Investigation of Hollow Cathode for Low Power Hall Effect Thruster

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Abstract: In this document we represent the basic set of experimental researches of the gas-discharge hollow cathode (0.2-0.5A) for low power hall thruster (LPHET). Researches were directed on creation of the cathode with a minimum of power and propellant flow consumption. Cathodes with heatless start which have the simplified design and launching heating by glow discharge are considered. It is shown, that the best cathode performance are reached under optimum conditions of pressure in the cathode 40-60 Torr and current density on the emitter 15-25 A/cm^2. Direct firing tests of cathodes emitters in the conditions of close to real during more than 10000 hours are represented. Level of power and the of a xenon consumption of the cathode in activity with SPT-20 does not exceed 5 W and 0.05 mg/with, accordingly.

Nomenclature

c = a velocity of light, 3x108 km/s
h = Planck's constant
k = Boltzmann Constant
n = refraction factor
T = temperature
ε = emissivity
λ = wavelength

I. Introduction

Last ten years are marked by boom in using of small satellites for the solution of various problems in a close space. Perspectives of electric propulsion system (EPS) using for them have led to growth of researches in a creation direction of low-power thrusters with high performance of efficiency and life time [1]. The efficiency of low-power thruster must reaches 40% for the most acceptability. Also it must have such behaviors as simplicity, compactness, low weight of power and propellant supplying systems. HET is satisfied these conditions.

Intensive enough development works and laboratory researches of the LPHET in the STC SPE (Scientific-Technical Centre of Spacecraft Propulsion and Energetics) of National Aerospace University "KhAI" have shown a capability of creation of flight models of such engines [2]. Thruster non-failure operation demanded from flight models. It assumes reliability of all thruster elements. The hollow cathode which can create significant losses in SPT is one of them.

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The review or literature on low-power cathodes for HET has shown unsuccessful attempts of using the flat heater cathode without a gas flow, level of which power expenses has exceeded expenses for thrust creation in HET with 100 W consumption [3]. Using of the hollow cathodes working on metals with low work function is unacceptable because of thruster ceramic contamination with a conductive film. High expenses of power for the hollow cathodes which use high-frequency discharge do them also unsuitable in low-power thrusters [4].

Long-term researches and successful gas-discharge hollow cathodes application on spacecrafts have shown high operational and resource capabilities of their conventional schemes. These are the cathodes which design represents: heatproof tube with impregnated emissive insert, a launching heater and a keeper. The inert gas (usually Xe) is pumped over through the cathode for the plasma conductive environment creation. However, researchers have found out discrepancy of calculations of known computer models to experimental results at creation of cathodes on small currents (less 1A) [5]. Attempts of electrical power and a gas flow rate minimization by reduction of the cathode sizes have led to more difficult picture of the physical phenomena in the orifice plasma region. The large attention in activities [5, 6] is given to processes near cathode exhaust outlet, its form, cathode thermal scheme, application of low heat conductivity materials, keeper form and operational mode.

The results of researches of low-current cathodes designed on heatless-start scheme with galvanic untied diaphragm [7] are represented in the given work. The experimental data of influence of gas pressure in a cavity and current density on the emitter is given. The resource estimation of impregnated insert for long full-scale tests is given. The method of the cathode soft start is resulted. The parametres of a cathode performance with SPT-20 are represented.

II. Research results

A. Breadboard models researching

Hollow cathodes used in this research and their breadboard models are developed and made by existing techniques and requirements to objects of fly-space tests. Experimental activities were conducted on some types of breadboards: cathodes with a replaceable diaphragm with metal (fig. 1) and glass (fig. 2) cases; a tight glass flask filled to optimum pressure with a xenon impregnated insert and anode (diaphragm) with an interval equal to a emitter-diaphragm backlash the in the hollow cathode. Impregnated inserts of these breadboards are identical each other and offered a Mo tube with impregnated cylindrical high-emissive insert. One of the emitter material selection conditions is an activity capability at the increased density of a current (15-25A/cm^2). In such conditions the sizes and weight of the emitter essentially decreased, that led to thermal losses decreasing. After long searching the selection has been stopped on the high-emissive emitter made by the way of high-temperature impregnation of a tungsten sponge with barium scandate. These emitters have passed vacuum tests for a subject of emissive, temperature, resource and anti-contamination properties.

B. Spectroscopic researches of emitter erosion intensity in the hollow-cathode plasma.

The high-temperature oxide-emitters considered as effective emitters of hollow cathodes for HET, in vacuum conditions have low (barium) [8], but this ablation will determine cathode service life. Cathode for HET is not vacuum-cathode and ablation speed of emission-active components can differ essentially from the values received at vacuum tests. That demands carrying out of special researches in the close to operational conditions.

Recently methods of optical spectroscopy [9, 10] are widely used for determination of EP sputtered details erosion speed. Active component erosion speed was estimated on presence of its components in external plasma column (behind a cathode diaphragm). Such estimations can be underestimated because this component will be carried away not only together with working plasma-generative gas, but also to be deposited on rather cold cathode parts. In the hollow cathodes intended for activity on small currents (~0.5) erosion speeds are small enough and in an external plasma column (behind a diaphragm) erosion substances concentration can appear so low that it will be impossible to identify tracks of substance reliably in external plasma column spectrum. For this reason, the active substance contents control is desirable to proceed in space between the emitter and cathode diaphragm.

The researches purpose consisted in technique working out of the emission-active component erosion speed control of the hollow cathode emitter and in finding-out of influence of basic plasma gas (Xe) pressure on erosion speed of emitter based on the barium scandate.

C. Ratio for a hollow cathode constructional elements erosion speed estimation.

In main discharge space of the heater-less hollow cathode and in space between the emitter and a diaphragm the length of free pass of the plasma forming particles appears considerably smaller than characteristic sizes of system. It means that for the analysis of the processes in noted areas the model of local thermodynamic equilibrium (MLTE) is quite comprehensible. Within the limits of such model with taking in account rather low speed of the plasma gas ordered motion erosion can be considered as diffusive process. Thus speed of ablation or weight carried away for a time unit dm/dt, at invariable geometry of system will be proportional to concentration of substance in any point of space n_{er} exception sorption surfaces:

$$\frac{dm}{dt} \propto n_{er}\,. \text{ (1).}$$

Presence of erosion substances and its relative concentration in diagnosed part of plasma is simply enough to determine by spectroscopic methods. Thus measured value is intensity of a spectral line which is proportional to number of radiating atoms N_u or average concentration of atoms n_u which is in the corresponding exited state:

$$I_{u,l} \propto A_{u,l} \cdot N_u \propto A_{u,l} \cdot n_u\,. \text{ (2).}$$

Here $I_{u,l}$ - intensity of the spectral line received at transition of atom from a condition «*u*» in a condition «*l*»; $A_{u,l}$ - Einstein's constant for corresponding spontaneous radiation transition; N_u - number of the radiating particles which are in an exited state «*u*».

Plasma of the hollow cathode is cold; hence the main part of particles is in the basic (not exited) condition. In an exited state (providing radiation) there is a small share of particles which according to Boltzmann distribution is equal:

$$\frac{n_u}{n_0} = \frac{g_u}{g_0} \exp\left(-\frac{E_u}{kT}\right), \text{ (3).}$$

Where g_u and $g0$ are statistical weights of the exited and basic conditions of atom.

As the basic part of particles in plasma is in non-exited state so far as substance ablation speed will be determined by concentration of particles in basic condition n_{er0} which can be expressed through concentration of exited atoms. From (3) follows

$$n_0 = n_u \frac{g_0}{g_u} \left(\exp\left(\frac{1}{kT}\right)\right)^{E_u} \text{. (4)}$$

The plasma temperature is uncertain in the ratio (4). For its definition it is possible to take advantage intensities of the basic gas - a xenon, two any intensities relation which spectral lines in a condition of thermodynamic equilibrium is equal

$$\frac{I_{Xe-\alpha}}{I_{Xe-\beta}} = \frac{A_\alpha}{A_{\Sigma\alpha}} \frac{A_{\Sigma\beta}}{A_\beta} \frac{g_\alpha}{g_\beta} \left(\exp\left(\frac{1}{kT}\right)\right)^{-(E_\alpha - E_\beta)} \text{. (5)}$$

Here α and β - the exited states of a xenon which are initial in corresponding radiating transitions; A_α and A_β - Einstein's constants for the transitions providing corresponding spectral lines; $A_{\Sigma\alpha}$ and $A_{\Sigma\beta}$ - the sums of constants of Einstein for all possible radiation transitions from corresponding exited level.

Taking into account all told above from ratio (1), (4) and (5) we will receive expression

$$\frac{dm_{er}}{dt} \propto I_{u(er)} \left(\frac{I_{Xe-\alpha}}{I_{Xe-\beta}}\right)^{\frac{E_u}{E_\beta - E_\alpha}} \text{ (6).}$$

It allows to execute estimations of erosion speeds on the basis of radiation spectrometry data.

Measurements of the hollow cathode emitter material erosion intensity were conducted in specially made breadboard model which external shell was the quartz polished tube. The breadboard model photo in working order (in the presence of category) is shown on fig. 4. The spectrum of radiation of an internal part of category between the emitter and a diaphragm was registered by optical emission spectrometer HR2000 at which the range of controllable lengths of waves lies in range 387-829nm. For the definition of erosion parametre value numerically characterising intensity of process, following spectral lines have been chosen: a resonant line of barium - $\lambda_{u,\,0}$ = 553,55nm, E_u = 2,24eV; xenon lines - λ_α = 823,16nm, E_α = 9,82eV, λ_β = 556,615nm, E_β = 11,81eV.

Thus computational expression for erosion parametre of (6) becomes:

$$\mu_{Ba} = I_{Ba-553}\left(\frac{I_{Xe-823}}{I_{Xe-556}}\right)^{1,126}.$$

Results of the barium scandate emitter ablation relation vs. Xe pressure in the cathode are resulted in drawing 5. Minimum presence on a curve indicates a capability of compromise searching between an overall performance and its resource at cathode designing stage.

D. Comparative operational analysis of the emitter in various conditions

The spectra of a plasma condition and VAC of discharge were chosen as activity comparison characteristics of emitters with and without gas passage. These researches are conducted on breadboard models of hollow cathodes with replaceable diaphragms and bodies from metal (fig. 1) and glass (fig. 2), and also a breadboard model of the gas diode in a glass flask (fig. 3) with optimum Xe pressure. The emitters of these breadboards were identical and corresponded to the real hollow cathode. The distance from the emitter to a diaphragm (in cathodes) and the anode (in the diode) has been sustained with accuracy of 0.2 mm.

The design of breadboards is heater-less scheme executed, therefore launching heating of cathodes was made by glow discharge from the special power source. After achievement of an emitter operation temperature the discharge passed in the low-voltage arc form then breadboards passed to extra earnings within several hours.

The pressure control in devices with a gas passage was conducted by the high-precision pressure gauge connected to a cavity of cathodes by a tube with large section.

VAC of discharges of the presented devices at Xe pressure 50 Torr from which it is visible the increased power of flowing discharges are shown On fig. 7. However it is possible to explain small discrepancies difference of emitter thermal schemes connected with discrepancy of their manufacturing and absence of the thermal screen at the transparent cathode.

Transparent breadboards have allowed carrying out the spectral analysis of a plasma column adjoining the emitter. For comparison of conditions of discharge plasma in the flowing hollow cathode (fig. 8a) and the diode in flask (fig. 8б) full spectra are resulted in a range of lengths of waves of 390-830nm. On fig. 9 intensity lines of Xe exited atoms with power levels close comparisons are resulted in ionisation potential **(**$\lambda_{Xe\text{-}I,\,810,2}$; Wu = 11,75 eV; $\lambda_{Xe\text{-}I,\,817,1}$; Wu = 11,34 eV; $\lambda_{Xe\text{-}I,\,820,6}$; Wu = 10,96 eV; $\lambda_{Xe\text{-}I,\,823,2}$; Wu = 9,82 eV).

Good enough intensity lines concurrence in full spectra speaks about gas structures affinity and its impurity in plasma of two discharges.

Spectral lines of exited Xe atoms show plasma conditions identity in flowing and landlocked discharges.

E. Researches of cathode launching characteristics

From the aforesaid it is visible, that a design of the cathode with galvanic untied diaphragm used as ignite electrode, has more perfect thermal scheme in comparison with conventional with heater. However, the effect from such scheme is shown and in source integration ignition pressure in system of power supplies of the main discharge of the engine under condition of a low voltage of breakdown in the cathode. Experimental results of tests heater-less cathodes show, that it is possible (fig. 12).

Heater-less start assumes heating of the cathode by energy of plasma of firing discharge. The power put in discharge, is the factor of speed of heating of a surface of the emitter, but should be limited by its erosive firmness. The aspiration to the minimum firing erosion is caused by the solution of problems with a considerable quantity of launches of the engine (cathode) exceeding thousand times.

Research of launching erosion in the previous activities [11] have shown its small share from fixed one, however at mass-dimensional minimisation of the cathode emitter the taking in account of launching becomes important. Inconsistency of characteristics of the power source and plasma load is usually accompanied by oscillating effect (рис13), alternating arc and glow discharge with fixations in discharge stains to a surface of the emitter of leading destructive erosion of a surface of the emitter.

It is known, that more than 90 % of power of glow discharge are allocated for surfaces under cathode potential. During the initial moment at low temperature of the emitter, or in another way, high activity of an exit of an emission insert thermal effect of discharge occurs on all emitter parts of the cathode and in regular intervals warms up it. Therefore, if to limit power of a source of a launching heating it is possible to receive stable glow discharge power to 30 watt which will allow to warm up emitter of low-current heater-less the cathode for tens milliseconds at the minimum erosion. On fig. 14 dynamics of change of pressure on ignite electrode of the low-current cathode is shown at limitation of a current of the launching power source.

F. Selection of optimum gas pressure in the low-current cathode

It is a necessary to increase current density from an emitter surface for low-current cathode thermal scheme optimisation as already it was marked above. However, thus it is necessary to find a range of gas pressure at which steady economic operational mode of the cathode can be realised. The scandate emitter Tests in a glass flask in diode mode have been conducted for this purpose at various Xe pressures. The geometry of a discharge interval, the sizes of the emitter and current density was equal to the real conditions realised in the low-current cathode. Results of tests are shown on fig. 6 in which two various operational modes of the emitter are revealed.

The first, at pressure approximately 10-100 Torr corresponds to a stable running and the diffusive form of fixation of discharge, in which the area (40-60 Torr) with a minimum of power expenses is observed. The second, at pressure above 100 Torr leads to transition in operational mode with a stain and to unstable, spasmodic change of pressure in discharge. This mode is accompanied by a local overheating of the emitter surface in a point of fixation with obvious signs of essential erosion that does its unsuitable for use in the hollow cathode.

So the received range of energetically expedient discharge (which finds out also in hollow cathode discharge) can be realised in the test tightly soldered volume which can be used for lifetime tests of emitters at the proof of activity adequacy for plasma intervals with and without a gas passage.

G. The emitters' resource tests results.

Five scandate emitters, with the impregnant contents from 20% to 35% are tested in diode-regime at Xe pressure 50 Torr within 10000 hours at a discharge current 0.3A and at current density of a 20 A/cm^2. Discharge pressure changing vs. time is presented on fig. 10.

After 2000 hours tests the time-relation of discharge pressure change for emitters with the different impregnant contents has been constructed (fig. 11). The emitter with 25-30 % additive contents has the lowest discharge power.

At finish of the tests it is supposed to conduct weighing of breadboard emitters and calculation of impregnant ablation speed.

H. Cathode tests with the LPHET.

Developing and researching of the low-current cathode in a 0.2-0.5A current range in were intended for supply LPHET with an electron source. HET of such class (100W) demand mass flow rate 0.2-0.3 mg/s. The mass flow rate through the cathode can seriously reduce total specific impulse, and high potential in the plasma orifice region bring to a power losses. The selection of the hollow gas-discharge cathode as it was already informed allows creating the most compensated plasma near the cathode at the expense of generation and the expiration of ions from a cathode aperture.

On the basis of the presented researches the heater-less gas-discharge hollow cathode has been made and full-scale tests with engine SPT-20 are conducted. The basic thruster parametres:

- full Xe mass flow rate 0.3 mg/c (cathode 0.05 mg/c);
- discharge voltage 300V;
- discharge current 0.3A;
- thrust 4.5 mN;
- power consumption 100W;
- efficiency - up to 36 %;
- cathode potential drop – 14V.

The last one parameter directly influencing on power of accelerated ions and depends only on quality of the cathode activity. It can be illustrated with help of RPA VACs received during SPT-20 plume analysis. The beam ion power decreasing is visible (fig. 15) for the thruster working with the lower efficiency cathode (a red curve).

III. Conclusion

In this paper was presented complex experimental research of the influence factors on hollow cathodes efficiency with a low working current, used for low-power SPT -20.

It is shown, that only operational mode with the minimum emitter erosion can be the most comprehensible for long-time work of the low-current cathode with low-power SPT. Moreover, deterioration thermal scheme and decreasing cathode efficiency accordingly is following simple emitter size and mass increasing. The regime with minimum of erosion was shown as spectral investigation result of internal plasma low-current scandium cathode.

Higher working pressure and emitter current density is main influence during cathode work. As you understand vacuum tested cathodes has not ion bombardment and give only estimation results. So long time test was needed for scandium emitter verification.

The direct emitter testing method was proposed in paper. It is test inside leakproof volume with xenon pressure equal working pressure inside hollow cathode. There are from 40 to 60 Torr. The long time tests results are shown. Non considerable difference was displayed between cathode test with and without Xe flow. It confirms accuracy proposing method for emitter lifetime determination.

Great decreasing start time and perfect thermal scheme can reach if to use heater-less hollow cathode.

Appendix

Figure 1. Cathode mock-up with disassemble diaphragm.

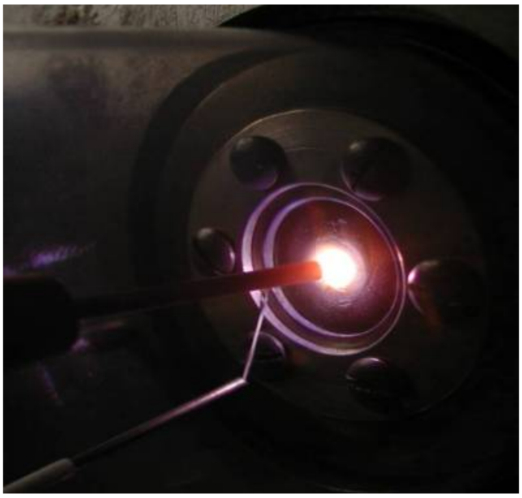

Figure 2. Cathode mock-up with gauzy body.

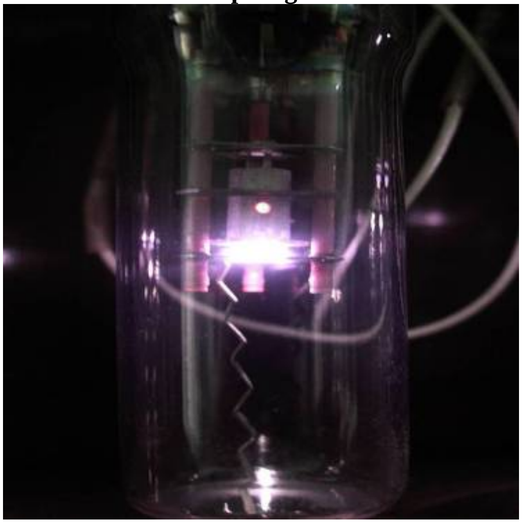

Figure 3. Waterproof glass volume for life-time tests of emitter.

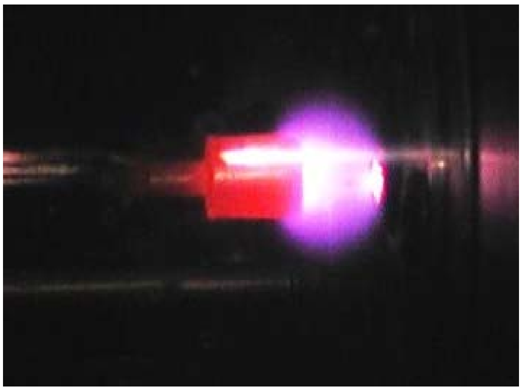

Figure 4. Flowing Xe discharge inside heater-less hollow cathode.

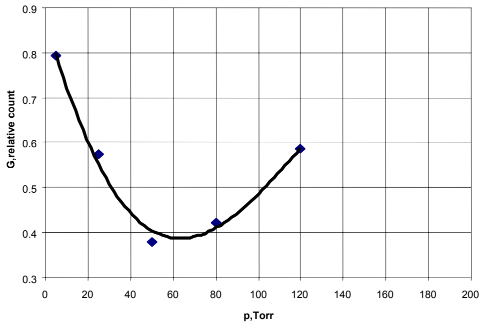

Figure 5. Ba erosion vs. cathode pressure.

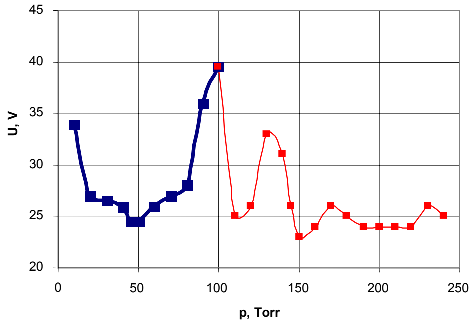

Figure 6. Xe discharge voltage as function of cathode mock-up pressure.

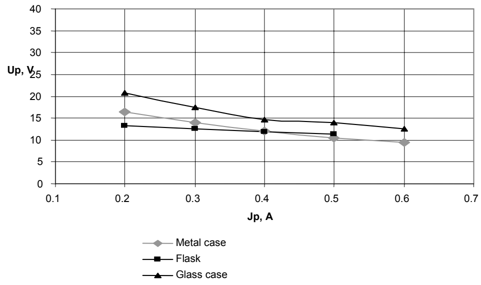

Figure 7. Volt-ampere characteristics

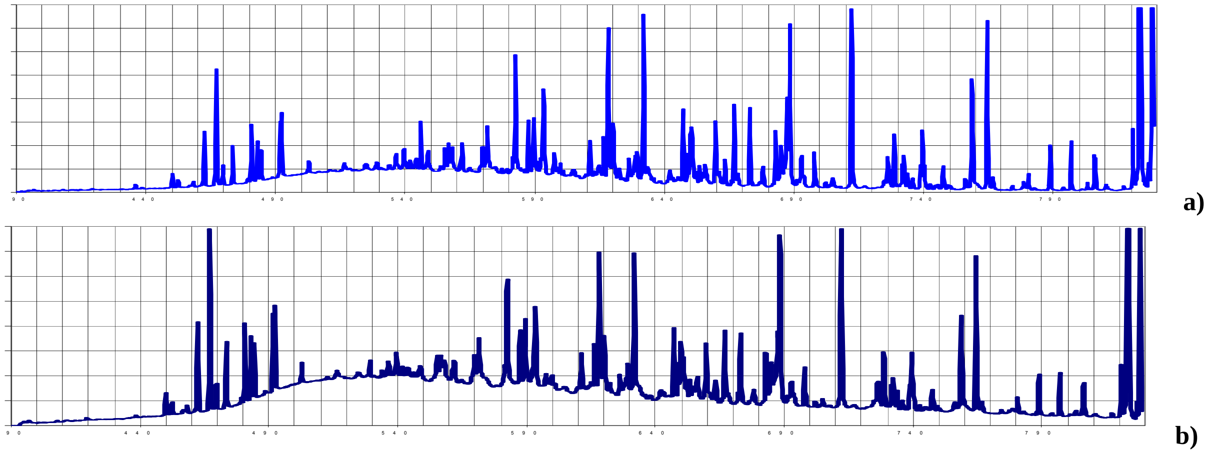

Figure 8. Spectral behavior of Xe discharge with Xe flow and without

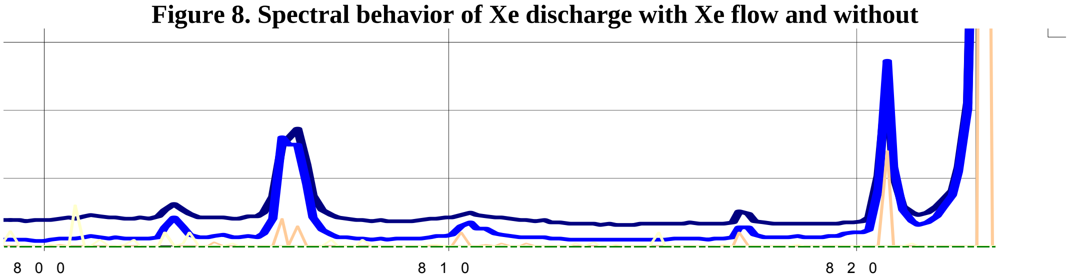

Figure 9. Xe excited atom intensity on discharge with and without Xe flow

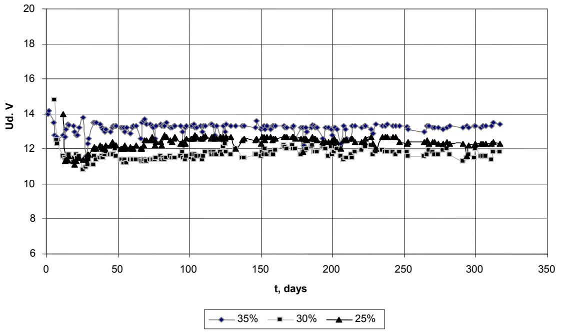

Figure 10. Discharge voltage vs. time of test inside leakproof glass volume.

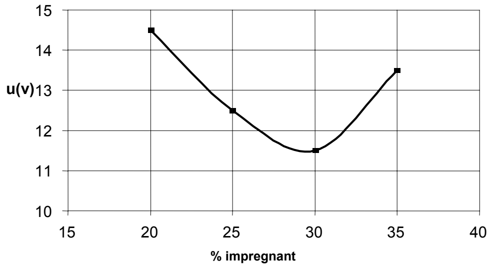

Figure 11. Discharge voltage as function of partial part of emitting addition.

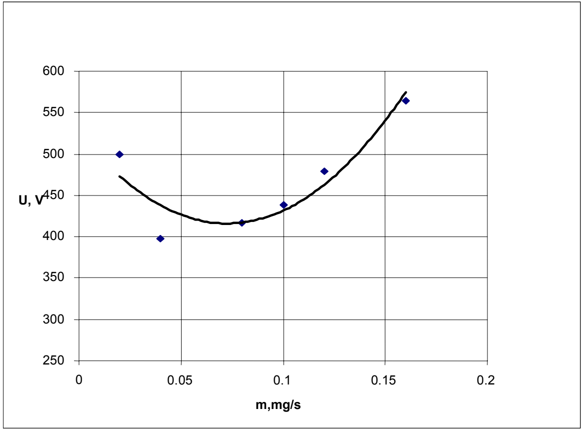

Figure 12. Breakdown characteristic.

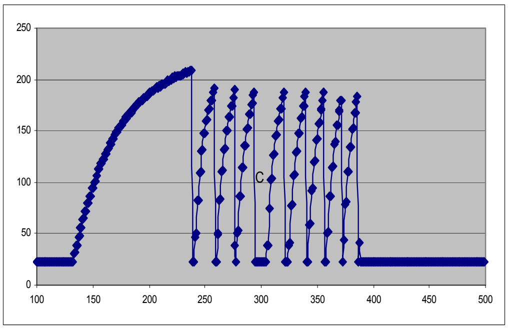

Figure 13. Cathode start oscillogram. PPU and discharge behavior is not co-ordinate.

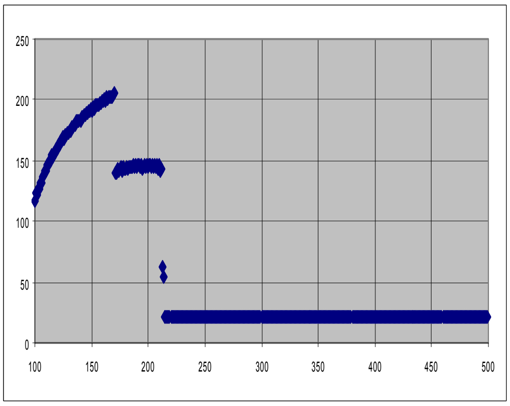

Figure 14. Cathode start oscillogram. PPU and discharge behavior is co-ordinate.

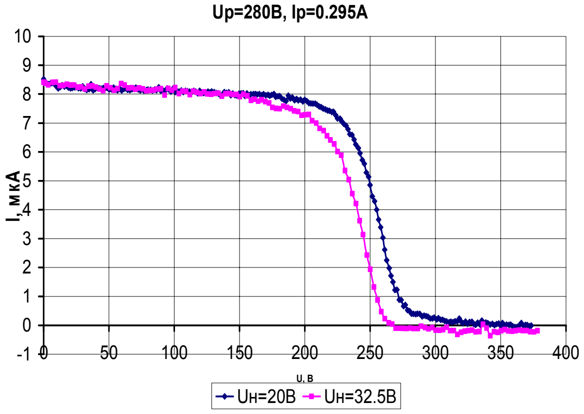

Figure 15. RPA volt-ampere characteristics.

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