

Development of a Long-Life Low-Power Hall Thruster

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Abstract: The development of smallsat constellations with aggressive cost per spacecraft is becoming the wave of the future for the space industry. In this context, the development of long-lasting and cost-effective low-power plasma thrusters is of paramount importance for the success of these challenging missions.

At present, EDB Fakel, in co-engineering with Airbus Defence and Space Toulouse, is engaged in the development of advanced low-power Hall thrusters. The flight-proven SPT-50 thruster was chosen as a prototype. To guarantee the requested operational lifetime, innovative magnetic field topology and discharge chamber material have been implemented. In addition, a new cathode has been developed to operate at reduced discharge currents and mass flow rates.

To support the definition of the advanced SPT-50 thruster (called SPT-50M), several engineering models have been manufactured and tested for performance, mechanical and thermal vacuum capabilities. In addition, to estimate the thruster performance during extended operation, a comparative analysis of the operating and lifetime characteristics of the advanced SPT-50M thruster and prototype thruster has been performed.

I. Introduction

DUE to new technologies and materials, avionics become more compact, light and energy-efficient. Spacecraft become lighter, and their service life is extended up to 15-20 years. Modern communication satellites can weigh about 300 kg. The Soyuz rocket can carry out about 30 such satellites in a single launch. It gives the possibility to create orbital smallsat constellations of hundreds and even thousands of spacecraft, as proposed by the SpaceX, Boeing, One Web and others.

It is required to develop an efficient thruster with a high total impulse in order to correct the orbit of satellites. With a large number of satellites in the constellation, the unit cost becomes more critical. Stationary Plasma Thruster (SPT) has been successfully used to correct the orbit since 1971. SPT construction is relatively easy to manufacture, making it relevant for small spacecraft.

Smallsats have limited on-board power resources. Therefore, the thruster should operate at low power. The propellant reserves for the thruster are also severely limited and therefore the specific impulse should be maximized while providing sufficient thrust for a timely insertion to the final orbit. The design of small spacecraft is more stiff, so the mechanical loads at equipment level are increased as well.

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II. Prototype

In order to use Fakel experience, the SPT-50 thruster was chosen as a prototype for 200W-class thruster. That thruster is a part of a propulsion system on Canopus-V and Canopus-V-IK spacecrafts¹. Appearance and characteristics of SPT-50 are shown in Fig. 1 and in Table 1. The cathode KЭ-1P is installed on the thruster. The cathode is qualified for 3000 start cycles. This cathode is designed to work with a discharge current from 1.25 A to 2.00 A. The mass flow rate in the cathode is less than 0.15 mg/s.

SPT-50 is qualified for Russian costumer. The qualification tests included:

- Acceptance test.
- Total firing time accumulating –20 hours and 50 cycles.
- Mechanical test (transporting, random vibration and shock).
- Thermocycles.
- Parametrical tests.
- Life test: 1200 hours and 3000 cycles.

Table 1 SPT-50 parameters

Discharge Voltage, V	180
Discharge Current, A	1.2
Discharge Power, W	220
Thrust, mN	14.0
Specific Impulse, s	860
Efficiency, %	26
Mass, kg	1.23
Operation life, h	≥2500
Status	Flight Model

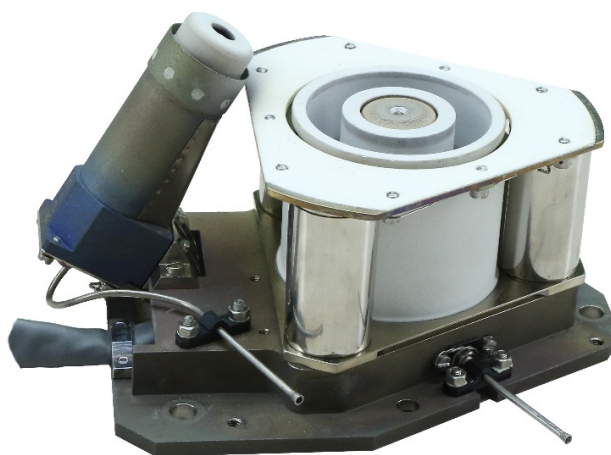


Figure 1. SPT-50 – is a prototype of SPT-50M

To adapt the thruster to new requirements, it was necessary to improve the following characteristics:

- Specific impulse.
- Mechanical design.
- Lifetime.
- Number of cathode on/off cycles.

III. SPT-50M. Design Changes

A. Magnetic system

The magnetic field has the greatest effect on thrust, specific impulse and life time characteristics. Therefore, the magnetic system has been optimized for new requirements. During the modernization the following tasks were solved:

- Increasing the magnetic field gradient.
- Creating a more focused configuration of the magnetic lens.
- Removal of the maximum induction beyond the exit plane of the accelerating channel.
- Providing margins of magnetic system elements by saturation.

The topology of the magnetic field and normalized magnetic field along centerline of prototype – SPT-50 and SPT-50M is shown in Fig. 2 and Fig. 3. The distribution of axial and radial induction along the discharge channel is shown in Fig. 4.

In the modernized magnetic system, the position of the magnetic field maximum along the centerline of the channel is taken beyond the exit plane of the discharge chamber of 1 mm. The removal of the magnetic field maximum will lead in decreasing the rate of discharge chamber erosion. The force line of the magnetic field $0.7B_{r \max}$ is also shifted towards the exit plane of the discharge chamber, it will reduce the width of the erosion zone. In an optimized magnetic system, a larger magnetic field gradient will improve the focusing of the ion beam.

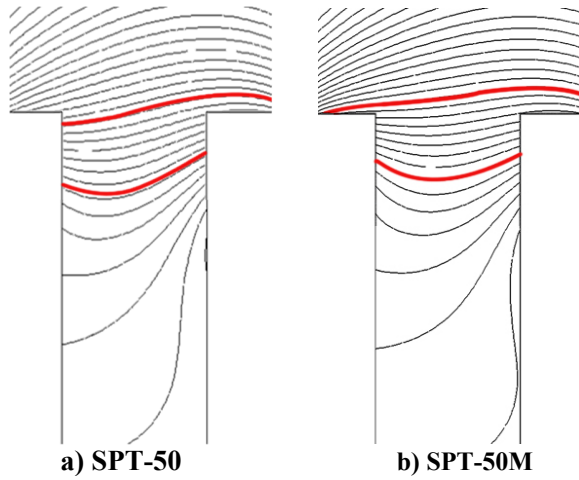


Figure 2. Magnetic field topology

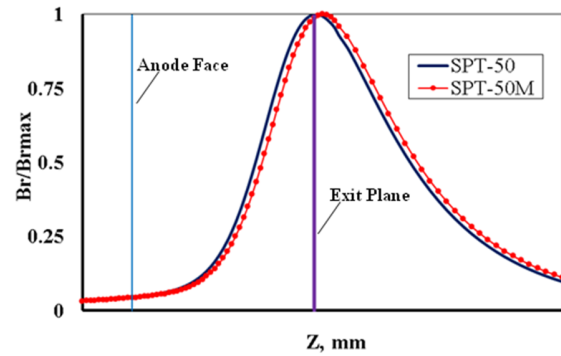


Figure 3. Normalized radial magnetic fields on centerline for the SPT-50 and SPT-50M

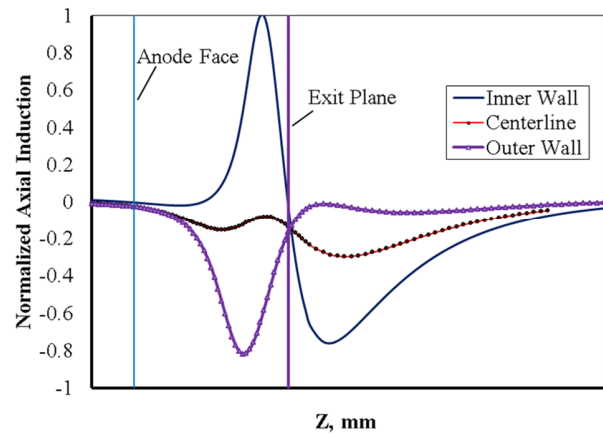
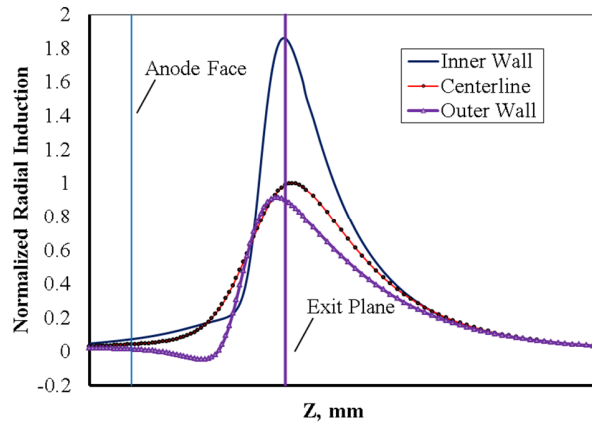


Figure 4. Normalized magnetic fields in the SPT-50M. The radial fields are normalized with the peak centerline value. The axial fields are normalized by the magnitude of the peak field on the inner wall.

B. Discharge chamber

Thruster lifetime is limited by the erosion of the discharge chamber. In addition to magnetic field and operating mode of the thruster, the erosion rate depends on the material of the discharge chamber. In the thruster SPT-50 the chamber is made of ceramics BGP-10. This material consists of 50 % boron nitride BN and 50 % silicon oxide SiO_2 . Despite silicon oxide provides good strength characteristics (150 MPa compressive strength), the resistance to ion sputtering depends on the BN content (Fig. 5). The SPT-50M thruster have to provide a long life, so its discharge chamber is made of High Purity Bore Nitride (HPBN) with a BN > 99.7%. The erosion resistance of this ceramics is between 1.3 and 1.7 times higher than that of the BGP-10 ceramics.

As an alternative to the material for discharge chamber, the GPNB ceramics is considered. It is a Russian analogue of HPBN ceramics with the same BN content.

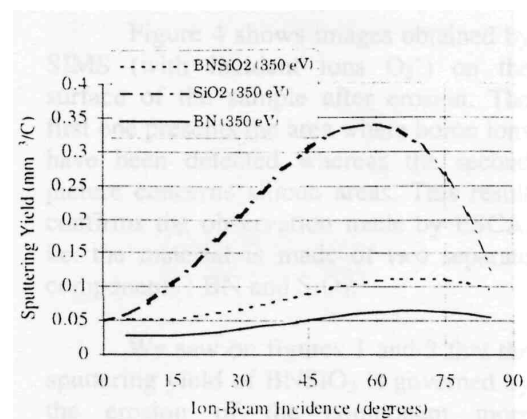


Figure 5. Sputtering speed for different ceramics

C. Mechanical design

The SPT-50M thruster designed for use in a spacecraft with weigh about 300 kg. Such satellites have small dimensions and highly stiff structure. That is why the spacecraft does not damp the loads from the launch vehicle. SPT-50M must withstand increased mechanical stresses.

The basement element is a plate. The plate is fitted with all the main thruster components. The outer pole with the discharge chamber and the anode fixed on the three outer coils. This subassembly, together with the magnetic circuit, is fixed to the plate. The central coil mounted on the magnetic circuit. The cathode mounted on the thruster plate using a bracket.

The strength diagram borrowed from the prototype SPT-50 without changes. The thruster strength improved without significant structural changes.

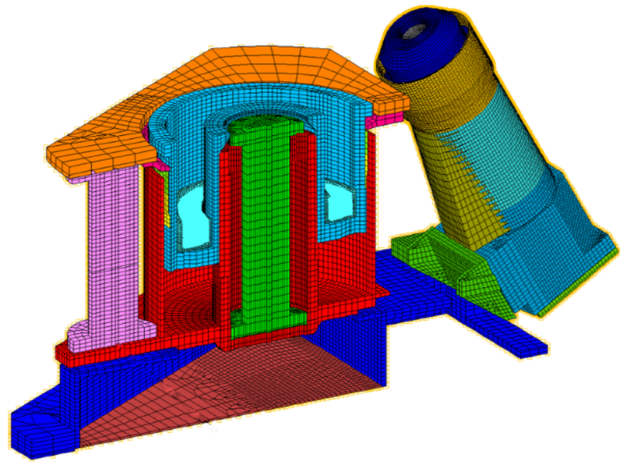


Figure 6. Strength diagram

D. Cathode

To increase the specific impulse, the cathode flow rate reduced. Reducing the cathode flow rate is challenging for its operation. Under such conditions, the cathode may have not enough heat flow to operate in auto mode. The cathode emitter made of LaB6 lanthanum hexaboride. For thermionic emission, the emitter must reach a temperature of 1400 °C. In the modified KE-1R cathode, additional thermal screens have been implemented to reduce heat fluxes from the emitter. This will require cathode time or power increasing for heat before starting the thruster. And it will allow cathode to work at discharge currents less than 1.0 A without additional power by the ignition electrode. The characteristics of the KE-1R cathode are shown in Table 3.

In addition to the design of the cathode, its position relative to the anode block has changed. In the old position, the ceramic cap of the ignition electrode quickly eroded (Figure 7). In the new position, the ions beam should not fall on the cathode. But at the same time, the cathode should have an optimum position in the magnetic field of the thruster in order to reduce the cost of cathode operation. The value of voltage "cathode-ground" U_{cg} characterizes these costs.

Tests have been carried out to determine the optimal position of the cathode. The cathode was mounted on a movable bracket and a position with a minimum U_{cg} and erosion rate was determined. To determine the rate of erosion, half-caps of titanium were placed on the cathode (Fig. 8). After testing in a new position, the caps were weighed to determine the erosion rate. As a result of the tests, the optimum position of the cathode pattern is determined. A comparison of the characteristics of the cathode in the new and old position is shown in Fig. 9.



Figure 7. Cathode erosion in prototype position



	Old Position	New Position
Test Duration, h	100	
Erosion Rate, mg/h	1.00	0.30
Erosion Rate of Ceramic (calculated), mkm/h	0.35	0.11
Total Sputtering time (predicted), h	4200	14000

Figure 8. Half-caps erosion

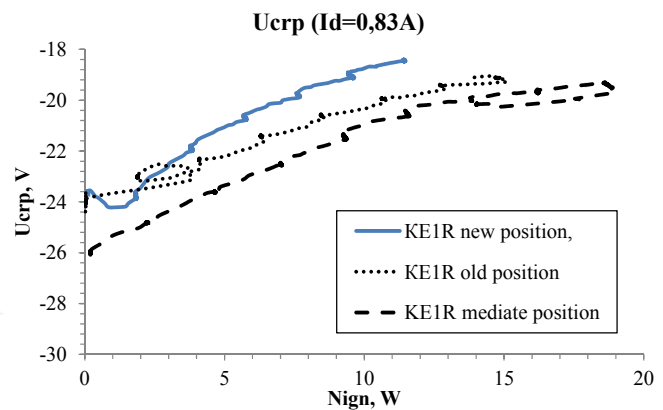


Figure 9. U_{eg} fore different position of cathode



Figure 10. SPT-50M manufactured models

E. Testing tools

To test the design decisions and thruster development, several models were made to validate performance at equipment and subsystem level. Also several working samples of the cathode were made. They were tested as part of thruster models and autonomously.

For fire tests, a technological assembly has been developed. The assembly includes XFCT-50, it provides a reduced flow rate to the cathode. As a result, the efficiency of the thruster rises.

All fire and mechanical tests were carried out at EDB Fakel premises on the bench equipment for flight products. The fire tests were carried out in a vacuum with a pressure not exceeding $4 \cdot 10^{-5}$ mm Hg (calibrated by air).

Another serious challenge for the SPT-50M thruster was the start-up problem. For the first time, an attempt was made to work with a small-sized thruster with fully autonomous feeding of the magnetization coils. The main problem with this was the thruster start. The first attempts to solve this problem by analogy with SPT-140, by decreasing the magnet current at the time of start-up, made it possible to ensure a stable start for the first time. However, when operating the thruster at extreme temperatures we ran into the problem of its stability.

The attempt to reduce the magnet current did not lead to the desired result. The main contribution to the solution of the stability was made by Airbus D&S, which developed dedicated electronics to allow for stable start-up in the whole temperature range.



Figure 11. Technological assembly for fire test

IV. Testing results

A. Parameters

The thruster is tested in the power range from 200 W to 500 W at a discharge voltage of 100 V to 500 V and a total flow rate from 0.8 mg/s to 2.5 mg/s. According to the test results, the minimum discharge voltage at which the thruster functions stably is 120 V. Reducing the discharge voltage of less than 120 V at low flow rates caused the thruster to go out. With a minimum gas flow rate of 0.5 mg/s, corresponding to a discharge current of 0.5 A, the thruster works stably, but with constant maintenance of the ignition voltage at the cathode with an ignition current of 0.5 A.

The voltage-current characteristics of the thruster were determined at fixed anode flow rates, providing discharge current from 0.50 A to 1.75 A. On each mode, the field was optimized for the minimum discharge current.

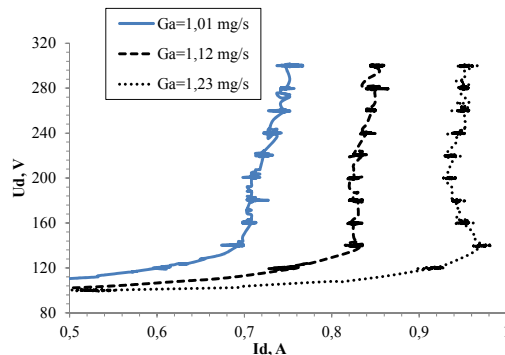


Figure 12. Voltage-current characteristics

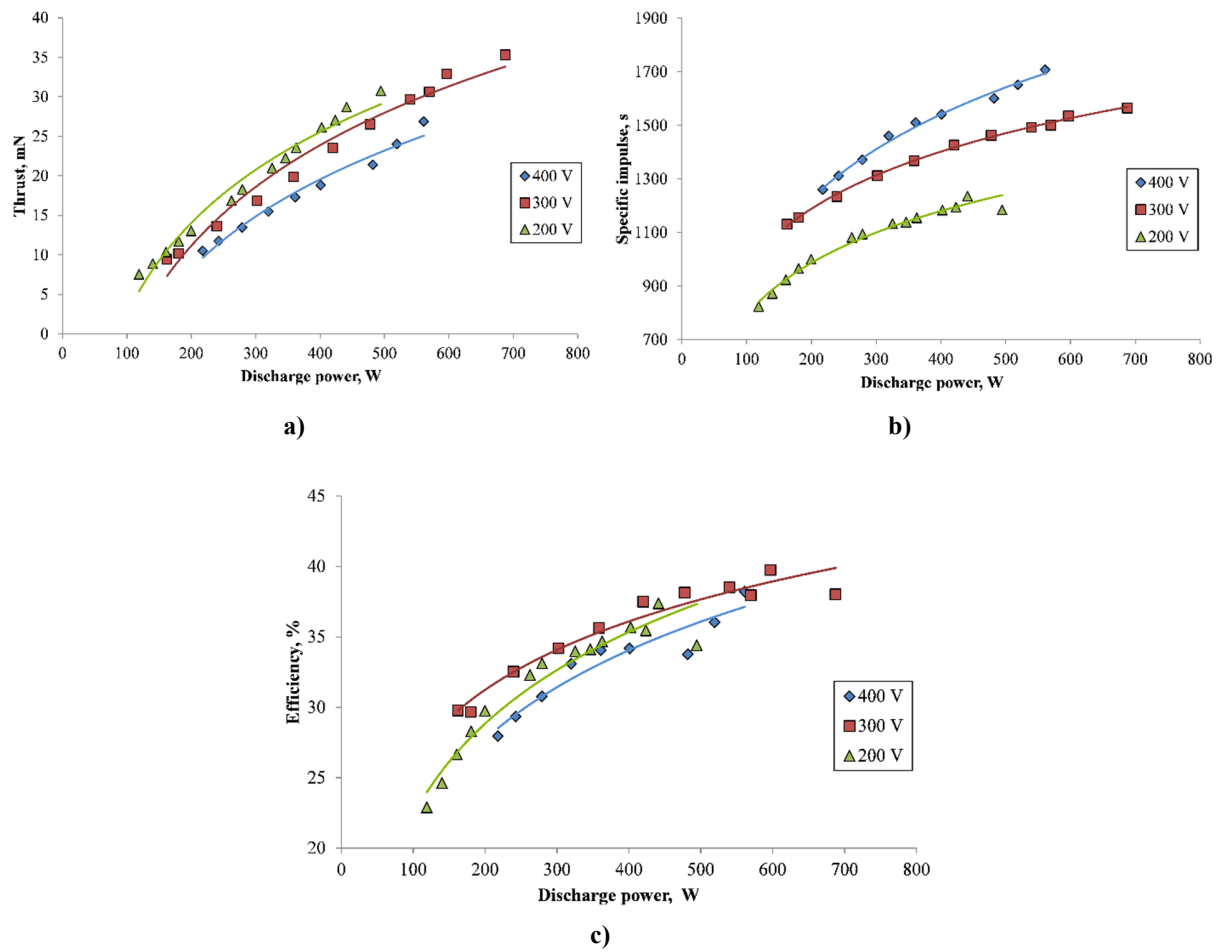


Figure 13. Dependence a) Thrust, b) Specific impulse, c) Efficiency on discharge power

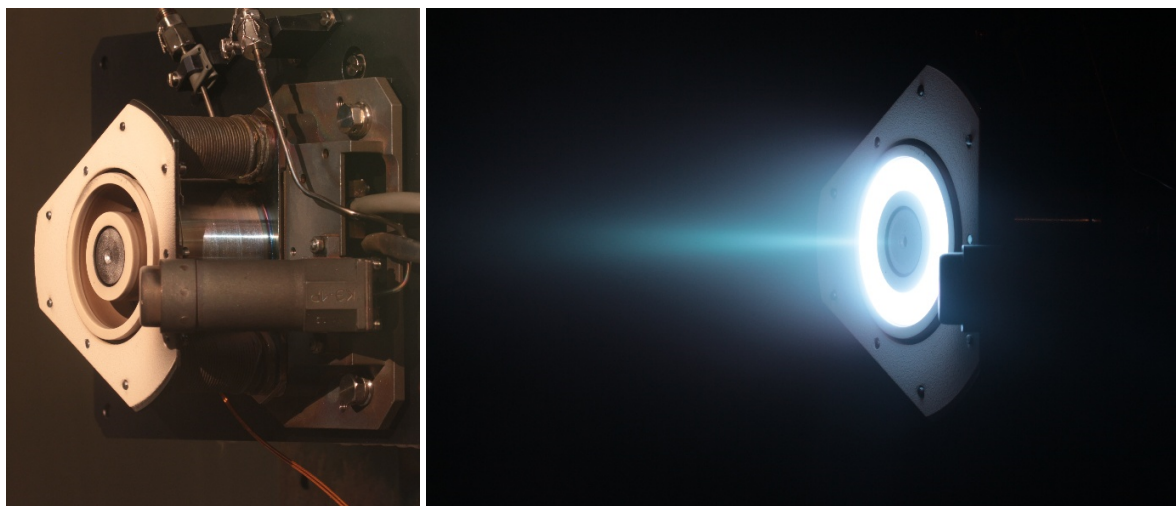
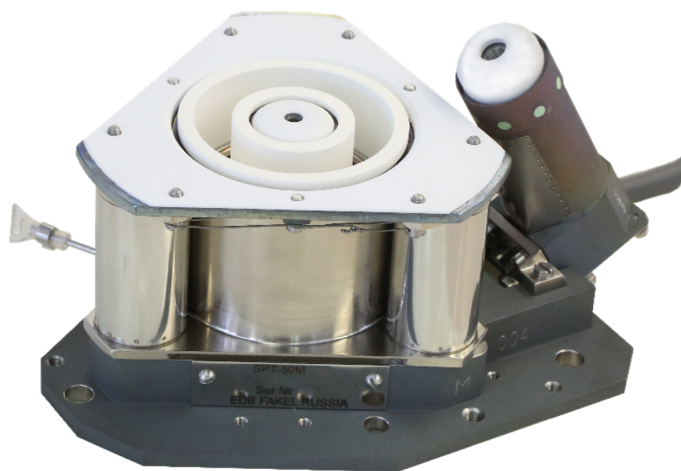


Figure 14. Operating SPT-50M



Discharge Voltage, V	up to 500
Discharge Current, A	up to 1.0
Discharge Power, W	up to 500
Thrust, mN	up to 30
Specific Impulse, s	up to 1800
Efficiency, %	up to 41
Mass, kg	1.32
Operation life, h	5000

Figure 15. Appearance and characteristics of SPT-50M

The thruster was tested with a low flow rate cathode KE-1R. The cathode is designed for operation at low discharge currents. The cathode is capable of operating at xenon flow rate from 0.10 mg/s. During the tests, the cathode worked stably at a flow rate of 0.11 mg/s. The Fig. 16 shows the dynamics of the voltage "cathode-ground" U_{cg} , which characterizes its operation in various modes of discharge current. The decrease in U_{cg} for a larger discharge current is typical of a hollow cathode.

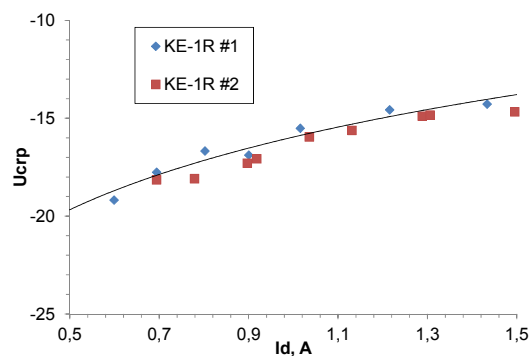


Figure 16. U_{cg} as a function of discharge current



	KE-1R	КЭ-1Р
Xenon Flow Rate, mg/s	>0.1	>0.15
Heating Power, W	90	90
Discharge Current, A	up to 1.5	up to 2
Cycles	11000	3000

Figure 17. Comparative characteristics of KE-1R and prototype

B. Life test

To determine the stability of parameters in the resource and erosion characteristics, resource tests were conducted. The first 950 hours thrust was fixed constantly, then every 100 hours. This is due to the test bench.

Figure 18 shows the change in the thruster parameters with the time of the life tests. As can be seen from Fig. 18a, the thrust behaves stably throughout life. The specific impulse shown in Fig. 18b decreases by about 70 seconds in the first 500 hours. In the future, the specific impulse stabilizes at the value of 1270 s. This is due to the erosion of the discharge chamber: with an increase in the cross-section area, the coefficient of utilization of the xenon is reduced².

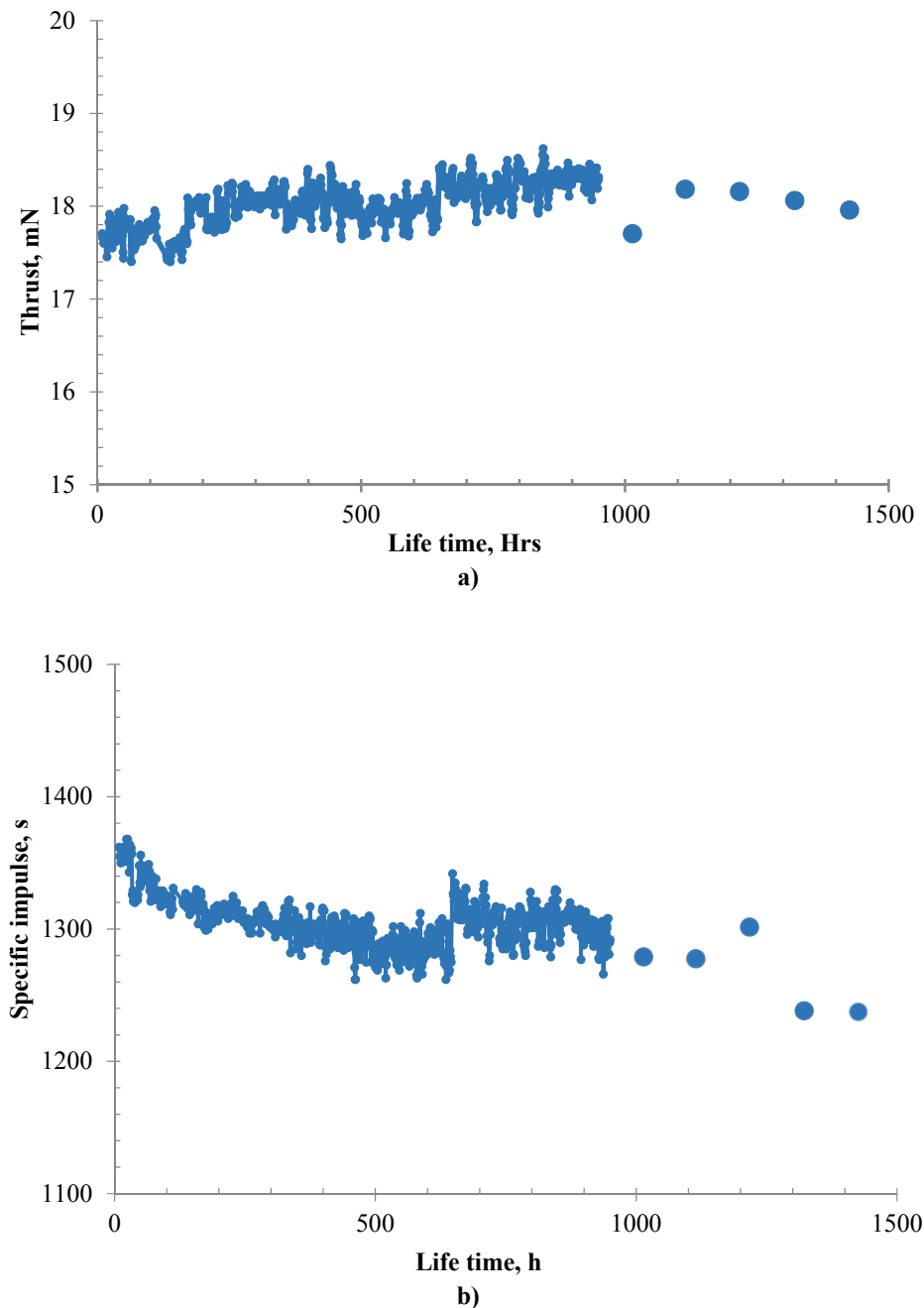


Figure 18. a) Thrust, b) Specific impulse dependence on operating time

C. Discharge chamber erosion

In the life test periodically measured the erosion profile of the discharge chamber made from GPNB. The measurements were carried out in six sections. Uneven erosion in different sections does not exceed 0.7 mm. Figure 19 shows the averaged profiles of erosion in the scale of the discharge chamber.

At the beginning of the life test, the sputtered part of the discharge chamber is rounded. This is typical for small thrusters. The width of the erosion zone in the first hundred hours was 2 mm for the outer and inner walls. Further, the beginning of the erosion zone descended deep into the chamber and, upon operating for about 400 hours, stopped at a depth of 3.4 mm along the outer and inner wall.

Often, the criterion for the thruster life is the time for which the discharge chamber erodes to such an extent that the ion beam begins to sputter the elements of the magnetic system³. Life tests of the SPT-100 showed that the thruster is able to work effectively and after the beginning of the degradation of the magnetic poles [3]. The estimated operating time of the SPT-50M before the beginning of erosion of the poles is 5000 hours.

In general, according to the results of erosion tests, it can be concluded that the erosion characteristics of the GPNB ceramics are not worse than HPBN.

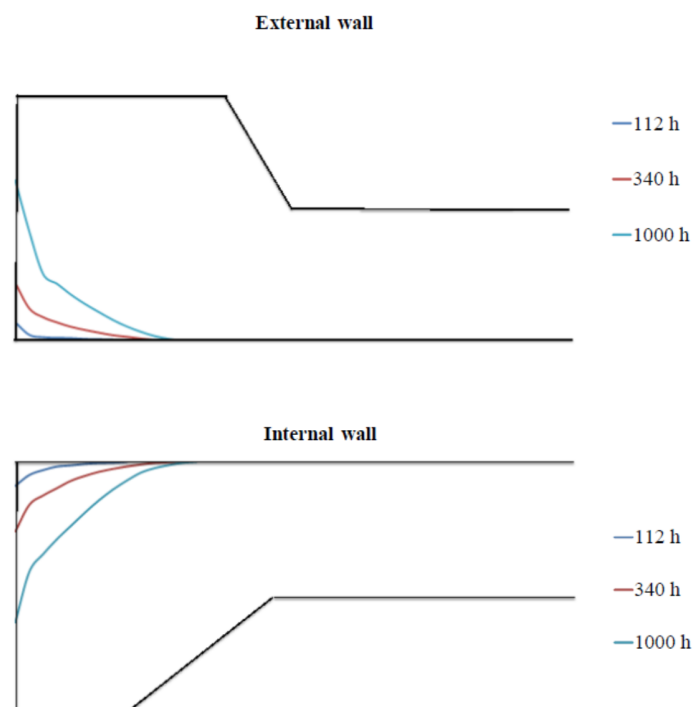


Figure 19. Erosion of a discharge chamber from GPNB

V. Conclusion

The thruster SPT-50M has been developed to answer the challenging needs of upcoming low-power applications. Comparative characteristics of the thruster developed in comparison with the prototype are given in Table 3.

Table 3 Comparative characteristics of SPT-50 и SPT-50M

	SPT-50	SPT-50M
Discharge Voltage, V	180	
Discharge Current, A	1.2	
Discharge Power, W	220	
Thrust, mN	14.0	14.8
Specific Impulse, s	860	930
Mass, kg	1.23	1.32
Operation life, h	≥ 2500	~ 5000

References

¹Gorbunov, A. V., Khodnenko, V. P., Khromov, A. V., Murashko, V. M., Koryakin, A. I., Zhasan, V. S., Grikin, G. S., Galayko V. N., Katasonov N. M.. "Propulsion System for Small Earth Remote Sensing Satellite "Canopus-V", *32nd International Electric Propulsion Conference*, Wiesbaden, Germany, IEPC-2011-042, September 11 – 15, 2011.

²Arhipov B.A., Bober A.S., Gnizdor R.Y. et al., "The Results of 7000-Hour SPT-100 Life Testing", *24th International Electric Propulsion Conference*, Moscow, Russia, IEPC-1995-039, September, 1995, pp. 315–321.

³Shagaida, A. A., Gorshkov O. A., Tomilin D. A., "Effect of discharge channel walls erosion on the efficiency of the stationary plasma thruster", *Journal of Technical Physics* Vol. 82, issue 08, 2012, pp. 42-49.