High-impulse SPT-100D thruster with discharge power of 1.0…3.0 kW

IEPC-2017-40

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

R. Gnizdor[1], A. Komarov[2], O. Mitrofanova[3], P. Saevets[4], D. Semenenko[5]

FSUE EDB Fakel, Kaliningrad, 236001, Russia

Abstract: A high-impulse SPT-100D thruster has been developed at EDB Fakel. The development was aimed at creating a thruster with an operating discharge power range from 1000 to 3000 W and discharge voltage range from 200 to 800 V, where the total thrust impulse is not less than 3.5 MN·s. Apart from that, the thruster should have a higher mechanical strength and lower thermal flux to the S/C design.

The SPT-100B thruster is the basic design variant of the SPT-100D. Several tasks were solved during development of the design of the new thruster. In particular, the magnetic system has been optimized to reach the required thrust, specific and life time characteristics of the thruster and to ensure the discharge power operating range. A more erosion resistant ceramics has been used for the discharge chamber. The cathode position has also been optimized, what made it possible to improve its life time capability. The thermal interface has also been modified.

The SPT-100D thruster experimental models have passed mechanical test (sine vibrations, random vibrations, shock impacts), thermal vacuum test, radiation resistance test. During the SPT-100D reference performance test its parameters in the discharge power range from 600 to 3100 W at the discharge voltages up to 800 V have been determined. The thrust and specific characteristics at the fixed discharge voltages of 300 and 350 V and discharge powers up to 2500 W have also been determined.

The life test of one of the SPT-100D has been carried out in the following modes: a 170 h operation at the discharge power of 2100 W (810 V/2.6 A), a 90 h operation at the discharge power of 2800 W (600 V/4.5 A) and a 920 h operation at the discharge power of 2500 W (600 V/4.17 A). A good parameters stability has been demonstrated in all the modes.

The results of the erosion zone parameters measurement and erosion rate show that the thruster has a potential to produce the total thrust impulse of up to 3.5 MN·s.

Nomenclature

I_{sp}	=	specific impulse
U_d	=	discharge voltage

[1] Senior scientist, Design Department, info@fakel-russia.com.
[2] Design engineer, Design Department, info@fakel-russia.com.
[3] Design engineer, PhD, Design Department, info@fakel-russia.com.
[4] Design engineer, Design Department, info@fakel-russia.com.
[5] Chief of SPT subdivision, Design Department, info@fakel-russia.com.

I. Introduction

THIS document presents the development results of the high impulse thruster SPT-100D. The development of the thruster was performed in the frame of the internal Russian Space Program, as well as in the frame of EDB "Fakel" internal activities.

Electrical propulsion systems are now recognized as a key technology that will ensure the operation of many spacecraft located in various orbits around the Earth[1], and also creates the possibility of conducting space exploration missions[2].

At present, there is a need for a thruster with high thrust and specific characteristics in the range of discharge powers from 1000 to 3000 W.

High specific characteristics can be achieved by increasing the discharge voltage and a sufficiently high propellant flow density in the discharge[3, 4, 5, 6]. The results of the analysis show that this thruster can be created on the basis of the SPT-100B thruster type.

In accordance with the abovementioned, the following objectives shall be achieved as the result of the SPT-100D thruster development:

- Discharge power from 1000 to 3000 W;
- Discharge voltage of up to 800V;
- Specific impulse of up to 2700 s;
- Total impulse of not less than $3.5 \cdot 10^6$ N·s;
- Increased mechanical strength;
- Reduced heat flow to the S/C structure.

The main tasks that were solved during the development:

- Development of thruster design with the increased electrical strength of electric circuits;
- Design strength testing to external impacts (mechanical loads, thermal vacuum cycles), resistance to radiation;
- Check of life performances of the discharge chamber materials during the erosion test and parameters stability during the direct life test;
- Development of test and checks technology.

In order to perform development test of the SPT-100D thruster design, eight thruster models were manufactured, including the thrusters with s/n 01, 05 and 08.

The majority of the tests were carried out on these thrusters. The test matrix of these thrusters is presented in Table 1.

Table 1. SPT-100D test matrix

Types of tests	s/n 01	s/n 05	s/n 08
Acceptance performance test	+	+	+
Performance tests in the range of the discharge currents and voltages	+	-	-
Mechanical test	-	-	+
Thermal vacuum test	-	-	+
Radiation test	-	+	-
Life time test	+	-	-
Erosion definition test	+	-	+

II. Design of the SPT-100D thruster and of its modification SPT-100BM

The baseline design of SPT-100D is the SPT-100B thruster. This fact allowed to use the main development/test technologies that are applied for SPT-100B.

The increase of thrust characteristics and range of the operating discharge power of the SPT-100D thruster is achieved due to optimization of the parameters of the magnetic system. The configuration of the magnetic lens was changed and the gradient of magnetic induction in the discharge chamber channel was increased.

The thermal interface is upgraded in order to reduce the heat flow from the thruster to the place of its mounting to the S/C at an increased discharge power. This upgrading is achieved by implementing a mounting plate made of Titanium alloy into the thruster design. The mounting plate is also the main load-bearing element of the thruster design.

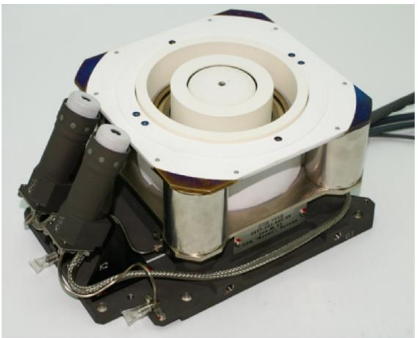
Life time characteristics of the cathode unit are increased by optimizing of the cathode positioning angle to the anode unit.

The discharge chamber material has been changed to a more erosion-resistant ceramics, which allowed to increase lifetime characteristics of the thruster and to ensure its operation in the modes of high values of discharge voltage and discharge power.

The weight of the SPT-100D thruster is 5.6 kg. Overall dimensions: L x W x H = 259x164x120 mm.

During SPT-100D performance test the achieved parameters of the thruster are significantly better than the SPT-100B parameters in the SPT-100B operation mode (300 V/ 4.5 A)[7]. The performance test results served as the basis for the modernization of the SPT-100B thruster design as it is called the SPT-100BM thruster. In the modified SPT-100BM the magnetic system configuration of the SPT-100D was used. The SPT-100BM magnetic system was optimized for the thruster operation at discharge current of 4.5 A. The coils of the SPT-100BM magnetic system are set into the thruster discharge circuit in-series as in the SPT-100B thruster. Electrical and mechanical interfaces are also taken from the SPT-100B thruster.

General views of the SPT-100D and SPT-100BM thrusters are shown in Figure 1.



a)

b)

Figure 1. General views of the SPT-100D (a) and SPT-100BM (b) thruster.

III. SPT-100D environmental test results

A. SPT-100D mechanical test results

Sine and random vibration tests were performed for each of three mutually perpendicular axes. Vibration test modes are presented in Table 2 and Table 3.

Three shocks were performed along each axis during the shock test. Shock test mode is presented in Table 4.

The general view of the thruster during the vibration test is shown in Figure 2.

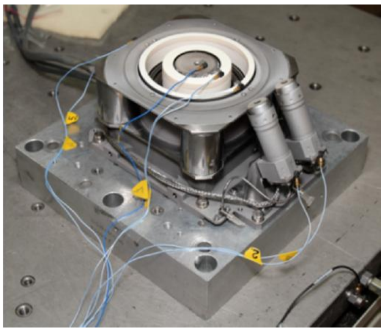


Figure 2. SPT-100D mounted on the vibration plate.

Table 2. Sine vibration mode

Frequency, Hz	Level
5 – 22.3	+/-10 mm
22.3 – 100	20 g

Table 3. Random vibration mode

Frequency, Hz	Level, g^2/Hz	Duration
20 - 70	+9.0 dB/oct	180 s each axis
70 - 165	1.0	
170 - 252	0.26	
300 - 900	0.13	
900 - 2000	-9.0 dB/oct	

Resonance test were performed for each axis before and after the mechanical test. The resonance frequency shift didn't exceed the required values after the mechanical test.

The thruster doesn't have resonance frequencies less than 150 Hz.

Conclusion based on the mechanical test results:

- no mechanical damages have been observed;
- status of electric circuits is within the requirement limits;
- thrust and specific parameters comply with the requirements.

Table 4. Shock mode

Shock direction	Frequency Hz	Shock spectrum, g
In plane X, Z	200	52
	4000	4200
	10000	4200
Out of plane. Y	200	140
	800	400
	4000	4200
	10000	4200

B. Thermal vacuum test results

Thermal vacuum test included thermal cycling test and thermal balance test.

A technological Xenon supply unit with the thruster was mounted directly at the test stand thermal plate, it provided obtaining and maintaining the required temperature level at the reference point on the thruster. The thermal plate has its own heaters and cooled Nitrogen supply pipelines, in order to regulate mounting surface temperatures in the range of positive and negative temperature values. The general view of the thruster during the thermal vacuum test is presented in Figure 3.

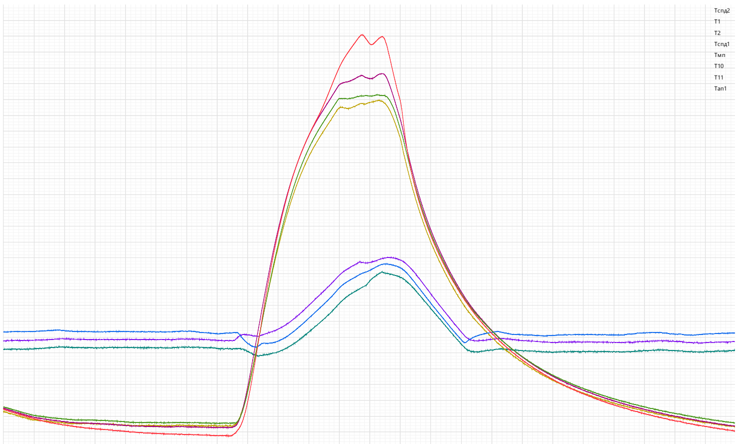
Outer space thermal conditions simulation was achieved by means of thermal screens, cooled down by liquid Nitrogen. In front the thruster was shielded by the front panel at a minimal temperature limit mode. The thermal front panel was open during operation of the thruster.

During the thermal cycling test eight cycles of the thruster startup at minimum (minus 45_{-3} °C) and maximum (200^{+3} °C) temperature levels have been performed with operation of the thruster on K1 and K2 cathodes alternatively.

The thruster was operated at discharge voltage of 810 V and discharge current of 2.6 A.

Typical temperature variation of the thruster and technological Xenon supply unit during the cooling down process and the thruster startups is presented in Figure 3.

a)



b)

Figure 3. SPT-100D before the thermal vacuum test (a) and typical temperature variation diagram during the test (b).

In accordance with the thermal balance test results, data were obtained that allowed verifying and clarifying the thruster thermal model.

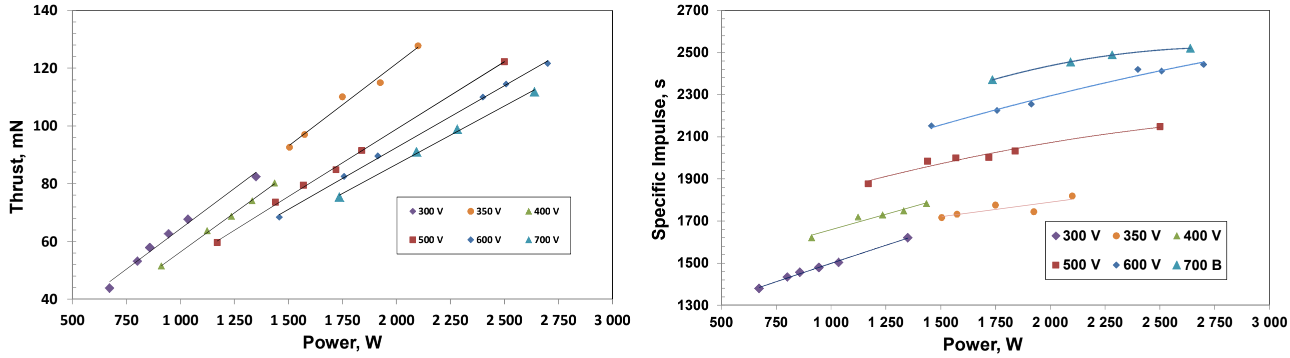
The heat flow from the thruster mounting place to the S/C at the discharge power of 2100 W:

- 44 W at the mounting place temperature of 150 ºC;
- 32 W at the mounting place temperature of 165 ºC.

The results of the performance test performed after the thermal vacuum test showed that the thrust and specific parameters of the thruster comply with the specified requirements.

C. Performance test results

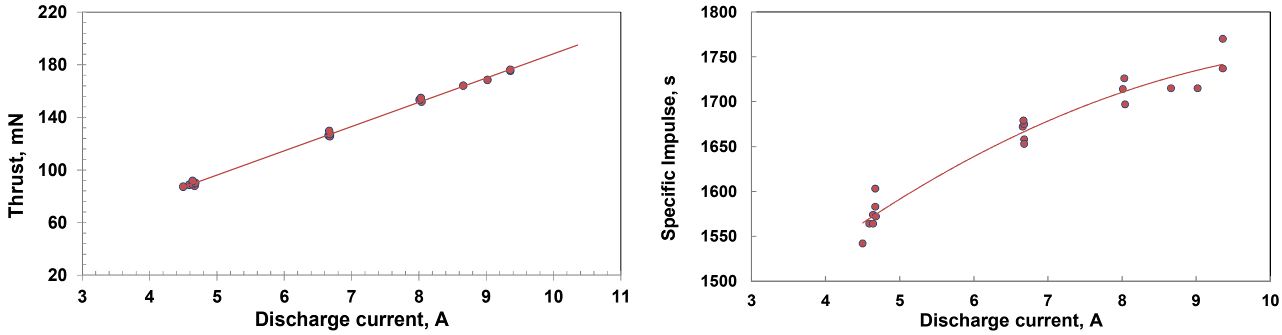
Performance test of the SPT-100D thruster was performed within a wide discharge power range of 600 to 3200 W at the discharge voltages of 300 to 800 V. The results of the performance test in the range of the discharge voltages from 300 to 700 V as a function of discharge power are presented in the Figure 4.



a) b)

Figure 4. SPT-100D performance test results: Thrust - Power diagram (a). Specific impulse - Power diagram (b).

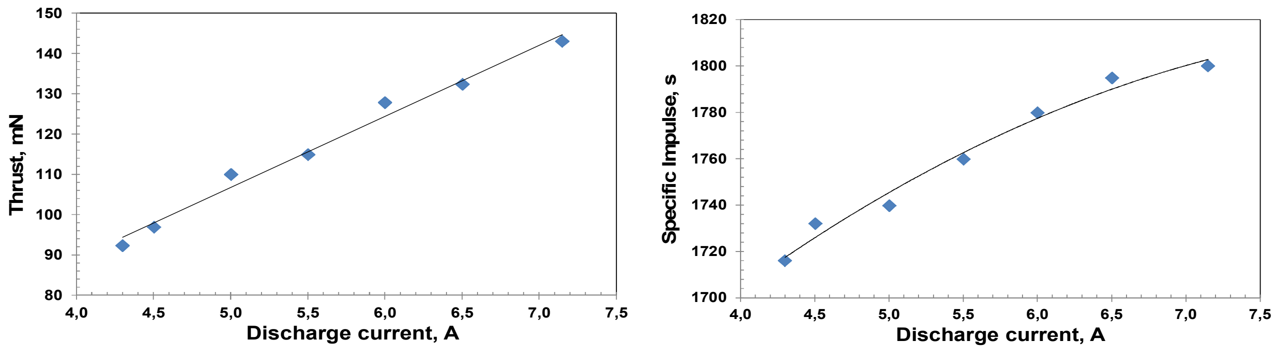
SPT-100D parameters have also been defined at the constant discharge voltage values. SPT-100D parameters at discharge voltage Ud = 300 V are presented in the Figure 5.



a) b)

Figure 5. SPT-100D thrust (a) and specific impulse (b) at discharge voltage Ud = 300 V.

SPT-100D parameters at the discharge voltage Ud = 350 V are presented in the Figure 6.



a) b)

Figure 6. SPT-100D thrust (a) and specific impulse (b) at discharge voltage Ud = 350 V.

These results can be used to preliminarily determine the SPT thrust and specific parameters of the selected operating point by the power available on the spacecraft, which can be used to support the operation of the thruster.

The results of the performance test show that the SPT-100D thruster can operate with high efficiency both in the field of high discharge power and discharge voltages, and at the operating point of the SPT-100B thruster.

Parameters of thrusters operating in the mode with the power of 1350 W and the ones of the SPT-100D thruster are shown in Table 4.

Table 4. Parameters of SPT-100B-based thrusters

Performance	SPT-100B (baseline thruster)	SPT-100BM	SPT-100D (in SPT-100B mode)	SPT-100D
Discharge Power, kW	1.35	1.35	1.35	2.5
Discharge Voltage, V	300	300	300	600
Discharge Current, A	4.50	4.50	4.50	4.17
Thrust, mN	83	92	92	112
Specific Impulse, s	1600 (nom. value)	Not less than 1700	Not less than 1700	Not less than 2200
Plume divergence	~ 45°	~ 30°	~ 30°	
Mass, kg	3.6	4.3	Not more than 5.7	
Total impulse, MN·s	Not less than 2.6 (qualified)	Not less than 3.5 (predicted)	Not less than 3.5 (predicted)	
Operating cycles	Not less than 5000	Not less than 5000	Not less than 5000	
Overall dimensions, mm	225x150x125	213x150x116	264×164×118	

D. Life time test results

Life time characteristics of SPT discharge chambers are determined primarily by the erosion resistance of the ceramic material to ion sputtering. The most resistant ceramics, which is currently used in the SPT design, is the ceramics based on pure Boron Nitride.

During the development testing of the thruster design, samples of ceramics from five suppliers were tested. Of these, the ceramics was chosen, which, in addition to a high erosion resistance, also has good performance characteristics (low hygroscopicity, high mechanical strength).

In order to test the stability of the thruster parameters during the life time test, the life test was performed with modeling of ceramic chamber wall profiles. These profiles simulated predicted erosion profiles, which correspond to the wear-outs at an accumulated life time.

In particular, the tests of the SPT-100D thruster were carried out in the estimated end of the thruster life time. Erosion is practically absent.

The tests were carried out in the mode with the discharge power of the SPT-100B thruster (1350 W).

As a result of these tests, the following parameters were obtained: Thrust - 91 mN, Isp - 1650 s.

The general views of the discharge chamber of the thruster at the time of the beginning of the tests and after operating time of 25 and 50 h are shown in Figure 6.

0 h **25 h** **50 h**

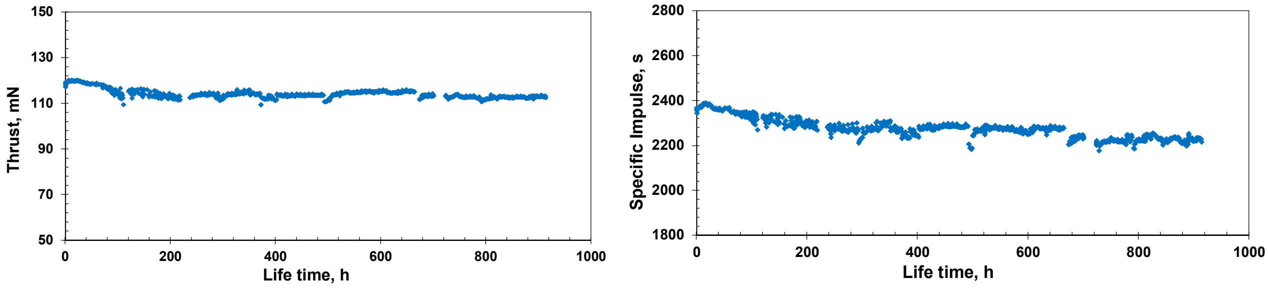
Figure 6. SPT-100D operation in the estimated end of the thruster life time. Erosion is practically absent.

As it was already said above, the SPT-100D thruster s/n 01 was subjected to direct life time test. The thruster was tested sequentially in three modes. The life time test sequence is shown in Table 5.

Table 5. SPT-100D s/n 01 life time test sequence

Test modes	Duration, hour
Life test at the discharge power of 2100 W (810 V / 2.6 A)	170
Life test at the discharge power of 2800 W (600 V / 4.5 A)	90
Life test at the discharge power of 2500 W (600 V / 4.17 A)	920

The thrust and specific impulse achieved during the tests of the thruster in a mode with the discharge power of 2500 W at the discharge voltage of 600 V are shown in Figure 7.

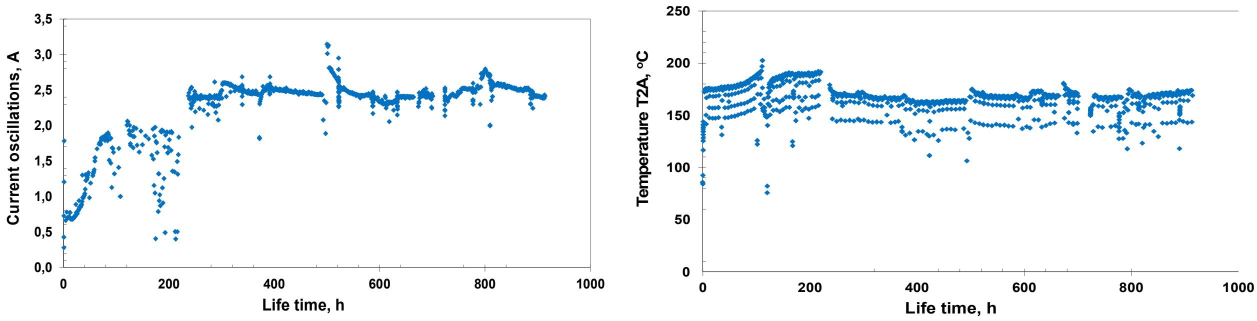


a) b)

Figure 7. SPT-100D thrust (a) and specific impulse (b) in the process of long-term operation.

As it can be seen from the presented results, after operating for about 300 hours the thruster parameters stabilized and remained approximately at the same level for the next 600 hours of operation.

This is also the result of measurements of the discharge current oscillations and the temperature of the thruster at the reference point (T2A). These results are shown in Figure 8.



a) b)

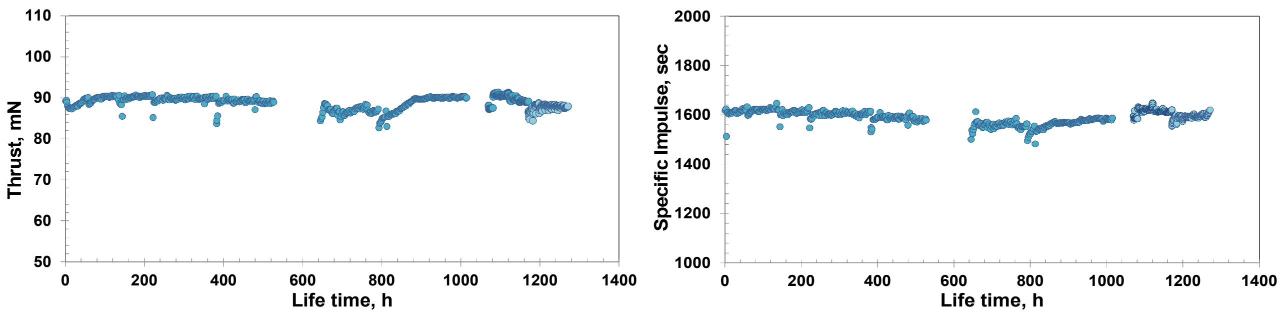
Figure 8. SPT-100D discharge current oscillations (a) and thruster temperature in the reference point T2A (b).

During the carried out 900-hour life test in the mode of 600 V/4.17 A (2500 W) parameters stability has been demonstrated:

- average thrust during the life test was 113.2 ± 1.2 mN;
- average specific impulse was 2250 ± 30 s;
- the achieved total impulse was 0.37 MN·s during this period of time.

The accumulated operating time for the thruster according to the life time test sequence was about 1200 hours.

Verification of the SPT-100D parameters stability in the operation mode with the discharge power of 1350 W was performed on the development model of the SPT-100BM thruster. These results are shown in Figure 9.



a) b)

Figure 9. SPT-100BM thrust (a) and specific impulse (b) during the life time test.

Structure of the erosion zone surface and erosion zone position with respect to the poles of the magnetic system allows predicting the total impulse of not less than 3.5 MN·s.

The stability of the parameters for even greater operating time is planned to be checked by modeling the erosion profiles on both thrusters.

IV. Conclusion

During the development of the design of the SPT-100D thruster, the following results were obtained:

- Design of the thruster with the operating discharge power of 700 to 3100 W for the operation in the modes with the operating discharge voltage of 300 to 800 V has been developed.
- During the reference performance test the thruster parameters have been determined within the power range of 600 to 3200 W (the discharge voltage range of 300 to 800 V).
- The thruster has a high efficiency both when operating in the SPT-100B thruster mode and in high-voltage discharge modes.
- The thruster has been tested for the following: mechanical loads (sine vibration, random vibration, shock), thermal vacuum cycles, radiation resistance, short-term life test.
- Check test of the thruster after the environmental test has demonstrated that the thruster retained its characteristics.
- Parameters stability during the long operation and ability to achieve the total impulse of not less than 3.5 MN·s have been demonstrated by the life test.

The SPT-100D thruster design is ready for qualification.

The SPT-100BM thruster is currently passing qualification under the requirements of the Russian customer.

References

1 Ronald L. Corey, David J. Pidgeon, "Electric Propulsion at Space Systems/Loral", *31th International Electric Propulsion Conference*, IEPC-2009-270, University of Michigan, Ann Arbor, Michigan, USA, September 20 – 24, 2009.

2 Koppel, C. R., Marchandise, F., and Prioul, M., "The SMART-1 Electric Propulsion Subsystem around the Moon: In Flight Experience," *Proc. 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, 10-13 July, 2005, Tucson, AZ, AIAA Paper 2005-3671.

3 Richard Hofer, Development and characterization of high efficiency, high specific impulse Xenon Hall thruster, PhD dissertation, University of Michigan 2004.

4 R. Hofer, A. D. Gallimore, Efficiency analysis of a high specific impulse hall thruster, AIAA-2004-3602

5 Manzella, D.H., Jacobson, D.T., Jankovsky, R.S., "High Voltage SPT Performance", 37th Joint Propulsion Conference and Exhibit, paper AIAA-2001-3774, USA, 2001.

6 A. Bouchoule, A. Lazurenko, V. Vial, V. Kim , V Kozlov, A. Skrylnikov, "Investigation of the SPT operation under high discharge voltages", 28th International Electric Propulsion Conference, IEPC-2003-303, Toulouse, France, 2003.

7 O. A. Mitrofanova, R. Yu. Gnizdor, V. M. Murashko, A. I. Koryakin, A. N. Nesterenko, "New Generation of SPT-100", *32 th International Electric Propulsion Conference*, IEPC-2011-041, Wiesbaden, Germany, September 11–15, 2011.