The procedure of determination of hollow cathodes erosion by relative line intensity of propellant and material cathode evaporated atoms plasma is described. The data on control of erosion of tungsten-barium metal porous cathode operating in xenon are given.

**Nomenclature**

- $U$ - the voltage of arc combustion;
- $I$ - the arc current;
- $G_X$ - the flow of gas (xenon) generating plasma;
- $T_e$ - the electron temperature;
- $G_{Ba}$ - the cathode erosion velocity (barium evaporation velocity);
- $m$ - the atom mass;
- $N$ - the particle concentration;
- $I_{Ba,Xe}$ - the line intensity of barium and xenon.

**Introduction**

For a large variety of practical applications, the arc cathodes with life-time above 10,000 hours at the current density above 10 $A/cm^2$ are necessary. This durability may be provided only with the cathode materials with a small work function like lanthanum hexaborid ($LaB_6$) or barium-calcium aluminate that is an active substance in metal porous cathodes. At such long-term required resources of cathode operation, it is necessary to have reliable methods of serviceability prediction.

The degradation of operating characteristics of such cathodes is usually connected with evaporation of substances with active emission capability.

Therefore, during life-tests, the rate of their evaporation is to be monitored. The data on temporal evolution of evaporation rate may permit estimation of the time in the course of which the cathode will lose the emission capability.

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Description of procedure

In this paper, the quantity of cathode erosion was checked through a ratio of radiation line intensity of gas atoms and ions generating plasma and cathode material. The advantage of this procedure that was used in [1] consists in possibility of monitoring of cathode evaporation rate.

The special feature of cathode-compensator operation of electric propulsion is a comparatively low electron concentration in a plasma flow - less than $10^{13}$ cm$^{-3}$. Therefore, population of excited states of cathode material atoms and ions may be calculated in the coronal model in which, it is assumed that excitation of atoms and ions takes place from the ground state as the result of electron impact, and deactivation - owing to radiation transitions. At the low electron concentrations, the inert gas plasma is considered optically thin, then for the ratio of plasma components concentrations within the homogenous source approximation, the relationship is true:

$$\frac{N}{N_j} = \frac{K_j}{K_i} \cdot \frac{\delta_j}{\delta_i} \cdot \frac{\lambda_j}{\lambda_i} \cdot \frac{I_j}{I_i},$$

where $K_j, \delta_j, \lambda_j$ and $I_j$ - the excitation level constant because of electron impact, the probability of a spectrum transition with a wave length $\lambda_j$ and the line intensity, respectively. As the estimation shows, the multiple ionization in plasma may be ignored, then the ratio of flows of working gas (xenon) and cathode material (barium) is defined from the formula:

$$\frac{G_{Ba}}{G_{Xe}} = \frac{m_{Ba} \cdot N_{Ba} \cdot (1 + N_{Ba})}{m_{Xe} \cdot N_{Xe} \cdot (1 + N_{Xe})} \cdot \left(\frac{N_{Ba}}{N_{Xe}}\right)$$

The ratios of concentrations of atoms $(N_{Ba}, N_{Xe})$ and barium and xenon ions $(N_{Ba}^*, N_{Xe}^*)$ are functions of electron temperature and optical transitions probabilities, and may be calculated from the known excitation cross-sections.

Thus, for determination of cathode erosion, it is necessary to measure the intensity for evaporated particles lines and plasma-generating gas lines, as well as an electron temperature.

The electrons temperature, as well as their concentration and the plasma potential were determined with the help of cylindrical tungsten-rhenium probes with a 50 µm diameter. The difficulty of probe measurements lies in the fact that the heat flux out of plasma is sufficiently large, hence to avoid the probe destruction and electron emission from the a probe, the measurements were conducted in a pulsed operation in supplying a saw-shape impulse of 0.5 - 2 ms duration to a probe. This time defines the time resolution of the probe procedure. The length of operating portion of a probe comprised 1 - 2 mm, the minimum distance from it to a cathode exit section - 1 mm. The signals of a probe circuit are input into the computer and processed according to the Bohm's theory, whose applicability was confirmed by measurement results.

Experimental results

The proposed procedure was used for check of erosion of tungsten-barium spherical hollow cathodes rated at nominal current values of 4.5 A and 14 A with active substance of the following composition: $3'BaO \cdot 0.5CaO \cdot Al_2O_3$, cathode porosity - 20 %. The diameter of cathode exit hole was equal to 0.8 mm. Anode was a molybdenum disk of 50 cm$^2$ area, which was 1 - 3 cm distant
from cathode. Typical volt-ampere and volt-flow rate characteristics for the cathode that were investigated are given in Fig. 1 and in Fig. 2.

Conducted was also the measurement of a cathode temperature by optical pyrometer. in doing so, prior to the measurements the arc extinction was carried out to eliminate the contribution from plasma radiation to measurements.

Fig. 1. Volt-ampere characteristic of discharge at the two values of xenon flow:

1 - $G_{Xe} = 0.34 \text{ mg/s}$, 2 - $0.5 \text{ mg/s}$

Fig. 2. Volt-flow characteristic of discharge at the arc current of $4.5 \text{ A}$. 
These measurements have revealed that the cathode brightness temperature increased from 1360 to 1470 K with current increase from 5 to 5 A at xenon flow rate of 0.35 mg/s, and from 1310 to 1460 K at xenon flow rate of 0.5 mg/s. The cathode temperature dependence on gas flow rate is nonmonotonic, i.e., corresponds to arc voltage variation.

The analysis of probe measurements has revealed that the plasma parameters and discharge stability degree differ essentially at various portions of the volt-ampere characteristic. One would be also noted that the discharge voltage depends on the anode geometry and anode-cathode distance.

The spectral measurements were conducted with the help of monochromator MDR-23. The base portion of a spectrum was selected in the range of wave lengths 4500 - 5500 Å. In spectrum of arc radiation apart from xenon atoms and ions, recorded were the lines of elements incorporating into cathode: barium, calcium, aluminium, as well as molybdenum out of which the cathode exit diaphragm was made. It is interesting to note that the enough strong lines of double-ionized xenon were observed too. Identification of spectral lines was performed by the data [2]. The lines selected for analysis of velocity of barium evaporation from cathode, are given in Table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Wave length, Å</th>
<th>Excitation energy, eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xel</td>
<td>4923.15</td>
<td>10.95</td>
</tr>
<tr>
<td>Xel</td>
<td>4582.75</td>
<td>11.14</td>
</tr>
<tr>
<td>Xell</td>
<td>4921.48</td>
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<tr>
<td>Xell</td>
<td>4540.89</td>
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</tr>
<tr>
<td>Bal</td>
<td>5555.48</td>
<td>2.24</td>
</tr>
<tr>
<td>Ball</td>
<td>4554.04</td>
<td>2.72</td>
</tr>
</tbody>
</table>

In Fig. 3 the distributions of plasma components radiation over the discharge gap are shown. For all lines near the cathode section, the maximum of plasma radiation intensity is observed. The fact, that the line glow intensity near anode was higher than near cathode at some regimes, proved to be unexpected. Apparently, it is connected with emergence of positive anode drop because of which the electron temperature increases.

In Fig. 4 shown are the results of variation of barium atoms lines intensity during life tests for the two different cathodes at the arc current of 14 A. Since the xenon lines intensity, as well as the discharge characteristics do not vary in the course of the test judging from the measurements, the barium lines intensity variation may be explained only by decrease of its evaporation rates.

Judging from the data in Fig. 4, the barium evaporation rates decreased approximately by an order in 50 hours of operation, but it did not result in cathode emission characteristics. One would note that at the test duration above 5 hours the barium line intensity decreases as the reciprocal of t½. The curve 3 in this Figure - the data on a rate of barium-calcium aluminate evaporation in
Fig. 3. Distribution of atom lines radiation intensity through a gap length. 

\[ I = 4.5 \, \text{A}, \ G_{x_e} = 0.33 \, \text{mg/s} \]

Fig. 4. Time variation of Ba-ion radiation intensity $\text{Ba II} \ 4554\, \text{A}$ for the two different cathodes - 1, 2, 3. 
3 - Time variation of barium evaporation velocity at the temperature of 1500 K [3]
vacuum with the same composition of active substance at 150 K temperature, cathode porosity - 25% [3].

The procedure in hand permits the comparison of evaporation rates for barium and calcium out of cathode. These two elements have close characteristics of level excitation and deexcitation for a set of lines. therefore, the ratio of line intensities is the estimated ratio of barium and xenon concentrations. It should be noted that there were regimes for which the calcium evaporation velocity has essentially exceeded the barium evaporation rates.

Judging from the relative intensity of xenon atom and ion lines in the rated mode of cathode operation, the extent of propellant ionization was evaluated. Thus, the ionization extent comprised 10 - 20% for an arc current of 4.5 A.

The stated procedure of barium flow measurement based on the relative line intensity is convenient for monitoring because of its comparative simplicity and obviousness.

However, the receipt of numerical data requires the fulfillment of some enough strict conditions: Maxwellian electron distribution by velocities, kinetics locality of excited states population and reliability of the data on excitation velocities from the electron temperature. All these conditions are not satisfied simultaneously in the operating regimes of cathode. The authors have proposed the procedure for determination of a barium concentration through absolute intensity of barium atoms and ions. For increase of accuracy of measurement, the special procedure for determination of electron distribution function by velocities was developed. It is based on nonparametric analysis [4] of probe signals. The results obtained in such approach may be used for calibration of the procedure of relative intensities.

**Conclusion**

The developed procedure for measurement of barium evaporation rate out of a hollow cathode through relative intensity of barium and xenon lines permits monitoring of the cathode erosion in an arc discharge. It is shown that at initial point in time the cathode evaporation velocity decreases with time, and this decrease connected with the barium surface concentration decrease does not result in discharge characteristics.

The preliminary data on a barium evaporation rates quantity reveal that at the nominal regimes of cathode operation its evaporation rate is considerably less than an evaporation rate in vacuum. This distinction is correlated, apparently, to processes going on in a cathode cavity.

**References**


