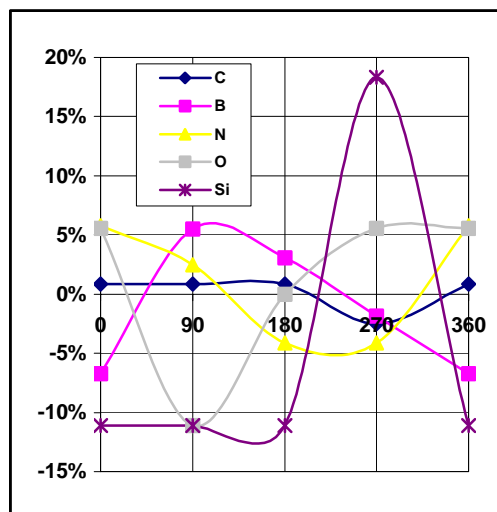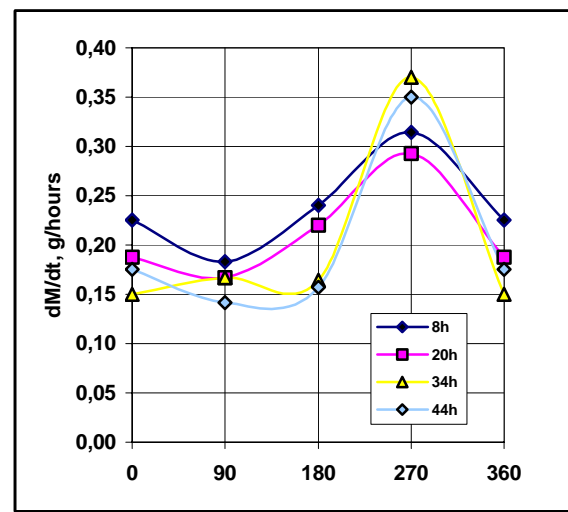

(a)
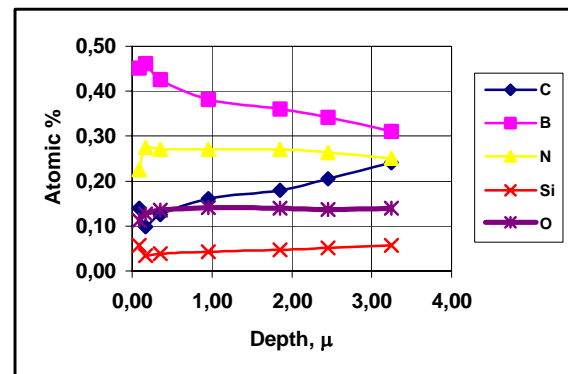
b)

Fig. 10. Ceramic elemental composition distribution over thickness at different moments of time: a) after 8 hours of thruster ignition; b) after 44 hours

(a)

(b)

Figure 11. Angular variation of: a) ceramic composition; b) erosion rate

First of all it is necessary to pay attention to the fact, that there is no nitrogen "washing out" both in old and new inserts. And what is more, if one compares concentration profiles for inserts 1 and 4 in the points 3 mm and 7 mm, it is possible to see, that nitrogen "washing out" is compensated by nitrogen ion flows.

The second conclusion, which can be done, comparing "old" inserts (inserts 2,4) and new ones (inserts 1,3), is the following: inserts prehistory influences insufficiently on to concentration profiles. For example, the profile difference for the inserts 2 and 3 in the point 7 mm is extremely small and visually insensible.

Sufficient "washing out" of nitrogen that one could see in the experiments after 44 hours of thruster operation could be correlated with nitrogen concentration decrease in point 7 mm for the inserts 1 and 4. May be this phenomenon is happened due to the fact that ion incidental angle decreases, but most probably it is due to the fact that jet composition influences insufficiently onto nitrogen distribution in the ceramic material. At the same time it is necessary to point out that we did not see such great drop of concentration in the previous experiments. And what is more, after operation at gas mixture the concentration profile of nitrogen restores (see Fig. 6 a) and b). But it is necessary to take into account that current density and ion energy were lower in the described experiment, which also could be the cause of nitrogen sputtering rate decrease and of profiles smoothing.
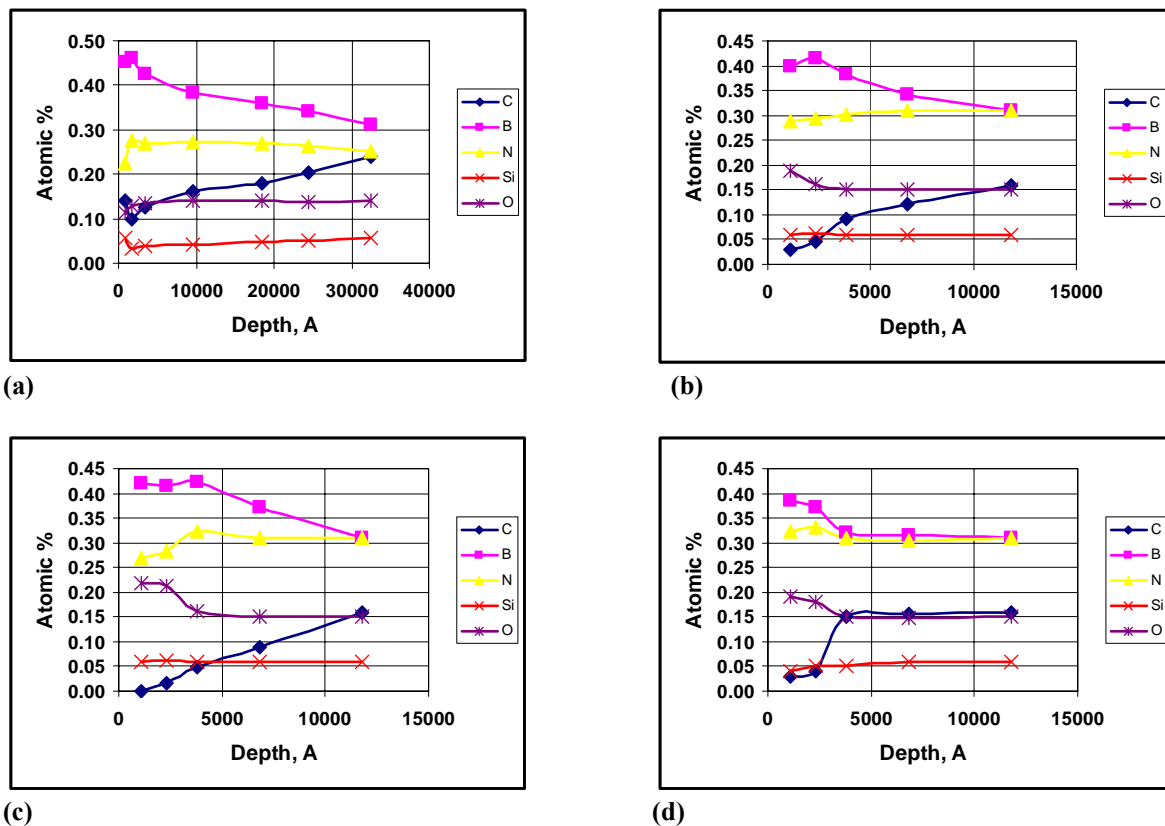

(a)

(b)

(c)

(d)

Figure 12. Elemental composition distribution in ceramic inserts a) #4, 3 mm, Xe, 44 hours; b) #4, 3 mm, Xe, 44 hours, Xe+N$_2$, 28 hours; c) #4, 7 mm, Xe, 44 hours, Xe+N$_2$, 28 hours; d) #1, 3 mm, Xe+N$_2$, 28 hours.

IV. CONCLUSIONS

1. The profile of ceramic components concentration over thickness is stabilized during first 10 hours of SPT operation and further is changing insufficiently.

2. The ceramic composition changes greatly with thickness, azimuth and along channel length.

3. The thickness of the destroyed layer can be 3-5 µm, if Xe is used as a propellant and it decreases down to 1 µm, if nitrogen is used.

4. The thickness of the destroyed layer depends on initial surface micro-relief.

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5. Nitrogen presence in the mixture decreases ceramic's nitrogen sputtering rate, but even under great nitrogen concentration in plasma such phenomenon is insufficient. There is no sufficient nitration of the surface that can be due to the self-sputtering phenomenon and due to nitrogen small thickness of penetration into ceramic.

6. During ceramic sputtering it was found out that a concentration of admixtures (ZnO_2 and HfO_2) increases greatly on ceramic surface and this phenomenon can influences greatly on to ceramic emission property.

7. The ceramic temperature during simulating test should be the same as it is in SPT during operation.

Acknowledgments

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Periodicals

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