

Development and qualification of Hall thruster KM-60 and the flow control unit

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Abstract: Qualification of correction unit consists of a thruster KM-60 and a flow control unit has been completed. Overview of the correction unit tests including lifetime tests is presented in this paper. The maximum correction unit operating time during the test is more than 4120 hours. At that the shown total thrust impulse more than $6 \cdot 10^5$ N·s at 8357 cycles. Average specific impulse shown during maximum lifetime test is more than 1860 s.

Nomenclature

γ_θ = coefficient characterizing the reduction of thrust due to the angular divergence of the ion beam
 γ_E = coefficient characterizing the reduction of thrust due to the non monoenergetic ion beam
 α = gas efficiency
 β = the proportion of the ion current to the discharge current
CU = correction unit
FCU = flow control unit
PPCU = power processing and control unit

I. Introduction

Nowadays increasing of spacecrafts lifetime and on-board power systems capacity are among main directions in progress of spacecraft systems engineering. As a result, new requirements for propulsion system specific impulse and lifetime arise. Hall thruster KM-60 and flow control unit (FCU) developed at the Keldysh Research Centre are intended for use on board the satellite platform "Express-1000" as correction unit (CU). CU has increased specific impulse in relation to existing models, which exceeds 2000 seconds in the beginning of the operation.

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II. Development and Qualifications of the Correction Unit

Feature of the developed correction unit is long-term work with a high specific impulse at a relatively low power. Development, manufacturing and qualification of the thruster and FCU have been conducted at Keldysh Research Centre.

A. The Main Parameters of the Thruster and the FCU

Main parameters of the thruster and FCU are presented in Table 1.

Table 1

Main parameters of the Thruster	
Thrust	42 mN
Discharge voltage	500 V
Discharge current	1.8 A
Specific Impulse (acceptance tests)	>2000 s
Average specific impulse (at the lifetime)	>1860 s
Total thrust impulse	>380 kN·s
Current in the coils of magnetic system	1.5...2.5 A
Mass	≤3.1 kg

Main parameters of the FCU	
Propellant	Xenon
Working inlet pressure	$1.75 \pm 0.15 \text{ kgf/cm}^2$
Valves power supply voltage	
– At startup (0.1-1 s)	$6.3 \pm 0.3 \text{ V}$
– On hold	$2.2 \pm 0.2 \text{ V}$
Mass	≤0.325 kg

In addition, there are a number of requirements to the CU, determined by its functional purpose, such as:

- large number of cycles (up to 8250 switching cycles);
- high level of vibration loads (random vibration with a standard deviation up to 25g);
- high level of single shocks reaching 2500 g.

Appearance of correction unit is shown in Fig. 1.

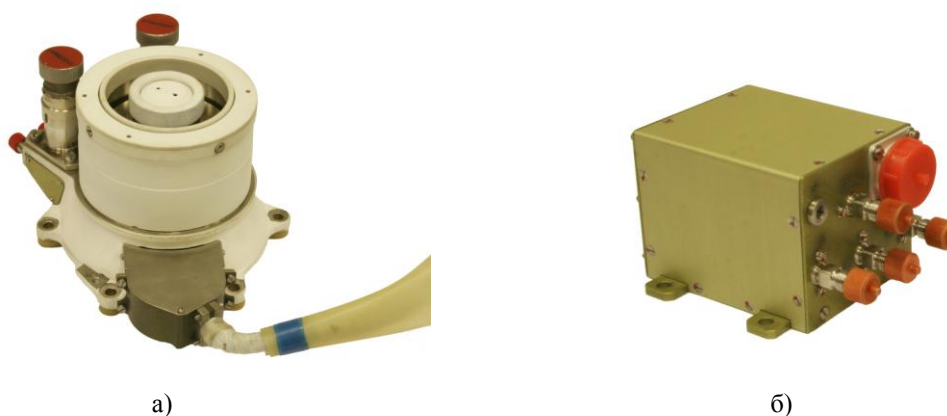


Figure 1. Appearance of correction unit based on thruster KM-60
(a - KM-60 thruster, b - flow control unit)

KM-45 was used as prototype of KM-60 thruster having similar type of magnetic system, discharge chamber and cathode units. This thruster had passed lifetime test for more than 1000 hours before starting of KM-60 development.

B. Test facilities

The fire tests of CU were carried out on KVVU-35 and KVVU-90 test facilities located at KeRC. Cryogenic vacuum test facility KVVU-35 has the main chamber section diameter equal to 3 meters and total volume equal to 35 m³. It is equipped with cryopumps with total capacity of 42 m³/s. The facility is equipped with a control and measurement system, which provides test operation in a fully automatic mode. The main purpose of the facility is carrying out of Hall thrusters lifetime tests. The facility is equipped with a system for remote insulators profile measurement and for video surveillance, which allows monitoring status of the thruster during lifetime tests. The KM-60 thruster, mounted in the vacuum chamber KVVU-35 is shown in Fig. 2 while setting diagnostic systems.



Figure 2. Thruster KM-60 in the KVVU-35 facility while setting diagnostic systems.

The vacuum chamber of KVVU-90 facility has diameter of 3.8 m and volume of 90 m³. It is equipped with cryogenic pumps with a total capacity for xenon equal to 140 m³/s. The chamber is equipped with two pre-chambers, which allow operational testing and replacement of thrusters without letting-to-air of the main part of chamber. The facility is used for fire tests of Hall and ion thrusters. Appearance of KVVU-90 is shown in Fig. 3.



Figure 3. Appearance of KVVU-90 vacuum chamber.

C. Sequence of correction unit development and qualification

The initial geometry optimization of the acceleration channel of the discharge chamber, magnetic field topology, parametric tests were performed on a laboratory model of the KM-60. The experience obtained during development and investigation of Hall thrusters at Keldysh Research Centre was used². Parameters of the KM-60 laboratory model in the range of discharge voltage from 280 to 680 Volts are presented in Fig. 4 and Fig. 5.

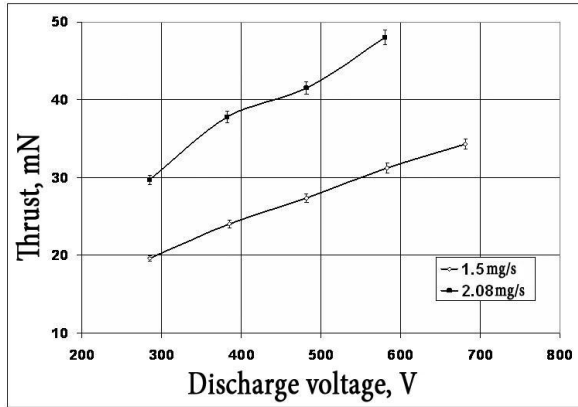


Figure 4. The dependence of KM-60 thrust on discharge voltage

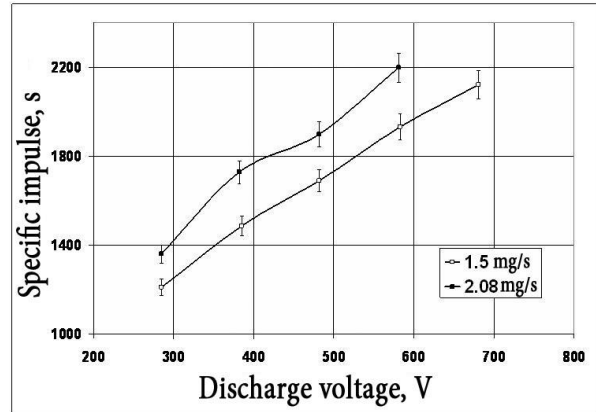


Figure 5. The dependence of KM-60 specific impulse on discharge voltage

Qualification of KM-60 thruster and FCU has been conducted in accordance with a complex program of experimental development. Testing of the KM-60 and FCU has been performed separately with the exception of joint and lifetime tests.

In accordance with program the following tests have been performed:

- autonomous tests of 2 cathode units on the number of cycles (20 000 cycles);
- the first stage of the CU autonomous tests (two engineering models of KM-60 and FCU);
- the second stage of the CU autonomous tests (two engineering models of KM-60 and FCU);
- joint test of CU (KM-60 + FCU) with the laboratory model of the PPCU;
- qualification tests of CU (three qualifying models of KM-60 and FCU);
- full-scale lifetime test of CU - 4100 hours.

D. Results of qualification

Climatic, mechanical, thermal cycling, firing tests and 500-hour lifetime test have been performed at the first stage of autonomous tests.

Modifications of the CU construction have been performed at the stage of autonomous tests to eliminate the identified faults and improve specific impulse and lifetime.

Operation of thruster after exposure to climatic, mechanical, thermal, transportation loads has been confirmed at the second stage of autonomous tests. Lifetime test of CU with duration equal to 513 hours has been performed. Variation of thrust and specific impulse during this test is shown in Fig. 6, 7.

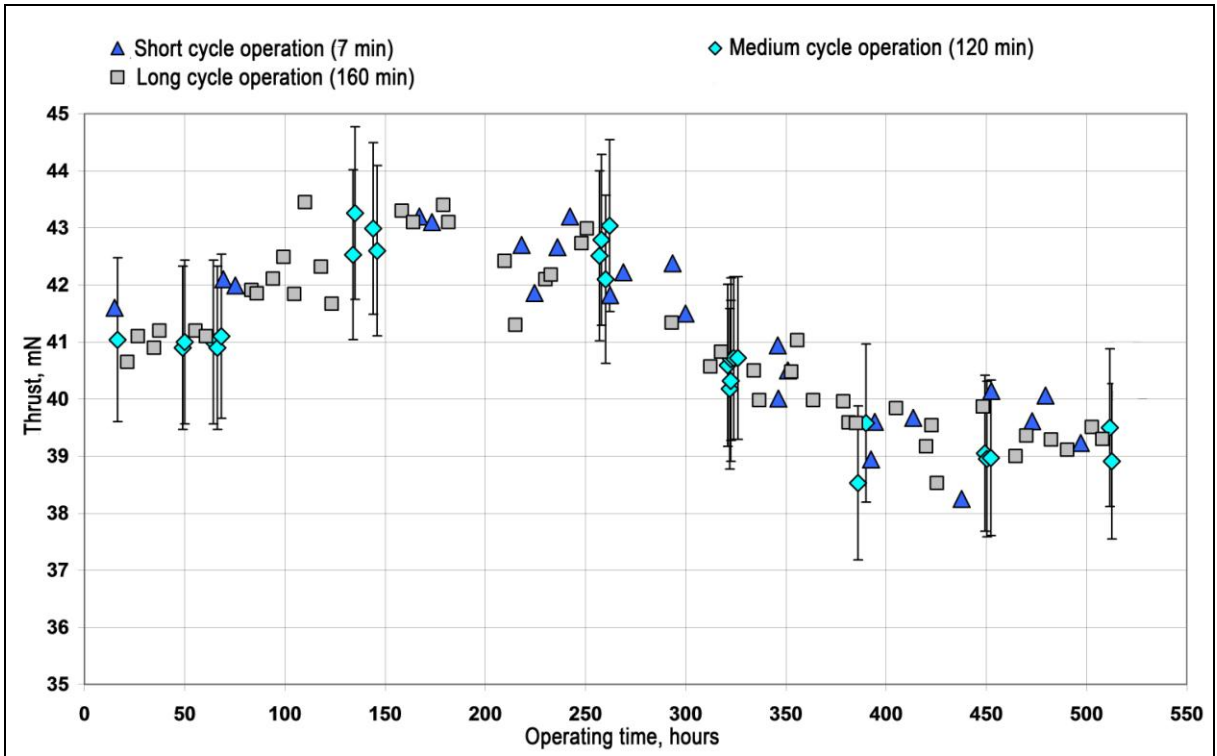


Figure 6. Dependence of thrust on operating time at the second stage of autonomous tests.

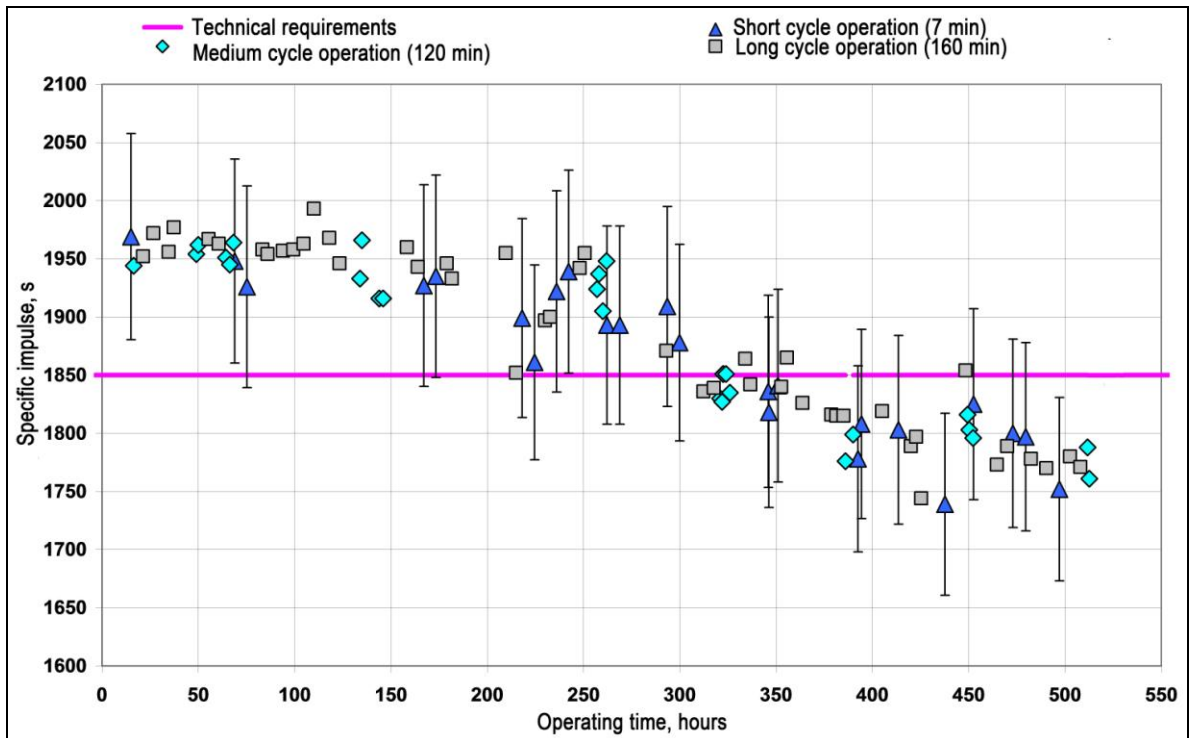


Figure 7. Dependence of specific impulse on operating time at the second stage of autonomous tests.

Parameters of the thruster ion beam before and after lifetime test were investigated during analysis of thruster performance degradation. The structure of anode efficiency³ defined on the basis of measurement data before and after the lifetime test is shown in Table 2.

Table 2

	KM-60 EM 0 hours	KM-60 EM 513 hours
γ_θ	0.93	0.94
γ_E	0.94	0.92
α	0.89	0.83
β	0.73	0.71

The dependence of the efficiency components on the operating time with the assumption that the γ^2 factor varies linearly during lifetime is shown in Fig. 8.

One can see from Fig. 8 that the gas efficiency starts to fall steadily after approximately 250 hours of thruster operation, which is the reason for reduction of specific impulse. Since the specific impulse depends only on the value of the $\alpha \cdot \gamma$ product it can be concluded that the main problem is reduction of gas efficiency. The question of the causes of such reduction is analyzed in Ref. 4.

Reduction of γ^2 during the test was not significant and was caused by the degradation of the energy component (lowering of the spectrum mean energy).

Modification of thruster design has been made with taking into account of additional tests results. It was based on the results of calculations of magnetic field topology and the position of the ionization zone in the accelerating channel^{5,6}.

Parametric tests of the upgraded KM -60 have shown high initial values of specific impulse (about 2000 seconds). In this regard, it was decided to conduct short lifetime test with equivalent operating time of at least 1400 hours.

The short lifetime test has been carried out in several stages according to the method described in Ref. 7. The parameters of the upgraded KM -60 have been measured in the equivalent period of operating time up to 1400 hours. Thrust was equal to (40 ± 1) mN, average specific impulse as the interpolation results for the tests was equal to (1860 ± 50) s. The predicted average specific impulse for the full lifetime was approximately equal to (1800 ± 50) s. The thruster KM -60 was admitted to the qualification tests based on the positive results of the shortened test.

Three correction units have been manufactured for qualification tests and they are shown in Fig. 9.



Figure 9. Qualification models of correction unit.

Parametric, climatic, thermal cycling tests, random and sinusoidal vibration tests, shocks impact, transportation tests as well as measuring the thrust vector have been conducted during qualification of CU. Further each of the three CU has been subjected to the lifetime test with duration not less than 500 hours.

The additional correction unit has been manufactured for carrying out of full-scale lifetime test and it also has passed through all qualification procedure just before starting of lifetime test.

Thus, 4 KM-60 thrusters and 4 FCU have passed through the qualification test procedure. The results of lifetime tests for all CU were similar so only results of full-scale test are presented below.

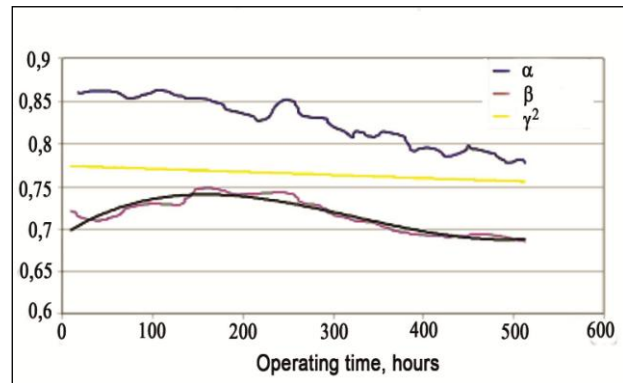


Figure 8. Changes in the structure of the anode efficiency during lifetime test

Significant effect of the atmosphere influence on the specific parameters of the thruster had been observed owing to opening of the vacuum chamber for measurement of the erosion profiles. Therefore full-scale lifetime test has been performed without opening the vacuum chamber.

Lifetime tests has been conducted in vacuum chamber KVVU -35. Pressure in the chamber was maintained at $(7.6 - 8.4) \cdot 10^{-3}$ Pa level by air calibrated vacuum gage scale in the course of the test. High purity Xe was used as the propellant. Xenon feed was provided by FCU. Flow measurement was performed using a commercial gas flow regulator in the measurement mode. Measurement error of xenon consumption was not exceeding 2.2%. Power supply of discharge was performed by standard facility power supply unit. During operation, the discharge voltage and discharge current were kept constant and equal to (500 ± 5) V and (1.8 ± 0.05) A correspondingly. Measurement error of the thrust was not exceeding 2.5%.The valves and regulators of FCU were supplied by the facility control system.

The functioning of the CU including start procedure was performed in accordance with mission profile. Starts with spare cathode were performed not rare than once per every 100 hours.

Initially it had been stated in the test program that the life test was to be divided into two phases. In the first phase it was planned to carry out 2500 hours test without opening the chamber. At least 5500 cycles were to be conducted on this stage. At the second stage, the remaining lifetime (up to 3750 hours) and number of cycles were supposed to be confirmed by shortened tests procedure. Taking into account influence of chamber opening on thruster parameters and difficulties associated with manufacturing with sufficient accuracy of insulators with erosion profiles for 2500 hours and more it was decided to continue the direct lifetime test without opening the vacuum chamber.

Intense detachment of films formed on the anode and cylindrical surfaces of insulators was observed after 500 hours of operation. Detached fragments of films overlapped accelerating channel, causing a change in thruster operation, reducing its effectiveness.

Reduction of the thrust by 10-20 % from the nominal value was observed at periods 800-1000 and 1200-1780 hours of operation. The most likely cause of trust reduction in these periods of operation is changing of the thruster operation mode due to films detachment and their accumulation in the cavity of the discharge chamber, as well as changes in geometry of the acceleration channel.

Operation of thruster was optimized by varying the magnetic field in the acceleration channel during lifetime test. The main purpose of this optimizing was to obtain the maximum value of thrust and specific impulse, stable operation and development of on-board algorithm of magnetic field correction for the flight units. Dependence of current in the coils on operating time is shown in Fig. 10.

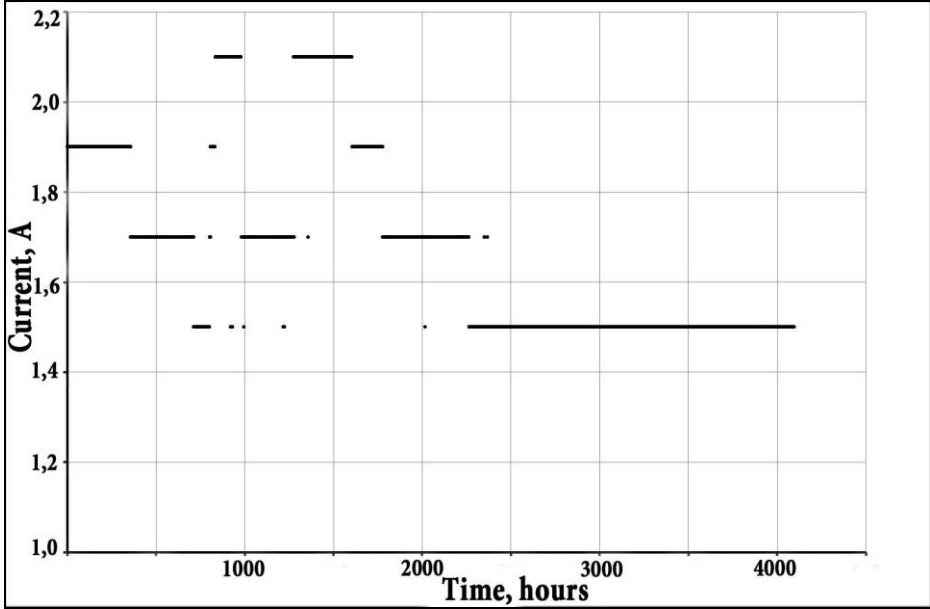


Figure 10. Dependence of current in the coils of the magnetic system in course of 4100 hours lifetime test.

Dependences of thrust and specific impulse on operating time are shown in Fig. 11 and 12 respectively.

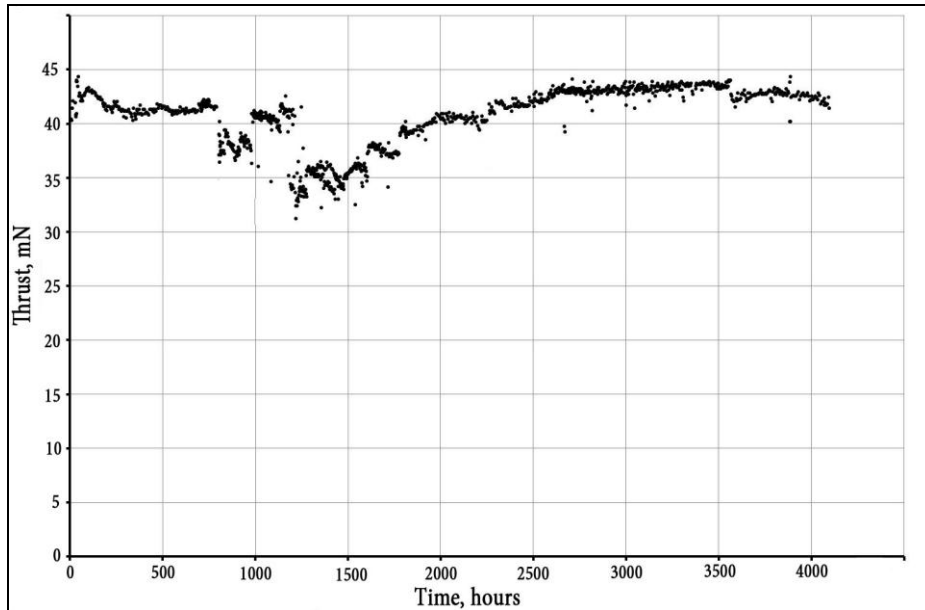


Figure 11. Dependence of thrust on operating time during 4100 hours lifetime test.

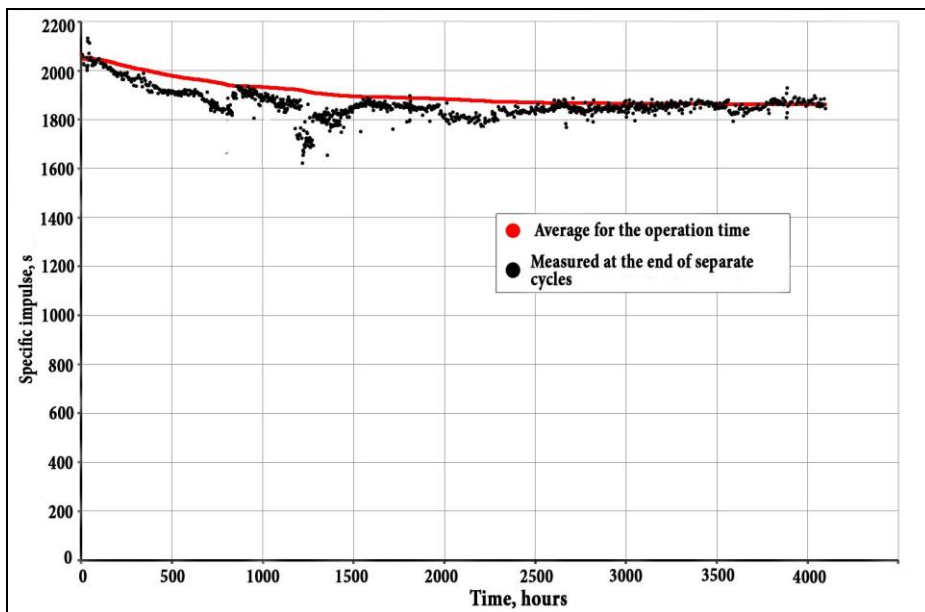
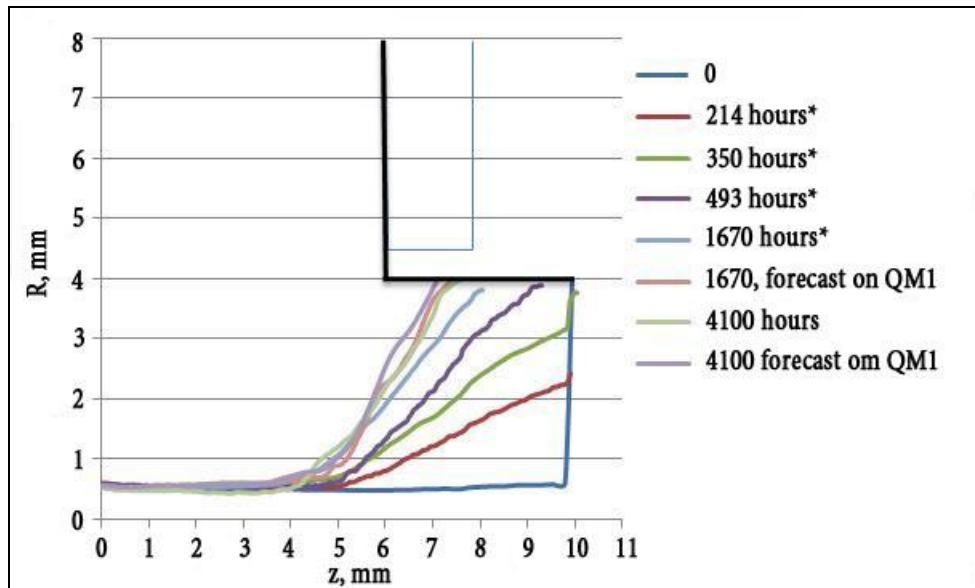


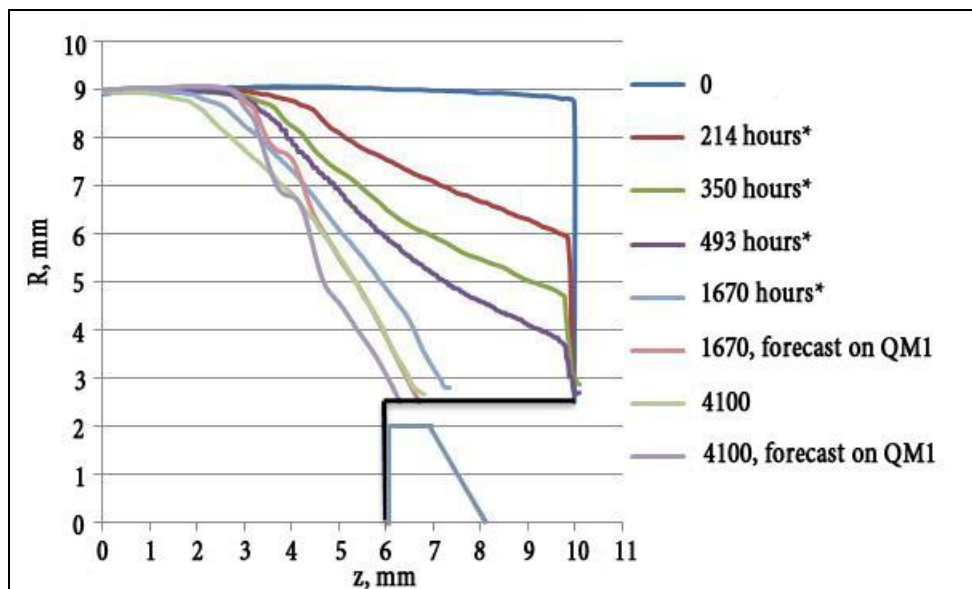
Figure 12. Dependence of specific impulse on operating time during 4100 hours lifetime test.

Ceramics erosion profiles during lifetime tests were measured by contact method and by laser range profilometer placed directly in the vacuum chamber. Diagnostic system also allows remote monitoring of the discharge chamber elements during pauses of thruster operation, taking photos and videos without opening the vacuum chamber.

The results of erosion profiles measurement are shown in Fig. 13. The results of erosion profiles prediction are also shown in this figure. Prediction had been made on the basis of first qualification model lifetime test with total operation time equal to 525 hours.



a)



b)

**Figure 13. Profile changing of the internal (a) and external (b) insulators of the discharge chamber during the 4100 hours lifetime test and comparison with the prediction of erosion made on the basis of QM1 525 hours lifetime test.
(* - Profiles measured with laser range profilometer)**

Profiles of the external insulator in different sections by azimuth not differ much after 4100 hours of operation. Four profiles for external insulator are shown in Fig. 14. The good agreement of the insulator erosion profiles indicates the azimuthal uniformity of propellant flow in the accelerating channel.

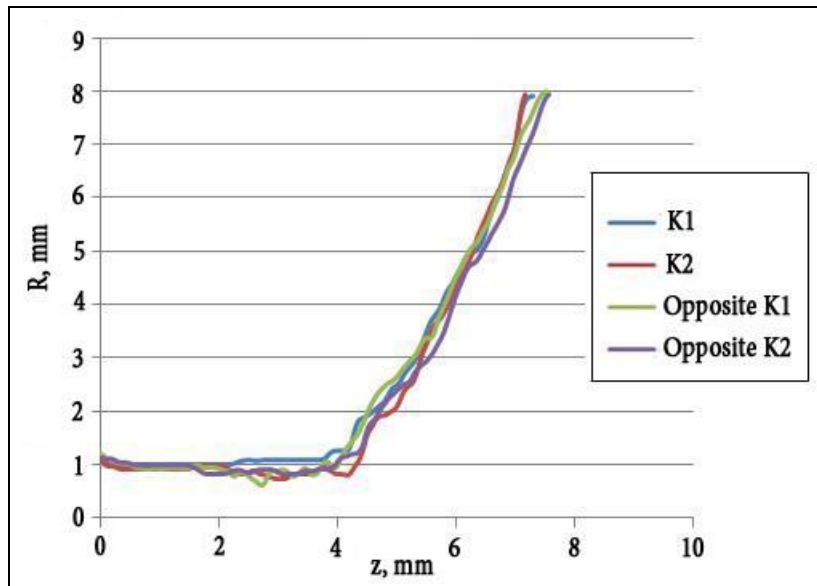


Figure 14. Profiles of the external insulator in different sections after 4100 hours of operation.

After erosion of protective coating erosion of magnet pole pieces was started at approximately 1550 hour of operation. The appearance of magnet pole pieces after the lifetime is shown in Fig. 15.



Figure 15. Appearance of KM-60 thruster after lifetime test.

Figure 15 shows that erosion of the inner pole piece is symmetric but erosion of the outer one is significantly asymmetric with a maximum sputtering level near to the spare cathode. Traces of erosion on the surface of the cathode ignition electrodes, which were under floating potential during test, are virtually absent. The type of magnetic poles erosion shows that it is likely determined by the backward ion flow to the surface.

Despite the erosion of the magnetic poles and ceramic insulators thruster was operable and its parameters were in concordance with technical requirements.

Thrust vector measurements were conducted before and after 4100 hour lifetime test to determine the deflection angle of the thrust vector from the axis of the thruster, also divergence of the plasma plume and the energy structure of the ions were measured.

Comparison of measured thrust vector deflection from the axis of the thruster is shown in Table 3. Measurement error of the thrust vector deflection angle does not exceed 12 angular minutes.

Table 3

Cathode	Main	Spare
The deflection angle of the thrust vector before lifetime test, angular minutes	37.0	38.0
The deflection angle of the thrust after before lifetime test, angular minutes	35.7	42.2

After lifetime test the thrust vector deflection angle does not changes considerably. The maximum value of deflection is 42.2 angular minutes.

Comparison of plasma plume divergence angle θ_{90} for the main and spare cathodes at distances 700 and 1500 mm from the thruster are shown in table 4.

Table 4

	700 mm		1500 mm	
	Main cathode	Spare cathode	Main cathode	Spare cathode
The value of the angular divergence of 90% of the ion current to the beginning of 4100 hours life test, degrees	54	54	54	54
The value of the angular divergence of 90% of the ion current after 4100 hours life test, degrees	43	44	44	47

Thus, the divergence angle of the plasma plume after 4100 hours lifetime test has decreased by 7-11 degrees. Ion current density on the thruster axis has increased about 1.5 times.

Analysis of ion energy distributions obtained at a distance of 1500 mm from the thruster have shown narrowing of the ion energy spectrum with increasing their average energy at small angles to the axis of the thruster and reduction of high-energy ions number with a drop of their average energy at the angles of 40-50 degrees from the thruster axis.

III Conclusions

Qualification of correction unit consists of Hall thruster KM-60 and flow control unit has been successfully completed.

Lifetime tests of the correction unit were conducted during qualification. The maximum operation time of single correction unit is equal to 4120 hours at 8357 cycles, the total shown thrust impulse is 602 kN·s with an average specific impulse -1862 seconds, thrust at the end of the test - 41.8 mN. At the end of lifetime test correction unit remained operable, and its parameters were in concordance with the specifications.

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