Development of KM-5 Hall effect thruster and its flight testing onboard GEO spacecraft "Express-A4"

*V.N. Akimov *, S.G. Baidakov*, V.N. Galayko**, O.A. Gorshkov*, Y.M. Ermoshkin***, V.A. Muravlev*, A.V. Nikipelov***, A.A. Sinitsin*, V.F. Petrusevitch***, V.N. Shutov*, A.I. Vasin*, D.V. Volkov****

** Keldysh Research Center, Onezhskaya st. 8, Moscow, Russia, 125438*

*** SPC "Polus", Kirov square, 2, Tomsk, Russia, 634050*

**** Reshetnev`s Scientific and Production Association of Applied Mechanics (NPO PM), Lenina st., 52, Zheleznogorsk, Krasnoyarsk region, Russia, 662972*

Abstract

The article presents the outcomes of development of KeRC KM-5 Hall effect thruster and experience obtained from the in-orbit exploiting of the thruster onboard NPO PM "Express-A4" GEO communication spacecraft. KM-5 is a multimode thruster with operational power range from 1 to 2.5 kW in contrast to other thrusters applied in space missions. It has higher thrust characteristics. It makes possible solution of orbit raising tasks to GEO for medium and heavy weight spacecrafts in addition to tasks of station keeping for geostationary spacecraft already being solved by Hall-effect thrusters. Furthermore, a thruster with such performance can be an efficient choice as a main engine for small interplanetary probes.

1. Introduction

Basing on predictions made by an American company COMSAT[1] for the forthcoming decade (2006…2015) one can say that 90% of communication spacecrafts (SC) launched to geostationary orbit (GEO) (17…19 SC per year) would have launching mass from 2.2 to 5.4 tons and more (SC mass on GEO from 1.5 to 4.0 tons) among them approximately 30% - of mass 1.3…2.5 tons on GEO, ~ 40 % – of mass 2.5…3.5 tons, ~ 20 % – of mass more than 3.5 tons. Active lifetime for commercial geostationary SC would be ~ 10…15 years.

A number of operating and being developed satellite platforms (SP) like Eurostar-2000+ (SC Astra 2B, Hot-bird-2, -7), Eurostar-3000 (Intelsat X-01, Anik F3, Inmarsat-4), Eurostar-4000, as well as SP Spacebus-3000 (AMC-9, Galaxy 17, Astra1K) and Spacebus-4000 (AMC-12, -22, -23, Koreasat-5, APStar 6) for advanced SC, which are produced by European companies Astrium and Alcatel allow creation of geostationary communication SC with mass on GEO of 2.5…4 tons.

Nowadays low power bipropellant liquid rocket engines as well as electric propulsion (EP), including Hall-effect thrusters and ion thrusters are applied as a part of SC station keeping propulsion system of geostationary SC. Application of EP with specific impulse of 1500…1700 s allows decreasing the amount of propellant needed to execute power-consuming (especially inclination control) maneuver of GEO station keeping approximately in 5…6 times[2] in comparison with low thrust liquid propulsion with specific impulse of ~ 300 s.

Hall-effect EP, mainly SPT-100 with power 1.35 kW and specific impulse of 1500 s, developed by EDB "Fakel" are applied on Russian geostationary space platforms, and by foreign SC producing companies: Alcatel and Astrium in Europe, as well as Lockheed Martin Astrospace in the USA. Boeing Satellite Space company applies ion thrusters XIPS-13 with power 0.65 kW and XIPS-25 with power 2.3…4.5 kW and specific impulse 3200…3800 s accordingly.

One of the tendencies of modern European SC development on the basis of mentioned above platforms is an increase of SC mass, and, accordingly, increase of on-board electric system power.

This means, that more electric power can be assigned to orbit correction system, so EP of more power (with higher thrust value) can be applied for SC orbit correction. This, in turn, would allow decreasing required time for SC fire operation, defined by total impulse.

With respect to the given features of SC development, a Hall-effect thruster KM-5 was created in KeRC[3]. The thruster is capable of effective operation in power range from 1 to 2.5 kW. At the same time thrust and specific impulse vary in a range of 52…140 mN and 1560…2100 s accordingly. At the nominal regime with power of 2 kW the thrust is 115 mN with specific impulse of 1700 s. In contrast to SPT-70 and SPT-100 HETs that are already

applied in space, KM-5 thruster developed by KeRC provides increased power, thrust, specific impulse.
KM-5 application onboard the station keeping system of a GEO SC improves its thrust to mass ratio and decreases the required firing time if compared to a case of SPT-100 application for the same task. In particularly, if a KM-5 thruster operates at power of 2.5 kW with thrust of 140 mN, its operation time required for a 4.5 tons GEO SC is not greater than 5000 hours, while SPT-100 required operation time is about 8000 hours. Such a decrease of demanded lifetime may decrease costs spent for thruster development and increase its reliability.
Higher power gives KM-5 thruster advanced capabilities in the field of orbit raising of medium and heavy satellites to GEO. In this case the payload mass of such SC can be significantly increased. Usage of Hall thrusters within a 10 kW electric propulsion system (EPS), in particularly 8…10 KM-5 units (including spare thrusters) having specific impulse of 1500…1700 s, even in a case of short operation time of 30…50 days, increases payload mass by 20…30% in comparison with a direct injection to GEO by a chemical propulsion boost vehicle or an apogee liquid propulsion system. If the launch is performed from Baikonur launch site by a “Proton-M” launch vehicle with a chemical propulsion “DM-3” boost vehicle the absolute value of payload mass increases by 100…200 kg. If the SC power to mass ratio on the GEO is 5 kW/t, EPS power is ~20…25 kW, and the injection time is increased up to 180 days, the payload mass can be increased in 1.5…2 times in comparison with chemical propulsion.
A Hall thruster can also be used for aerodynamic drag compensation of low-orbit SC used for Earth remote sensing in order to prolong their active operation time (up to 5…10 years). If the EPS is equipped with Hall thrusters providing ~100…120 mN of thrust and having lifetime of 6000 hours, it can keep a 300 km high orbit of a SC with mass equal to 1 t and power to mass ratio ~ 2.5 kW/t. This allows to increase resolution of the SC optical system. In this case, the EPS spends an amount of Xenon equal to 10…15% of total SC mass while operating for 5 years with a specific impulse of 1700 s.
Missions to planets of the solar system are among the reachable tasks for small SC with main EPS. For example, KM-5 thruster with power of 1.5…2 kW allows transferring a spacecraft with 165 kg initial mass from LEO to Mars orbit with a height of pericenter equal to 600 km and orbital period of two days. The SC mass on the orbit of Mars would be 80…90 kg, including dry EPS mass of about 35…40 kg. The flight time will be less than 2 years.
Considering the prospective of development and possible commercial interest in such equipment by Russian and foreign customers, in April 2001, KeRC and NPO PM decided to perform flight qualification of KM-5 multimode thruster onboard “Express-A4” spacecraft.
KeRC held out manufacturing, testing and delivery of the thruster and gas distribution unit (GDU). KeRC also provided the models and documentation required to confirm the suitability of the equipment for installation onto the SC.
NPO PM performed integration of the thruster, supplying power, executive instructions, propellant gas, held out combined checkups and coupling control. NPO PM also controls the thruster in orbit and gathers telemetric data.
Since the power supply for KM-5 thruster onboard “Express-A4” satellite can be provided only by the standard power source, with output voltage 300 V and discharge current 4.5 A, there was made a decision to operate in this mode, rather than in nominal mode (350 V, 5.7 A). A special matching and control unit (MCU) was developed and manufactured by SPC “Polus” to provide power supply and control of the thruster.
In this way, an additional propulsion unit (APU) applicable for “Express-A4” SC was developed by NPO PM basing on KM-5 thruster and GDU.

2. Propulsion unit description

The propulsion unit developed for a flight test onboard “Express-A4” consists of a KM-5 thruster and a gas distribution unit. An outlook of the KM-5 thruster and the gas distribution unit is presented on Fig. 1.

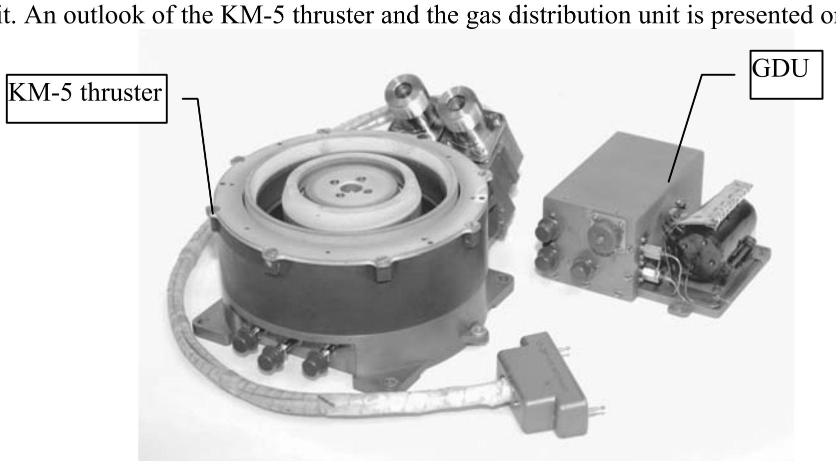


Figure 1: Hall thruster KM-5 and gas distribution unit

2.1 Flight unit basic specifications

The basic specifications of the orbit correction propulsion unit flight model are presented in Table 1.

Table 1: Basic specifications of the propulsion unit flight model

Parameter	Value
Discharge voltage, V	300±15
Discharge current, A	4.5±0.1
Thrust, mN	80±4
Specific impulse, s	1550 or greater
Lifetime required for the experiment onboard "Express-A4", h	4000
Number of on/off cycles	4000
Thruster mass (cable included), kg	4.9 or less
GDU mass with filter-getter unit, kg	0.8 or less

2.2 The thruster

Discharge chamber and walls of the acceleration channel are wholly made of Boron nitride based ceramics (hot-pressed mixture of Boron nitride and Silicon dioxide). Outer wall diameter of a cylindrical part of the acceleration channel is 116 mm, the channel width is 15.5 mm.

Two hollow cathodes with W-Ba emitters are used as neutralizers. One of them is spare. Cathode startup is performed with preliminary emitter heating of by an ohmic heater. The heater is also used for emitter outgassing before in-orbit thruster startup.

The thruster was primarily developed as a multimode thruster capable providing total impulse of $2.2 x 10^6$ Ns and nominal power of 2000 W. Besides it was to be capable performing prolonged operation in de-rated power mode (1350 W) and to be able to carry out short runs at enhanced power of 2500 W. The output parameters achieved in the course of optimization are as shown in Table 2.

Table 2: KM-5 thruster performance

Power, W	Voltage, V	Thrust, mN	Specific impulse, s	Efficiency, %
1350	300	82	1570	47
	350	71	1780	46
	450	65	1830	43
2000	350	111	1880	51
	450	102	1970	49
2500	350	137	1970	53
	450	128	2090	52

2.3 The gas distribution unit

GDU is responsible for Xenon feed of the thruster and controls magnitude of the discharge current. Xenon runs from the propellant feed subsystem of the main propulsion system through the GDU to the KM-5. While the thruster is operating, Xenon pressure at the GDU inlet is supported at level of 2.5±0.2 kgf/cm^2. The functional pneumatic diagram is presented at Fig. 2.

The GDU has a main and spare xenon feed lines for both cathodes and the anode in order to increase its reliability. The required cathode flow rate is obtained by installation of a suitable throttle. Varying magnitude of current running through a thermal throttle according to a command from the matching and control unit supports a given value of anode flow rate.

The cathode feed line is equipped with a filter-getter (FG) to protect the cathode emitters from poisoning by admixtures contained in Xenon and structural material of the feed line elements. Xenon passes through porous chemically pure Titanium held in an ampoule of the FG at temperature of about 750 °C. At that the admixtures in the propellant (mainly Oxygen and water) come into reaction with Titanium and are absorbed by it as a result.

The power consumed by the FG heater during stationary operation is no more than 17 W. The total of GDU power consumption is no more than 23 W.

The parts and structural units used as elements of GDU and KM-5 thruster were subject to a large amount of tests in the course of T-160 and ROS-99 propulsion units development, including 500-hour and 2500-hour life tests, respectively.

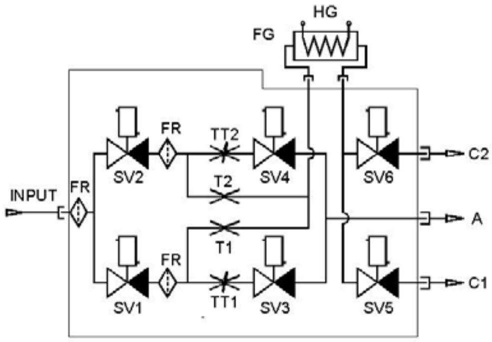


Figure 2: GDU functional schematics
FR – filter, SV – electromagnetic valve, TT – thermal throttle, T –throttle, FG – filter getter, C –cathode pipeline, A –anode pipeline, HG – heater of the filter getter

3. Propulsion Unit Qualification Activities

As the "Express-A4" onboard electric power of KM-5 can be supplied only by the standard onboard power source with output voltage of 300 V and discharge current of 4.5 A it was made a decision to carry out operation of the KM-5 in this mode, while using the discharge current to power magnetic coils. For this purpose the electric circuit of magnetic system was changed.
Taking into account features of onboard operation, the already manufactured engineering models of KM-5 and GDU were modified and separately put to mechanical tests with qualification load levels and functioning tests. Coupled firing test of the KM-5 and GDU engineering models (EMs) were also performed. At that time plume measurements were carried out as well as temperature measurements of thruster parts. As it was defined by the plume measurements, 95% of ion flow passes within the limits of 58˚ divergence angle. The EM coupled test also allowed defining electric filter parameters and magnitude of the thermal throttle current more exactly. According to the test results EMs were accepted to coupling firing tests with the spacecraft equipment held at NPO PM.
Except functioning tests, qualification models (QM) of KM-5 and GDU were tested for resistance to mechanical and thermal effects. After that they were subjected to a 500-hour life test.

3.1 Mechanical and environmental tests

The mechanical tests of KM-5 QM and GDU QM were performed separately. Load levels and duration are presented in the Table 3. The linear acceleration was replaced by an equivalent sinusoidal effect. To define the equipment condition before and after applying full-scale vibration loads, amplitude-frequency characteristics were studied. Control procedures were held after mechanical tests in order to check up conformance to the requirements of design documents.
KM-5 QM examination procedure included its startup and operation at nominal power mode using main and spare cathodes, thrust, anode and cathode flow rates and temperature measurements. In the course of thruster firing tests vacuum facility backpressure varied in a range of $2x10^{-4}…1x10^{-2}$ Pa.
GDU examination procedure included a valve operation check, determining of flow rate value while operating with main and spare pipelines, determining of flow rate in cathode and anode gas circuits, measurement of thermal throttles standby current, pipeline pressurization check, verification of conformance to design documents.
Thermal environment tests of KM-5 QM and GDU QM were aimed to prove experimentally their resistance to cyclically changing heat loads in a vacuum environment.
KM-5 QM was subjected to 10 test thermal cycles in a qualification range of temperatures, which is from the minimum level (-70 °C) to the maximum level (+160 °C). The range corresponds to "firing" operation onboard a spacecraft. At that the startup was performed at minimal (-70 °C) as well as at maximal temperature (+160 °C). Each thermal cycle included cooling of the thruster down to -70 °C, exposition at this temperature for 2 hours or longer, until the thermal equilibrium was achieved, startup ("cold startup") and subsequent functioning for 180 minutes at I = 4.6 A and U = 315 V, until the equilibrium temperature (~160 °C) was achieved. After reaching this temperature the

thruster was switched off and, after a 5 minute pause started up again in “hot startup” and then operated for 90 minutes. After that the cycle was repeated.

Table 3: Levels and Durations of Mechanical Loads

Load type	Parameters	Values
Sinusoidal vibration	frequency range, Hz acceleration, g; duration per axis, min	5…100 1…20 10
Random vibration	spectral density, g^2/Hz; duration per axis, min σ, g	0,002…0,133 6 12,9
Linear acceleration	acceleration, g; duration per axis, min	± 10 10
Shock	acceleration, g; pulse duration, ms; number of shocks per axis;	45,3 4,3 6
Vibration endurance	frequency range, Hz acceleration, g; duration per axis, min	5…2000 1…12 30

While performing GDU QM thermal qualification activities there were made 10 cycles of negative (–30 °C) and positive (+ 70 °C) temperature effect onto the base part of GDU QM. Duration of the cycle was ~150…170 min with functioning of GDU QM elements. The tests included FG operation, Xenon flow rate feed to the pipelines and measurement of cathode throttle panel and GDU QM wall temperatures. Examinations of equipment condition that had been performed after the tests showed that the GDU QM elements performance was nominal. Leakages and over-flows in valve couples were equal to the initially measured values.

Coupled firing tests were performed to verify equipment functionality after shock tests imitating transport loads as well as to check functionality in a case of discharge voltage, valve voltage, thermal throttle current and Xenon input pressure deviation from nominal values (within the specification limits). The thrust was in a range of 78.4…83.2 mN, and the specific impulse in a range of 1560…1600 s when the discharge voltage varied from 285 to 315 V, GDU input pressure of Xenon varied from 2.3 to 2.7 kgf/cm^2. Anode current overload duration was less than 10 ms and its amplitude value was 4.8 A.

Plume parameters, namely: ion energy distribution and divergence angle, that was 58…59 degrees, were measured in the end of the test. Thruster firing time amounted to 47 hours and 23 minutes in the course of qualification tests, number of on/off cycles was 35.

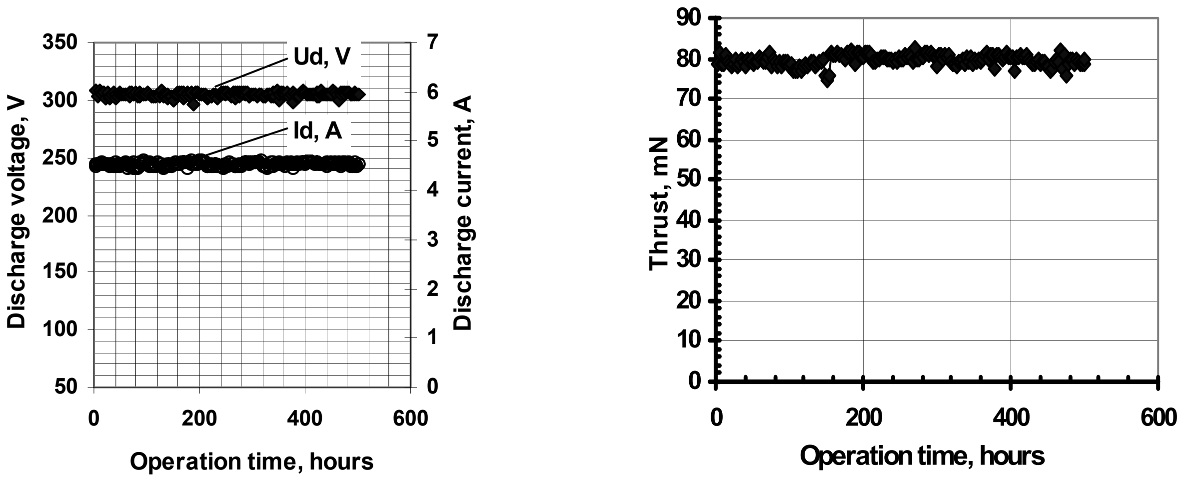
3.2 Life test

500-hour life test was divided into cycles. Each cycle lasted for 180 minutes (firing time 160 minutes). Cathode heating time (4 min) was included into the duration of pause. During the test the discharge voltage and current were permanently supported equal to 300±6 V and 4.5±0.1 A, respectively. A total number of on/off cycles performed during the test was 188, with 5 of them using spare cathode.

Every ~ 100 hours of operation there were made plume measurements and functioning using spare cathode. Total firing time of the QM in the course of the life and qualification tests amounted to 554 hours with 225 on/off cycles, from which 11 firings were performed after exposure in the atmosphere. During the tests KM-5 QM switched on and operated together with the GDU QM without any failures.

Thrust measurement was performed in the end of each cycle, at the moment of thruster turnoff. Registration and measurement of other operating parameters of the thruster and the GDU were held out shortly before the turnoff. Calibration of the thrust measurement device (TMD) was performed after each thrust measurement since such a procedure allows avoiding an error caused by TMD zero drift.

In the course of the life test the thruster parameters were stable (thrust 80±4 mN, specific impulse ~1550 s, power ~1350 W) and matched the specification. History of discharge voltage, discharge current and thrust changing is presented on Fig.3. Angular divergence did not change during the tests period and was equal to 56 degrees.

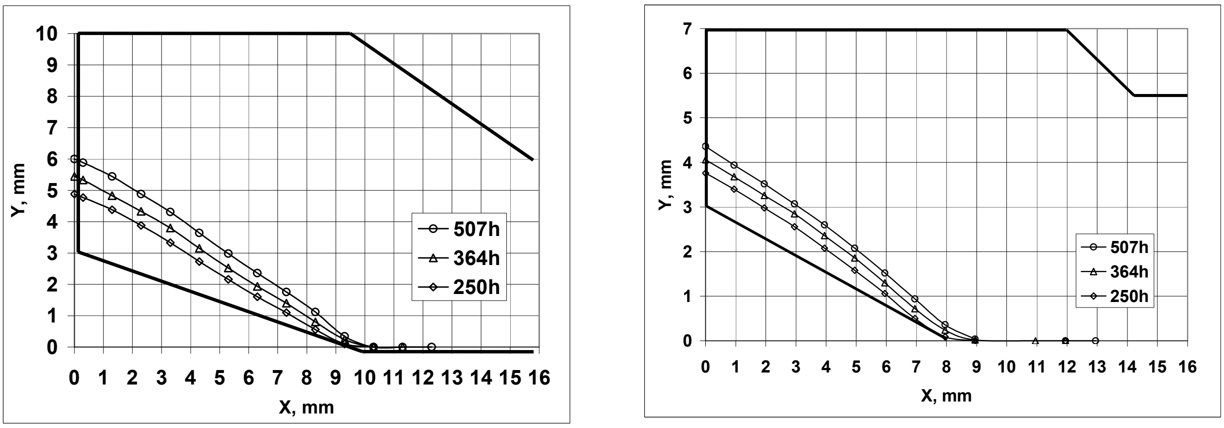


a): Current and voltage vs time

b): Thrust vs time

Figure 3: Evolution of parameters during the life test

Wall erosion measurements were made before the life test, then after 120, 250, 364, and 507 hours of operation. The profile of eroding parts of the insulator was measured on different distances from the channel exit, in 8 cross-sections, uniformly distributed through the azimuth. The profiles for 250, 364 and 507 hours are presented on Fig. 4. Straight lines correspond to the initial profile.



a): Inner wall erosion

b): Outer wall erosion

Figure 4: Insulator profile change during the life test

The rate of the inner wall erosion is much higher than that of the outer wall, so at the given thickness of the insulator walls near the channel exit, the lifetime is limited by the thickness of the inner wall.

A value of acceleration channel lifetime estimated according to procedure described in Ref.4 with a use of results of the 554-hour thruster operation is ~6500…7000 hours.

4. Integration of the propulsion unit with the spacecraft and flight tests

In the course of integration of the additional propulsion unit based on KM-5 thruster into the "Express-A4" ("Express-A1P") spacecraft, the following actions were performed:

- mechanical fixation of APU on the "Express-A4" SC, outside the pressurized container;
- Xenon input from the standard station keeping propulsion system into the gas distribution unit and further into the KM-5 thruster;
- creation of electrical interface, including power supply of the thruster and GDU elements, transfer of control data from and telemetric data into the onboard telemetry system;
- taking away the generated heat;

A special matching and control unit was developed for power supply and control of a KM-5 thruster. Since the power supply for the discharge circuit was provided by the standard power source, a special connector was included into the MCU to switch the discharge power from a spare DK4R thruster to the KM-5 and back. As the power supply

parameters required for KM-5 thruster, except the discharge power supply parameters, differ from that of the M100 thruster, the MCU was equipped with upgraded discharge current stabilization system, cathode heater current stabilizer, ignition system and valve power source. The operation modes are defined according to analog telemetric data that is gathered by the MCU elements and transferred to the onboard computation system. The data includes discharge current and voltage, cathode heater current, thermal throttle current. The MCU is developed basing on the solutions used in the power processing unit (PPU), with the only difference that hermetically sealed contactors (“gerkons”) are replaced with electromagnetic two-position relays. Since the MCU is integrated into the spacecraft as an additional unit, it was installed onto the SC outside the pressurized container, closely to the thruster and its only protection is provided by thermal radiation reflecting film. Autonomous thermal vacuum and mechanical tests proved the correctness of the aforementioned design schematics and technological solutions.
Block diagram of the electrical interface between the APU and “Express-A4” SC systems is presented at Fig. 5.
Pneumatic diagram of the APU units, pipelines and their circuit connection with the standard station keeping propulsion system (SKPS) is shown at Fig. 6. APU utilizes Xenon that is stored in the SKPS tanks. The same Xenon is utilized by the standard M-100 thrusters.

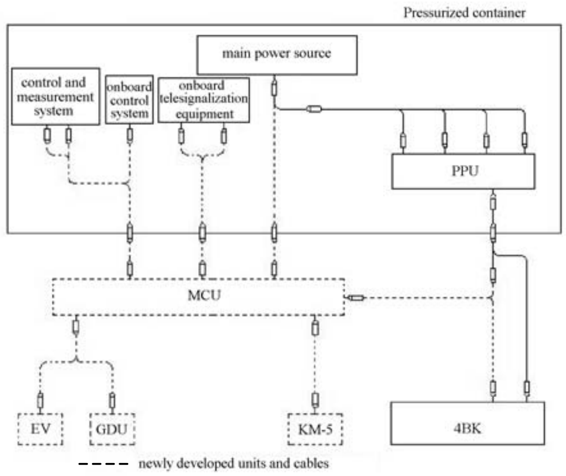


Figure 5: Block diagram of the electrical interface and APU circuit connection

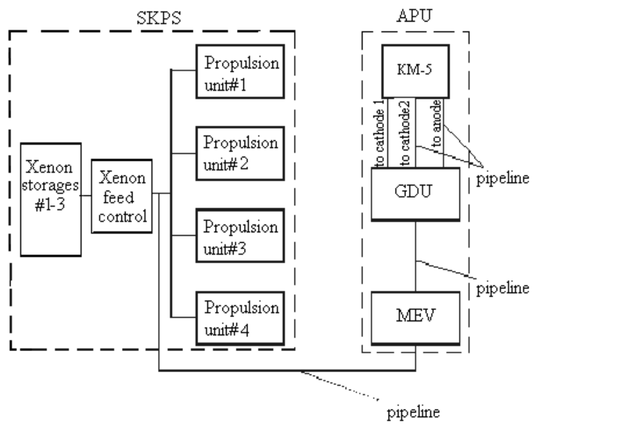


Figure 6: Diagram of APU and SKPS pneumatic circuit connection

To prove the combined operability of the APU, namely KM-5 thruster, GDU, matching and control unit, main electric valve (MEV); as well as to verify compatibility of the APU with the power processing unit (PPU), SKPS propellant subsystem and electric power system of the spacecraft; NPO PM performed a coupled firing test. The test proved:
- electrical compatibility of MCU and PPU with KM-5 thruster, GDU and MEV;
- MCU and PPU combined operability;
- that the GDU and KM-5 thruster can operate while utilizing Xenon from SKPS propellant subsystem;
- reliable work of PPU overload protection at a discharge current of KM-5 thruster increased above the operation gap;
- correctness of MCU control logics;
- KM-5 startup stability while it is performed by MCU and achievement of required discharge current stabilization accuracy;
- gathering of the required telemetric data;
- APU operability while running with the SC power system. It was shown that SC power system 27-V bus voltage pulsation magnitudes and levels of its transient processes are within the allowed limits.

The content of the APU mechanical interface test activities performed on the SC EM was as follows:
- harmonic vibration strength test;
- wideband random vibration strength test;
- combined (electrical tests).

The APU electrical tests within the “Express-A4” SC included addressing checkup of control and telemetric circuits between the onboard integrated control unit (ICU) and the APU control unit.
The APU stationing onboard the “Express-A4” spacecraft is shown on the Fig. 7.
The full-scale test phase of KM-5 (T-120) thruster was started on the moment of “Express-A4” injection to GEO, that was on 10 June 2002.

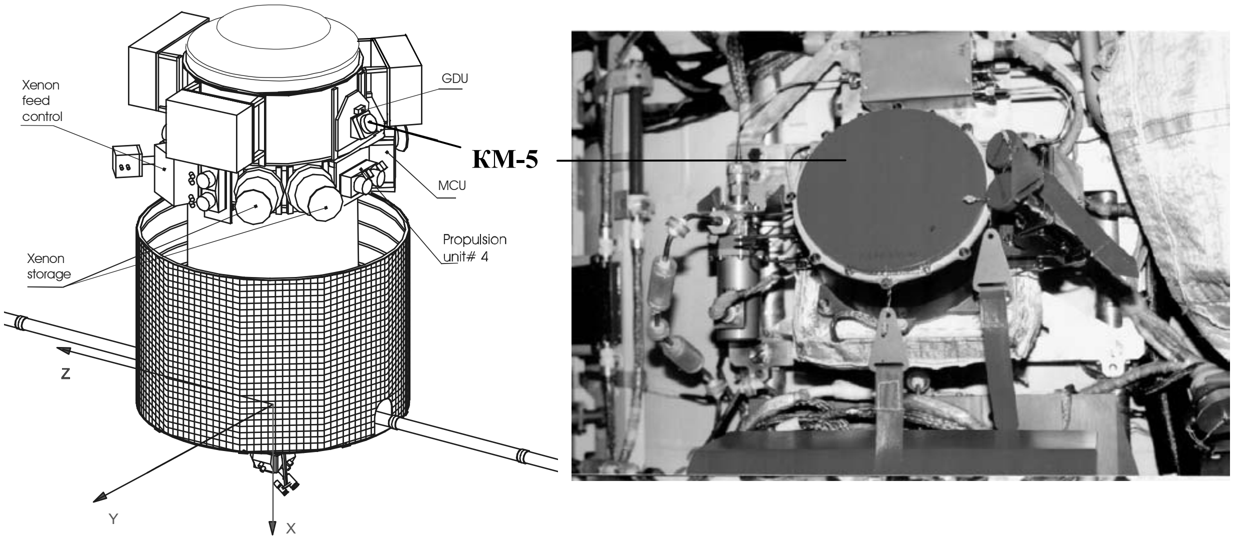


Figure 7: APU equipment stationing onboard the “Express-A4” spacecraft

The APU preparation included evacuation of propellant feed pipelines, cathode outgassing and 4 verification firings of the KM-5 thruster with different combinations of cathodes and Xenon feed lines in GDU. The total operation time during these firings was 25 minutes 50 seconds. All the startups and firings were performed according to the prescribed logics and without any failures.

MCU reliable operation during the flight test since June 2002 on board the SC proves ionizing radiation resistance of the used elemental base and that the design provides normal thermal conditions of electric and radioelements.

Now the KM-5 (T-120) thruster is used for “Express-4A” orbit inclination keeping. No failures are observed. To date of 28.05.2007 total operation time of the thruster is 1074 hours at 583 on/off cycles.

5. Conclusions

5.1. KM-5 thruster, with 2 kW nominal power, developed at KeRC, is advantageous as compared to all Hall thrusters already being used in space since it has a multimode operation capability and is capable operating in the de-rated power mode (1.35 kW) and the enhanced power mode (2.5 kW).

5.2. Qualification activities have been performed for a propulsion unit composed of a KM-5 thruster and a gas distribution unit. The aforementioned propulsion unit is integrated into “Express-A4” spacecraft.

5.3. The KM-5 thruster and GDU are being tested since June 2002. To date of 28.05.2007 total operation time of the thruster is 1074 hours at 583 on/off cycles. No failures are observed.

5.4. KM-5 thruster application is a promising solution for such tasks as station keeping and orbit raising of medium and heavy class GEO spacecraft. It can also be efficient as a main engine of small interplanetary probes (particularly for missions to the Moon and Mars).

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