DEVELOPMENT AND RESEARCH OF HEATERLESS CATHODE-NEUTRALIZER FOR LINEAR HALL THRUSTERS (LHD) AND PLASMA ION THRUSTERS (PIT)

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ABSTRACT

This report discusses the development issues regarding heaterless cathodes-neutralizers (HLC) on Xenon and HLC design options, presents the main results of experimental investigation, problems and solutions are analyzed and electrical design is discussed.

Work led to HLC experimental model with the following performance:

- discharge initiation voltage 400-500 V;
- discharge current in LHD 1.5-6.0 A;
- time needed to reach the stationary mode discharge current (thruster start-up time) 3-20 msec; with gas distributor - 200 msec;
- isolation resistance in cold HLC >1 Mohm, minimal resistance after test ("hot" HLC) >5 Mohm, trend to further decrease it in process of testing was not observed.

One of HLC modifications was subjected to life test for 10^5 firings. The Russian Federation Patent on the developed HLC №2031472 of 20.03.95 was obtained, priority 05.10.92, and issuing of patent on HLC power system was approved, priority 11.01.94.

INTRODUCTION

Current status and future of space investigations set more strict requirements to spacecraft attitude control and station-keeping.

Stationary Plasma Thruster (SPT) is currently the one looking the most promising as having sufficiently long life, high dynamic characteristics and high number of cycles, that's very important for spacecraft attitude control.

In such conditions the SPT development is substantially determined by progress in developing the cathode-neutralizer, which plays an important role in process of generating and accelerating plasma. That's why development and investigation of operational cathode design using inert gas and characterized by long life and high cycle number, is one of the most important tasks in SPT-based EPS development.

It's known that in Russia and othe countries cathodes with heaters (gas discharge electron sources on basis of hollow cathode) are generally used as cathodes-neutralizers using both liquid metals and inert gases.[1,2]

Such cathode is started by turning on a heater power that should heat up thermal emitter (source of electrons) to the effective thermal emission temperature and after that propellant is fed into the cathode. Then ignitor and discharge voltages are applied, electric arc ignites and thruster starts up. Such cathode start-up time is normally 150-220 sec. It can be seen that heater of such cathode due to its thermal stress and high number of thermal cycles is a critical design element and the manufacturing process for it is complicated.

To upgrade cathode dynamics and to simplify its design EDB "Fakel" has done investigation in the field of heaterless cathode using inert gases. Other scientific research organizations are going the same way: Keldysh Research Center, Russia [3], Kharkov Aviation Institute, Ukraine, Lewis Research Center, NASA, USA [4] and others.

In heaterless hollow cathode thermal emitter is heated with gas discharge occurring after igniting high-voltage arc in the gap between electrodes.

Actual start-up time for heaterless cathode is less than 1 sec accounting for dynamics of propellant supply subsystem. Heaterless cathode being developed at EDB "Fakel" for SPT can be successfully used also in Anode Layer Thrusters (LXT) and in Plasma Ion Thrusters (PIT) both in gas discharge chamber and for gas beam neutralization.

Use of HLC in SPT, LXT and PIT allows to broaden the task range for EPS on spacecrafts and, in particular, opens a possibility to use it for spacecraft attitude control and station-keeping.

EDB "Fakel" has developed experimental heaterless cathodes which passed research, parametrical and life tests aimed at investigation of start-up duration and stability factors, selection of ignition conditions and design features. The results of that work is discussed below.

HLC DESIGN.

EDB "Fakel" has developed 6 laboratory models using design principle presented in Fig. 1. Envelope dimensions of two HLC modifications (HLC-4, BN-8) are also provided. Fig. 2 presents the latest model of heaterless cathode HLC-9.

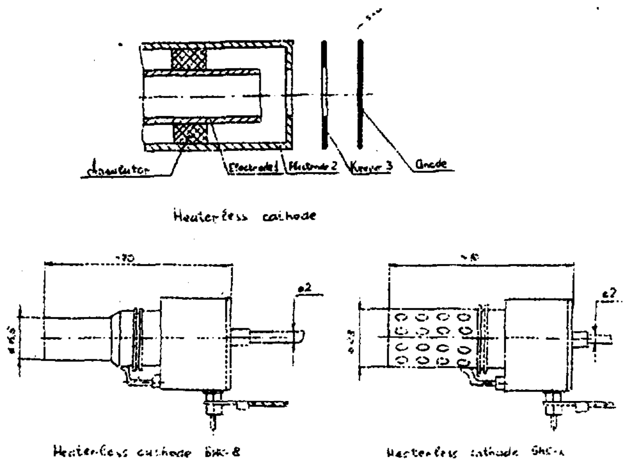


Fig.1 HLC circoit design

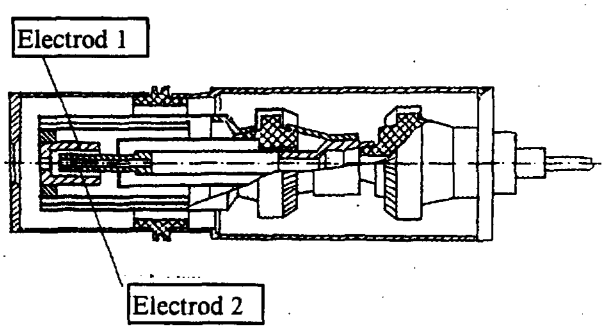


Fig. 2 HLC-9 modification

Each model is supported with design and technology documentation, fabrication of each model was done by lots of 5 pieces each. gap configuration, thermal design, electrical isolation and emitter design.

Models are started up with igniting voltage in the gap between electrodes where high pressure zone is first generated by supply of propellant. Interelectrode gap is formed between surface of Electrode 1 and Electrode 2. Electrical arc is then ignited. Applying voltage on Electrode 3 supporting discharge is ignited which purpose is to extract the arc discharge out of the cathode. Main discharge ignites with applying anode voltage and thruster then starts up.

HLC PARAMETRICAL TEST RESULTS.

Immediately after fabrication each model was subjected to parametrical test to determine their operation capability. Some models was subjected to preliminary tests to determine their life. Operation capability of each model was demonstrated by capability to start up an SPT. SPT-100 was used. After starting up cathode was operated for 30-45 min in operation mode I_D=4.5 A and U_D=300 V at the Xenon flow rate in cathode 0.35–0.4 mg/sec. Parametrical test also was used to investigate conditions of heaterless start-up, select and optimize parameters of discharge ignition and on other purposes.

To provide the stable arc discharge porous tungsten saturated with activator (salts of Barium and Potassium) was used in fabrication of thermal emission Electrodes 1 and 2 that emits sufficient amount of electrons when small zones on Electrodes are heated with an arc. Choice of tungsten base is determined by requirement to maintain configuration of Electrodes during long operation of cathode to maintain constant flow rate and arc voltage.

HLC start-up is based on law showing that break-through voltage U is function of (P×D), where P is propellant pressure and D - distance between electrodes. In test minimum was determined experimentally for each model. On that purpose voltage was applied at discharge ignition circuit steadily rising from 150 V until current ramp occurred indicating break through the gap between electrodes. Test was done within propellant flow rate range 0.2–1.0 mg/sec. Fig. 3 presents results of measurement of minimum for certain models. It was experimentally demonstrated that minimum for all six models laid in range 250–350 V at cathode flow rate in range 0.–0.8 mg/sec.

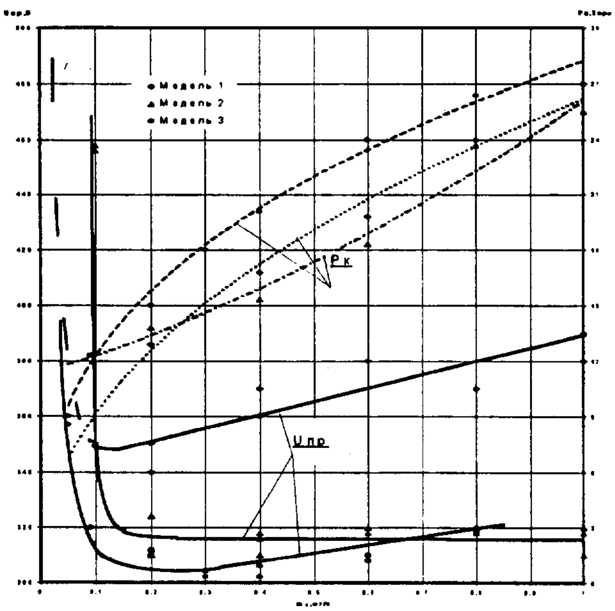


Fig.3. Break-through pressure and voltage to the flow

Having measured decrease of mass of Electrodes 1 and 2 it is demonstrated (Fig. 4) that at Xe flow rate 0.35-0.4 mg/sec mass drop is minimal and at flow rate over 0.4 mg/sec mass drop is constant at any flow rate increase. At flow rate about 0.32 mg/sec and lower mass drop increases steeply.

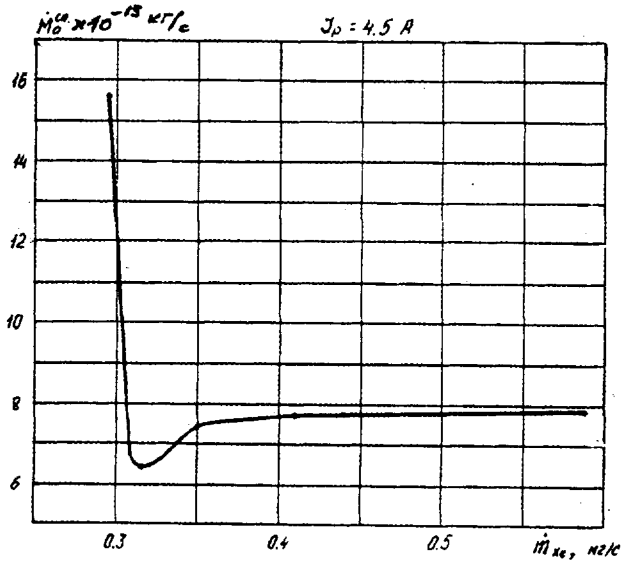


Fig.4 Doping material errosion rate vs cathode flow rate

Prelimiary research showed that electrode erosion rate during cathode start-up is roughly equal to erosion in steady-state operation.

Hence, research on effect of cathode Xe flow rate on parameters allowed to set the optimal propellant supply mode: during start-up and operation 0.4–0.5 mg/sec. Pulsed propellant supply mode appears the most economical during cathode start-up by adding a valve in propellant supply subsystem and operation at 0.4 mg/sec. Such Xe supply mode shall provide for minimal electrode mass drop that increases the entire cathode's life capability.

Flow rate 0.4–0.5 mg/sec is optimal also from the point of view of reliable cathode start-up.

Fig. 5 presents relationship between breakthrough voltage pulse number and Xenon flow rate demonstrating that at flow rate over 0.45 mg/sec it is enough one or two pulses to start up the cathode and at about 0.4 mg/sec no less than 10 high-voltage pulses are required.

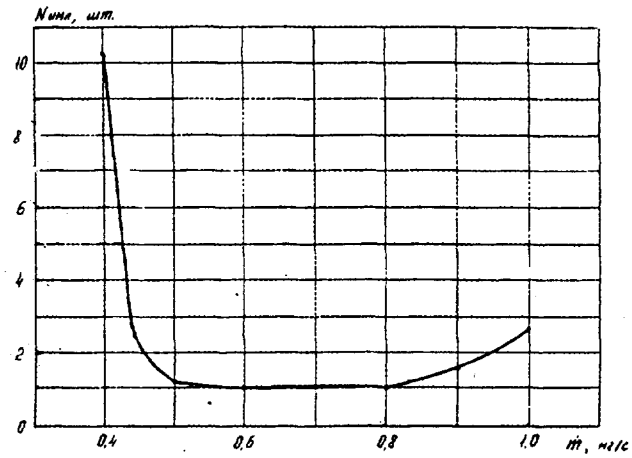


Fig.5 Number of ignition impulses for cathodde to swith on vs cathode flow rate

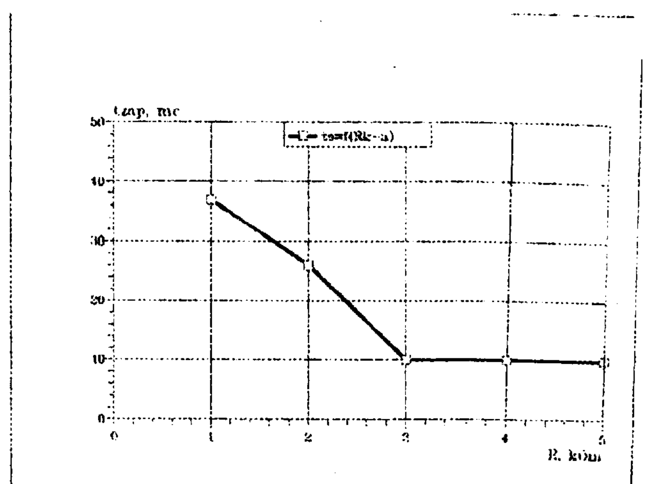


Fig.6 HLC firing relationship to the insulation resistance

Optimal Xenon flow rate at 0.4–0.5 mg/sec is seen in Fig. 7 as well where a cathode-to-vacuum chamber potential U_{KZ} characterizing cathode losses and cathode efficiency vs. flow.rate is presented showing that at 0.4 mg/sec U_{KZ} is minimal and equals to roughly 13 V.

While testing all models it was revealed that cathode failure to start is directly tied to isolation resistance between Electrodes 1 and 2. Measurement of isolation resistance between electrodes failed to start after several successful attempts demonstrated that after starting up resistance drops (initial isolation resistance after fabrication over 20 Mohm). While cooling (pausing) resistance increases. Experiment demonstrated that starting up any model cathode occurs at minimal resistance about 5 kOhm. HLC's start-up isn't hard when cold state (characteristic for heater cathodes) but when hot. Pause between firings should be sufficient to obtain resistance about 5 kOhm. Heaterless cathode startup time vs. isolation resistance is presented in Fig. 6.

Initially, the isolation problem solution was expected to be found in change of cathode thermal design. On that purpose some models were upgraded so that to decrease temperature of gas-electrical connectors and to reliably protect the isolator surfaces against probable dusting with blends. Upgraded cathodes' testing demonstrated that such design changes allowed to lower temperature significantly in zone of gas-electrical connectors. However, that problem is not solved completely isolation resistance drop had been revealed once more. Cathode inspection found that isolation resistance between Electrodes 1 and 2 is built up of several components, one of them was isolation resistance in gas-electrical connector and other was resistance of isolation of the gap between electrode. Conducting deposit was found on inside surface of parts in close proximity to the gap. Experiments were done unsuccessfully to find the cause of deposition of conducting film. During another upgrade of one of the models HLC-9 design of parts critical to isolation resistance in the gap was changed. As a result the conditions were arranged in the gap when isolation resistance drops after startup yet it was substantially higher than demonstrated during testing of other models (about 1 Mohm). Parametrical test demonstrated no drop of it.

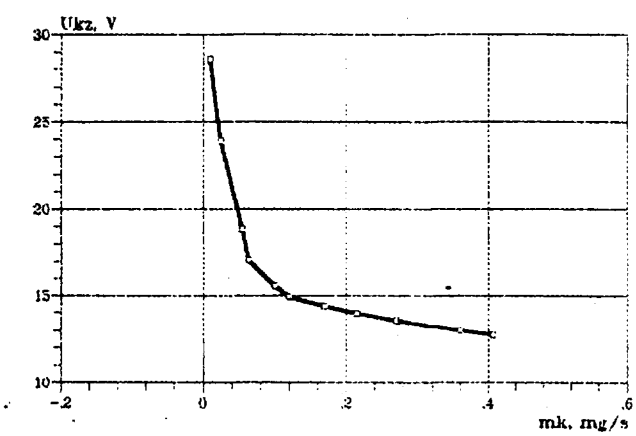


Fig.7 Ukz relationship to the HLC-8 flow

HLC ELECTRICAL DESIGN.

IGNITOR.

Fig.8 presents the electrical design of HLC.

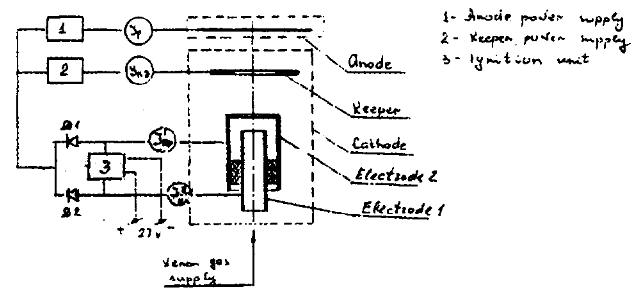


Fig. 8 Heaterless cathode power supply and flow arrangement

Ignitor BP-HLC was developed upon testing of heaterless cathodes aimed at selection of configuration and characteristics of gap break-through Fig. 8 (3).

Ignitor applies high voltage at the gap between Electrodes 1 and 2 in form of pulses with aplitude up to 1 kV, frequency 10 kHz and duration 10 μsec. Immediately after occurrence of arc pulses are stopped and keeping current 0.25 A is maintained until I_D reaches nominal level 4.5 A. Ignitor power voltage is ~27 V.

Several experimental ignitor models were made including vacuum version. In that case ignitor was installed in vacuum chamber in close proximity to cathode to resolve the issue of high voltage cabling and airtight connectors.

BP-HLC ignitor vacuum version draws 1.3 A in idle mode (without discharge) at input voltage 27 V (35.1 W). While igniting discharge in thruster current drawn drops down to 0.3 A and power to 8.1 W.

Temperature range at BP mounting locations is +40 -60°C with option to rise it up to 100°C. BP-HLC envelope is 79x77x40 mm. Mass is 0.4 kg.

Fig. 9 presents experimental models of BP-HLC and HLC-8 heaterless cathode.

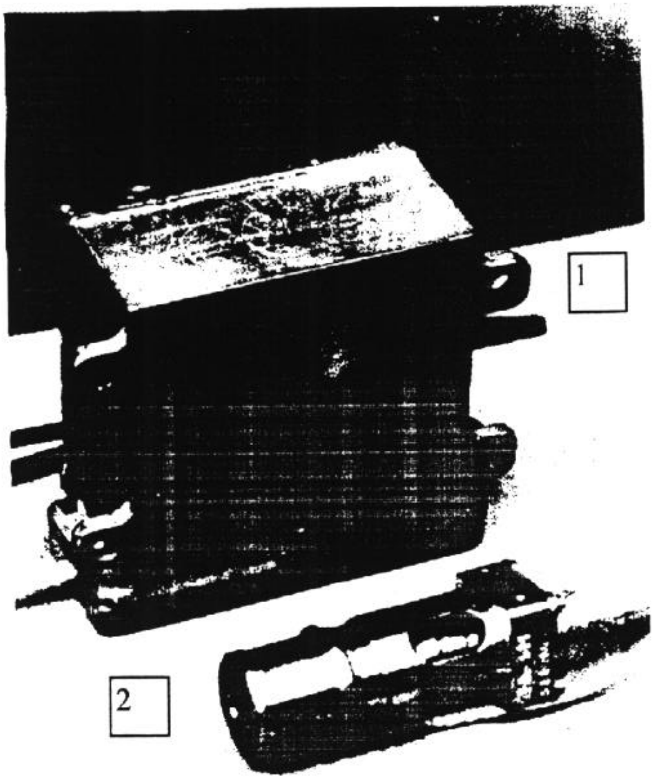


Fig.9
1 - BP-HLC and 2 - HLC-8 heaterless cathode

Development of HLC electrical design aimes at resolving the issue of making cathode life longer and its startup more reliable.

The task was solved with connection of discharge power supply negative pole to HLC Electrodes 1 and 2 with diodes D1 and D2 in the power subsystem of a plasma source with heaterless cathode.

Galvanic coupling of Electrodes 1 and 2 with discharge circuit makes effective emissive surface larger and provides an opportunity to automatically start that cathode which near-cathode potential drop is lower or simultaneously Electrodes 1 and 2 if electron emission properites of those are roughly the same.

The said diodes preclude current leakage through galvanic coupling between Electrodes 1 and 2 while using discharge ignition supply of constant or pulsed voltage.

In the beginning of thruster use discharge current is connected mainly with Electrode 1, while activator being sputtered off its surface deposits on Electrode 2. Further both electrodes emit electrons simultaneously redistributing the activator flux between those electrodes. Galvanic coupling of Electrodes 1 and 2 allows to automatically couple the discharge in cathode with that electrode which near-cathode drop is lower that provides for consequent steady operation of other electrode, i.e. it is regenerated.

Using the ignitor-forming alternating voltage pulses discharge may be ignited with either Electrode 1 or Electrode 2 that enhances startup reliability.

Such power subsystem design allows for multiple use of activator during cathode operation that enhances its life as well.

Besides, electrode 3 is added to cathode to enhance the startup reliability by maintaining the discharge after ignition of arc in the gap between Electrodes 1 and 2.

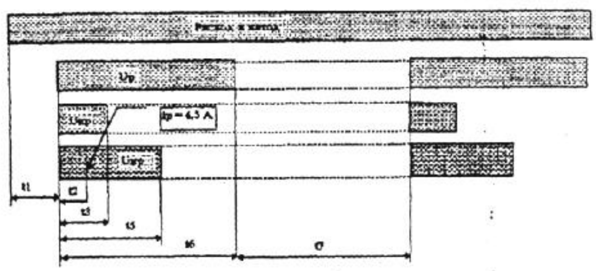
In compliance with selected heaterless cathode startup procedure voltage applies to Electrode 3 after ignition of arc and additional discharge is ignited extracting discharge out to anode. Cathode may be started up without auxilliary discharge of Electrode 3 but on several occasions startup didn't occur while blue lighting was observed inside the cathode (gap bridged) and applying voltage at Electrode 3 startup always occurred. Cathode startup applying voltage at Electrode 3 demonstrates the requirement to have the Electrode 3 in cathode design to add reliability to startup and life.

Test demonstrated that effect of voltage on Electrode 3 is monitored already having achieved 30 V level. Electrode 3 voltage (U_{PR}) value was previously selected and optimized at ≥60 V.

Investigation on effect of auxilliary discharge at Electrode 3 during life test is planned.

Thus, electrical design proposed during HLC use is investigated, developed and proposed.

Fig. 10 presents a recommended HLC startup procedure.



t_1 - cathode flow arrangement time; t2 - firing time (not more than 1s); t3 - voltage reeping time for suppoting discarge (additional electrode - not more than 5s); t5 - ignitor unit operation time (not more than 20s); t6 - cathode operation time; t7 -break between firings.

Fig.10.

LIFE TEST

Work regarding a heaterless cathode's life capability is accoplished.

Life capability of any cathode whether heater or heaterless depends on emitter life (in this case Electrodes 1 and 2; Fig. 2). Electrodes 1 and 2 are made of porous tungsten saturated with salts of Barium and

Potassium. Preliminary estimate of their life capability was done by direct cycle life test. HLC-4 cathode was tested independently with diodes (with a trap). Worked didn't focus of cathode design, upon failure cathode was reworked and test continued. Emitter mode in testing was the most arduous, i.e. operation consisted only of cathode startups, cathode operation at the trap after startup and reaching nominal current (~4.5 A) for 2 sec, puase between cathode firings was 2 sec.

Life test demonstrated the capability of HLC-4 electrode pair to perform 10^5 firings (startups). After test cathode was disassembled for inspection of parts. Inspection found that both Electrodes 1 and 2 retained their configuration, no material loss was observed.

To estimate the entire design's life HLC-8 was life tested with SPT-100.

Test focused on monitoring the capability of cathode to startup the SPT-100 thruster for no longer than 1 sec and to reach operation mode at I_D=4.5 A and U_D=300 V.

The chart of HLC-8 life test is presented in Fig. 11. Cathode Xenon flow rate during the entire test was 0.4 mg/sec. Initially cathode was operated for 2 hours after the first SPT-100 startup and reaching the operation mode (I_D=4.5 A and U_D 300 V) (Cycle 1). After pause (16 hours) cycle life test started. Test included 5 cycles at 400 firings each. 16 hour pause followed each cycle. Cathode operated 3 sec after each firing (SPT-100 startup) (operation mode). Pause between consequent firings was 20 sec (hot firings). Total number of firings during life test was 2000 of those 6 were cold (the first firing of each cycle) while all other were hot. Electrode 3 voltage was not applied during that test.

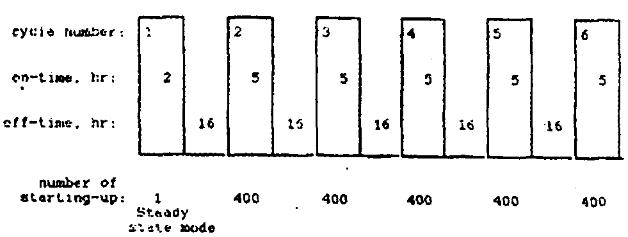


Fig.11 Test sequence

The chart of HLC-8M cathode life test is presented in Fig. 12. Xenon flow rate in cathode during the entire test was 0.4 mg/sec as well. Testing was cycled. First 14 cycles included 144 firings each, after each thruster startup and achieving the operation mode (I_D 4.5 A and U_D 300 V) it operated for 10 sec with consequent pause 5 sec (hot firings). Cycles 15 through 20 contained only one firing each. Pause between each two cycles was 25 min.

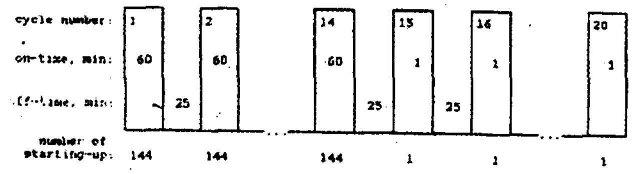


Fig.12. HLC-8 life test sequence

Thus, test demonstrated the HLC-8M 2000 firings capability, of those 20 firings were cold (the first firing of each cycle 1 through 14 and each firing of cycles 15 through 20).

Cathodes HLC-8 and HLC-8M were still operational after test

COMPARATIVE TEST OF HEATER AND HEATERLESS CATHODES WITH SPT-100 THRUSTER.

To complete the work heater and heaterless cathodes were tested with SPT-100. Volt-ampere characteristics of SPT-100 were monitored within range from 100 up to 300 V both with heater (KE-5) and heaterless cathode (HLC-8) (Fig. 13); effect of cathode flow rate on module operation was investigated as well (Fig. 14 and 15). The presented charts demonstrate that within cathode flow rate range 0.2-0.4 mg/sec SPT-100 thrust and U_{KZ} operating with both heater and heaterless cathodes are nearly the same and characterized with stability demonstrating high efficiency of heaterless cathode.

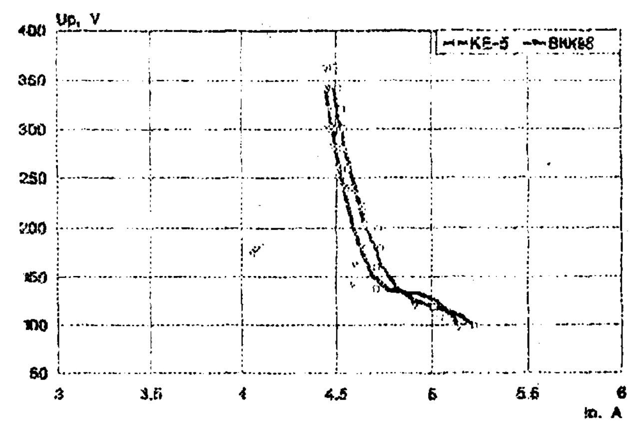


Fig.13 SPT-100 VA performances

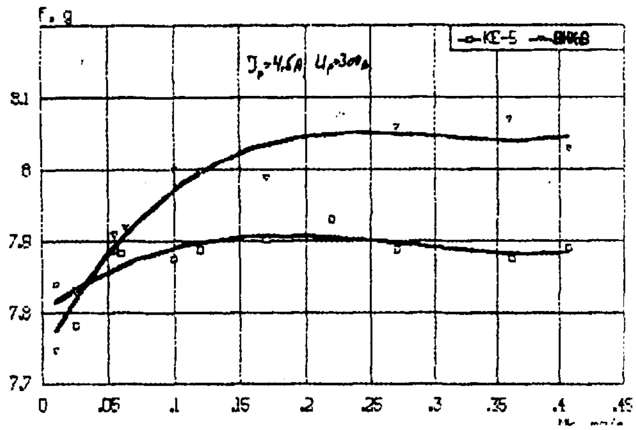


Fig.14 SPT-100 thrust relationship to the cathode flow

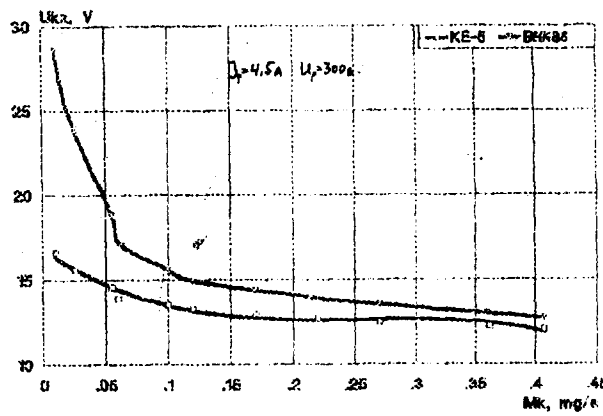


Fig.15 SPT-100 Ukz relationship to the cathode flow

Fig. 16 and 17 present characteristic oscilloscope readings during SPT-100 startup with heaterless cathode (HLC-4) at the cathode flow rate 0.4 mg/sec (Fig. 15) and 0.5 mg/sec (Fig. 16).

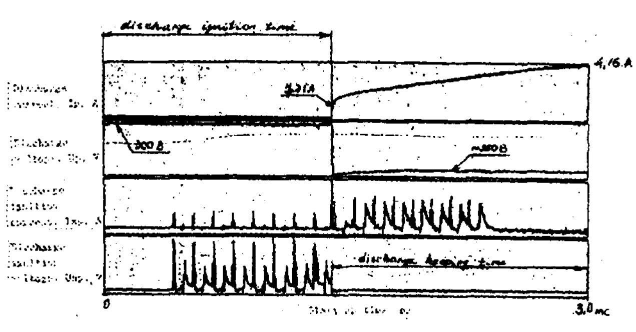


Fig.16 HLC-4/SPT-100 assembly start-up sequence (cathode flow rate is 0.4 mg/s)·

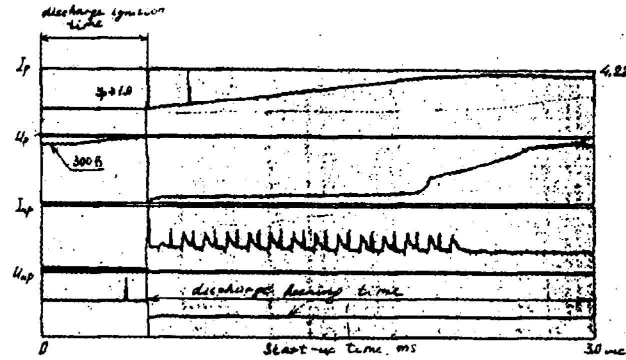


Fig.17 HLC-4/SPT-100 assembly start-up sequence (cathode flow rate is 0.5 mg/s)

CONCLUSION.

1. Experimental research at EDB "Fakel" has led to developed of row of operational models of heaterless cathode-neutralizer (HLC) to be used with LXT and PIT.

2. Operational experimental HLC models provide for SPT-100 startup and reaching the nominal SPT discharge current within 3-20 seconds at cathode Xenon flow rate 0.35-0.5 mg/sec and initiating voltage 340-500 V.

Operating SPT with gas distributor (XFC) time to reach the nominal discharge current is ~200 msec.

HLC provides for maintenance of thruster discharge current in range 1.5-6.0 A and discharge voltage over 100 V.

3. Electrical design and nominal electrical parameters of HLC are selected. It is demonstrated that auxilliary discharge (Electrode 3, Fig.1) enhances startup reliability and stability of transient of SPT discharge current to nominal mode. Nominal isolation resistance between HLC initiating electrodes should be minimum 5kOhm for reliable HLC startup.

4. Ignitor BP-HLC vacuum version is developed, its parameters are as follows:

ignition voltage pulse amplitude (max) 1000 V;

ignition pulse frequency 10kHz;

power voltage 24-32V;

opeational temperature +40°C...-60°C.

Location of BP-HLC in close proximity to HLC resolves the issue of high voltage transport to HLC.

5. SPT parameters supported with HLC, comply with those supported with heater cathode. HLC operation is demonstrated with cycle life test up to 105 independently and $2 \cdot 10^3$ firings with SPT-100.

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