Electric Propulsion Activity in Russia[*†]

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An overview of Russian activity in the field of electric propulsions (EP) is presented in the paper. As it is known, the most significant progress was achieved in Russia in the field of the so-called Hall thruster development and application. The first satellite with Hall thruster of SPT type was launched in December, 1971. So, the 30-th anniversary of the SPT appearance in space is celebrated this year. And a lot of research and developmental works in the field of SPT were realized since that event. The main steps of these works are considered in the paper. As a result, over 140 SPTs operated or operate in space for spacecraft orbit correction and, in particular, for the geostationary satellite final positioning and their stationkeeping. Nowadays, the SPT technology becomes the worldwide, namely: some developments of own SPT versions are realized in France and USA, SPT implementation on board Western satellites was started. Developments of new SPTs are naturally continued in Russia. And some of their latest results are represented in the paper, as well as the main results of R&D works on other EP types.
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Introduction

Intensive enough electric propulsion investigation and development were started in the USSR in the end of 1950-s – beginning of 1960-s. The most part of EP concepts known by now was studied, and some impressive results in the ion and plasma thruster development were achieved, namely:

- In 1964 pulse plasma thruster (PPT) was tested in flight for the first time on board "Zond-2" spacecraft, and during several hours a PPT-based propulsion system (PS) provided spacecraft attitude control [1];
- A series of ion thruster models was developed and flight tests of ion sources on their base were realized [2];
- By the end of 1960-s, lithium magnetoplasmadynamic thruster (MPDT) models able to operate under the powers of up to 500 kW stationary with thrust efficiency of about 60% and specific impulses of ~ 4000 s were developed and tested [3];
- Double-stage TAL models (thruster with anode layer) were developed and tested, which were able to operate with Bi and other propellants under the powers of up to 100 kW at thrust efficiency of up to ~0.8 and specific impulses of up to 8000 s [4];
- The first so-called stationary plasma thruster (SPT) was launched in 1971 and tested

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successfully on board "Meteor" satellite in 1972 [5].

But nowadays the main part of real developmental works in Russia is connected with Hall thrusters – SPT and TAL. Taking into account that this year is the 30th anniversary of the first Hall thruster appearance in space, it seems interesting to review the main steps of these thrusters development and application, as well as to consider the modern trends in other electric propulsion activities in Russia.

1. Hall Thruster Development

The first stationary plasma thruster (SPT) laboratory models were designed and investigated in Russia by the Kurchatov Institute of Atomic Energy (KIAE) under the leadership of professor Alexey Morozov in early 1960-s. And by the end of 1960-s a possibility was shown to obtain the SPT thrust efficiency at a level of 0.2-0.35 under specific impulses of (1000-2000) s while thruster operates with gaseous propellant under the power of several hundred Watts. It was difficult to obtain such level of thrust efficiency under the mentioned conditions for other types of electric propulsions. Therefore, SPT was considered as perspective enough in the USSR, and complex of physical studies for its operation peculiarities were conducted. In particular, it was shown that the ion velocity at the thruster exit corresponds to potential difference passed by ions, i.e. that the ion acceleration is quasi-electrostatic one. At the same time, the plasma quasi-neutrality is realized inside the accelerating channel. Therefore, there is no restriction in the ion current density by space charge, and this density may be by several orders of magnitude higher comparing to that of the ion thrusters.

Plasma parameter distributions along the accelerating channel were studied also, as well as some plasma oscillations having significant impact on electron transport across the magnetic field and on thruster efficiency.

It is necessary to note also that the principal schemes of the first SPT type thrusters were proposed in USA and USSR almost at the same time. Due to the absence of scientific cooperation in the field of rocket propulsion development at that time, the works in USSR and USA were proceeding almost independently. Nevertheless, similar results mentioned above were obtained by the end of 1960-s, but different decisions were made on the basis of these results in USSR and in the West, namely:

- In the West the Hall thruster studies were gradually frozen;
- In the USSR a decision was made to study the possibility for using SPT for an auxiliary mission - spacecraft orbit correction, and in 1969 KIAE and Design Bureau (DB) that is called "Fakel" now started the development of the first SPT-based experimental propulsion system (PS). As it was mentioned, that PS was successfully tested in 1972.

During the first test, the SPT-based PS operated in space for more than 170 hours, changed the height of the " Meteor" satellite orbit by ~17 km and positioned satellite into the sunsynchronous orbit. So, during the first test SPT had solved the practical task on the operational satellite orbit correction. Compatibility of the SPT-based PS and other satellite subsystems was demonstrated then.

Taking all the mentioned into account, it was decided to develop the SPT-based PS for the practical application, and that task was solved by "Fakel" DB under the scientific and technical support of KIAE and other Russian institutes and enterprises (Moscow Aviation Institute, Central Institute of Motor Building, et al.). And for to-day, over 140 SPTs were operationally used or are in use on board the Russian satellites and satellites developed and manufactured in Russia for western customers (Table 1).

Operational use of SPT-based EPS for the "Meteor" type satellite orbit correction was started in 1976 (see Table 1). That EPS comprised the SPT-50 type thruster – the 1st one of the second generation thrusters.

SPT application for geostationary satellite (geosat) final positioning and stationkeeping in the East-West direction (E-W SK) started in 1982, and since 1994 it is used for the geosat final positioning, E-W SK and North-South stationkeeping (N-S SK).

Nowadays the SPT-based propulsion systems are implemented into the western spacecrafts, and launches of the following geosats were scheduled for 2001: "Stentor" (French technological), "ASTRA-1K" (European commercial) developed by Alcatel, and

"Telstar-8" (US commercial) developed by Space Systems/Loral. It is necessary to add that over 10 other commercial satellites (INTELSAT-X, INMARSAT-4, et al.) are under development, which are to be equipped by SPT-based PS and are to be launched within the next 3..5 years.

Table 1. SPT-Based EPS Flight Tests and Applications

Year	User	Satellite type	Mission	Number of thrusters
1972	VNIIEM	Meteor#18 (H≈900km)	Flight test, orbit correction	2 SPT-60, η_t=0.15-0.21
1974	VNIIEM	Meteor-Priroda#1	Flight test, orbit correction	2 SPT-60M, η_t=0.26-0.28
1976	VNIIEM	Meteor-Priroda#2	Orbit correction (S/C positioning)	2 SPT-50, η_t=0.33
1977	VNIIEM	Meteor-Priroda#2-2	Orbit correction (S/C positioning)	2 SPT-50, η_t=0.33
1978	VNIIEM	Astrophysics	Orbit correction (S/C positioning)	2 SPT-50, η_t=0.33
1981	VNIIEM	Meteor-Priroda#2-4	Orbit correction (S/C positioning)	2 SPT-50, η_t=0.33
1987	Arsenal	Plasma	Orbit correction	2x6 SPT-70
1982-2000	NPO PM	Kosmos, Loutch, et al.	S/C positioning and E-W SK	16x4 SPT-70, η_t=0.45
1995-2001	NPO PM NPO PM NPO PM PSC Energiya	GALS (2 S/C) Express (4 S/C) SFSAT Yamal-100	S/C positioning and E-W and N-S SK	2x8 SPT-100 (η_t=0.5) 4x8 SPT-100 1x8 SPT-100 1x8 SPT-70

Accounting for the fact that France and USA are now developing their own SPT and SPT-based EPS, it is possible to conclude that this technology becomes the worldwide one.

Several complexes of investigations and developmental works were realized during the considered period. They allowed to improve the SPT design and performances. As a result, SPT-70 and SPT-100 thrusters were designed and qualified by Fakel Design Bureau for the flight (Table 2). Due to their specific design features, these thrusters may be characterized as the thrusters of the second generation. But SPT-100 thruster has specific configuration of the magnetic system, anode, cathode, and discharge chamber allowing to reach long thruster lifetime. The SPT-140 design was improved further, and this thruster may be considered as the thruster of the third generation. It is developed according to the ISTI R&D program.

Table 2. SPT Development Status and Performance.

Performance	SPT-50	SPT-70	SPT-100	SPT-140
Nominal operation mode power, kW	0.35	0.7	1.35	5
Nominal thrust, mN	20	40	80	300
Specific impulse, s	1100	1500	1600	1750
Lifetime confirmed by ground test, h	1500	3000	9000	>7000 (expected)
Thrust efficiency (BOL)	0.35	0.45	0.5	>0.55
Stage of development	Flight proven	Flight proven	Flight proven	Under qualification

Besides SPT flight models, a great enough number of laboratory experimental and flight SPT prototypes covering the power range from ~ 50 W to ~ 30 kW was naturally developed and investigated, namely:

- Small SPTs developed by RIAME MAI with the outer accelerating channel diameter from 20 mm to 30 mm and acceptable performance level under the power of up to 100 W, and SPTs with accelerating channel outer diameter of 30-50 mm developed by Fakel DB, MAI and KeRC, operating with acceptable performance level under the power of 100-500 W;
- A series of SPT-70 and SPT-100 scale thruster experimental models developed by MAI, RIAME

MAI, MIREA, KeRC and having improved performance level relative to the flight versions of SPT-70 and SPT-100;

- A series of laboratory and experimental SPTs with the outer accelerating channel of over 120 mm (SPT-180 of MAI and RIAME MAI, ROS-2000 and T-160E of KeRC, SPT-200 and SPT-290 of Fakel DB) covering the power range from ~ 3 kW to 30 kW and able to operate effectively enough under the specific impulses from ~ 1500 s to 3000 s;
- A possibility is studied for the development of an efficient enough SPT on propellants alternative to Xe, namely Ar, Kr and their mixtures with Xe. This study is being conducted by KIAE, MAI, RIAME MAI and MIREA in cooperation with French Institutes under the support of INTAS (Project No. 99-1225). Similar study is being made by RIAME according to the internal Russian R&D program.

These works had some notable results, namely:

- It is possible to obtain an acceptable performance level for a small SPT under its operation with the total power consumption of 60-100 W. Using such small SPT-25 as a base, Fakel DB has developed a demo model of a small SPT unit consisting of SPT with the heaterless cathode and xenon flow controller. The demonstrated total thrust efficiency of such unit was ~14% under the power consumption of about 60 W and specific impulse of ~ 550 s, and 18% under the power consumption of about 100 W and specific impulse of ~ 800 s. The expected lifetime is ~ 600 hours. So, such SPT unit could be effectively used on board mini sats;
- It is possible to obtain thrust efficiency of over 0.6 for the SPT-100 scale thrusters under the power consumption of less than 2 kW and specific impulse of higher than 3200 s. Such performance level is demonstrated by X-85 SPT model developed by Keldysh Research Center;
- Thrust efficiency of ~ 0.58 was reached for the SPT-140 qual model, that is higher significantly than the SPT-100 efficiency. As it was mentioned already, this model is going successfully through qualification. T-160E model was prepared for the flight test on board "Express" satellite;
- A possibility was demonstrated earlier to obtain the SPT-290 thrust efficiency at a level of 0.65-0.70 under the discharge power of 25-30 kW and specific impulse of ~ 3000 s;
- A possibility was shown also to obtain thrust efficiency for the SPT on Kr of over 0.5 under specific impulse of no less than 2500 s and moderate discharge power. So, it is possible to reduce the propellant cost to be stored in EPS and to be spent during the ground test.

As a whole, it is possible to conclude that a scientific and technological base was created by these works for increasing the SPT and SPT-based propulsion system application effectiveness and extending their application field.

The history of thrusters with anode layer (TAL) is not so rich. First TAL investigations and developments were realized in the USSR under the leadership of Askold Zharinov. As it was mentioned, these works were oriented to the development of powerful EPS for primary missions. But it was recognized in 1970-s that such missions were far enough from realization. Therefore, in 1980-s the TAL development was turned to the thrusters able to operate efficiently under the power of ~ 1 kW.

A series of single and double stage TAL models with the performance competitive to SPT ones was developed as a result. The first TAL flight test was realized on board the US satellite in 1999. As TAL has some potential advantages over SPT, development of TAL models competitive to SPT and ion thrusters and operating with xenon is continued. In particular, the following models were developed by TsNIIMASH experts:

- Small power TAL models of D-27 and D-38 types able to operate within the power range of 100-500 W at the accelerator efficiency η_a (calculated not accounting for the cathode mass flow rate) of 0.2-0.4 (higher efficiency corresponds to the higher power) and specific impulse within the range of 1000-2000 s;
- D-55 model able to operate within the power range of 0.30-1.5 kW at the accelerator thrust efficiency of 0.4-0.6 and specific impulse of 1000-2500 s;
- D-100 and TAL-110 single stage models able to operate within the power range of 1-6 kW at the accelerator thrust efficiency η_a = 0.4-0.6 and specific impulse of 1500-3000 s, and D-150 model able to operate at the power of up to ~15 kW with

the same level of thrust efficiency and specific impulse;

- D-100 II and TM-50 double stage models able to operate at a power of up to 15 kW and 30 kW at least, correspondingly. These models demonstrate the ability to operate under specific impulses of 1000-2500 s, as well as under specific impulses of up to 5000-7000 s;
- D-80 TAL laboratory model able to operate as a single stage thruster with maximum thrust when it is necessary to obtain high thrust, and as a double stage thruster with high specific impulse when it is necessary to save propellant. Thus, application of the thruster of such kind makes it possible to reduce the final geosat orbit transfer time by operating thruster with high thrust, and then to use its operation mode with high specific impulse for the further geosat stationkeeping.

Thus, a series of TAL models with the performance competitive to SPT and ion thrusters was designed, developed and tested. The main problem still unsolved for TAL is the confirmation of its great lifetime.

Several lifetime tests with the duration of ~ 1000 hours were realized for TAL models up to now. Duration of the most extended of them was ~ 1400 hours. Results of these tests show that the TAL expected lifetime under nominal operation modes may be high enough (for example, the estimated lifetime of TAL-110 model under its operation with the power N=3 kW exceeds 5000 hours).

In view of the fact that SPT and TAL based electric propulsion subsystems may be almost identical, one can conclude that due to the mentioned works there was created a scientific and technological base in Russia for the development and application of Hall thruster based EPS for the most part of missions considered nowadays for EP.

2. Ion Thrusters

Ion thruster development is currently aimed at the thrusters operating with the power of up to 500 W. Ion thrusters with the power of over 300 W were developed already in different countries. They are successfully used in space, but development of thrusters with less power connected with definite difficulties is still actual. It is known that the reduction of gas-discharge chamber size causes the decrease in the propellant ionization efficiency, ion cost growth, and reduction of the propellant efficient use. Another problem is the development of efficient cathodes for the low power thrusters.

Two prototypes of low power ion thrusters were developed by KeRC in cooperation with MAI. The diameters of ion-optic systems of these prototypes are 50 and 100 mm. Thrusters operate within the power range of 50-500 W. Main output parameters of these thrusters are presented in Table 3.

Table 3. Ion Thruster Performance

Performance	IT-50	IT-100
Power, W	50-140	150-500
Thrust, mN	2-5	7-18
Specific impulse, s	2300-3500*	1900-3300
Efficiency, %	50-60*	45-55

* - without losses in neutralizer.

During the tests, main attention was paid to the possibility to use string-like ion-optic systems with different geometry of electrodes. It was shown that such accelerating systems with high transparency of emitting electrode allow the reduction of power losses in the gas-discharge chamber comparing to the traditional axially symmetric accelerating systems. However, the thruster parameter adjusting range becomes substantially narrower when the string-like systems are used.

Special attention during the low-power thruster development was paid to the designing of efficient cathodes capable to operate at low propellant consumption and power losses for maintaining the operation temperature. So, within the frame of work under ion thrusters, a cathode laboratory model with emitter of lanthanum hexaboride was developed that may be used as a part of low-power ion thruster both as the discharge chamber cathode, and as neutralizer. This cathode operates as neutralizer at xenon consumption of 10-30 equiv.mA and igniting electrode circuit power of 15 W. This allows its use with the thrusters having power of over 120 W. Cathode-compensator for a low-power Hall thruster was developed on the basis of ion thruster cathode.

In addition to low-power thrusters, KeRC is currently developing a 30-cm ion thruster with the nominal power of 2 kW for the orbit correction of heavy geostationary spacecrafts.

3. Pulsed Plasma Thrusters

As it was noted, pulsed plasma thrusters were tested in space as long ago as in 1964. But during the subsequent years the work under PPT in the USSR and Russia was continuously curtailed, and currently only RIAME MAI, "Kurchatov Institute" Russian Scientific Center (KIRSC) and Keldysh Research Center (KeRC) continue works under PPTs. They are mainly aimed at the development of competitive ablation PPT (APPT) for the correction and attitude control systems of small satellites.

Relatively low thrust efficiency is one of the APPT disadvantages, but RIAME MAI in cooperation with KeRC succeeded in their work under APPT during the last years: nearly periodic dependence of discharge current on time and better coordination of propellant yield and its acceleration were obtained because of better coordination for the outer circuit parameters and plasma processes. As a result, Teflon APPT efficiency of up to 22-24% was reached at the energy release of ~ 100 J per discharge.

The known APPTs have thrust efficiency at a level of 10-12% at the same energy release per discharge. Thus, a thrust pulse increased by 1.5 times and a higher specific impulse were obtained, as well as the reduced propellant yield at the above energy release per discharge.

In addition, reduction of losses allowed obtaining of low current and voltage amplitudes, and reducing the mass of thruster and capacitor. In this case, "dry" mass of APPT with the energy release of ~100 J per discharge and number of operations of $\sim 10^7$ is about 4-4.5 kg.

New propellant with improved ionization characteristics was developed also. Its testing showed that there is a possibility for further thrust efficiency increasing by 1.5-1.7 times more comparing to the thruster operating with Teflon. So, APPT developed by RIAME MAI and KeRC is becoming one of the perspective electric propulsions.

Activity of KIRSC is devoted to the development of powerful PPTs and plasma sources on their base [6].

4. High-Power Heavy-Current PlasmaThrusters

Russia has valuable experience in the development and testing of high-power heavy-current magnetoplasmadynamic thrusters. As it was mentioned already, models of lithium magnetoplasmadynamic thrusters with the power of up to 500 kW were developed and tested in Russia as long ago as in the end of 1960-s – beginning of 1970-s. But as there were no real problems to be solved by such thrusters, work in this direction was curtailed, and during the last years they were continued in MAI and RIAME MAI only. Important results, obtained during the last years, include development and successful tests of the lithium end Hall thruster under the order of Jet Propulsion Laboratory. Its power is up to 200 kW, thrust efficiency is over 0.45, and specific impulse is over 4000 s. Work under such thrusters is now continued in limited volume by RIAME MAI and MAI. Its main purposes are the investigation of possibility to reduce cathode temperature due to the barium admixture adding to the lithium flow and development of MPDT of new design.

Conclusion

The represented results show that due to long term Electric Propulsion activity there was created the Scientific and Technological bases for the Electric Propulsion Development in Russia for almost all missions considered now for EP.

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