Overview of electric propulsion activity in Russia.

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Abstract: The paper provides a review of major activities in the Russian industry and research organizations in a field of research, development and application of Electric Propulsion. Leading spacecraft manufacturers in Russia - NPO PM (Krasnoyarsk), Rocket Corporation “Energiya” (Korolev city), Khrunichev Space Center (Moscow), VNIIM (Moscow) continue successful EP application on GEO and LEO spacecrafts. Design Bureau “Arsenal” (Saint Petersburg) and NPO Mash (Reutov city) plan to use EP on their satellites. Growing EP application generates new requirements to the parameters of the propulsion systems and stimulates development and research activity at EDB “Fakel”, RIAME, TsNIIMASH, MIREA, Keldysh Research Center. For Hall thrusters the main directions of these activities are to expand operation range in regard to specific impulse, thrust and power. Several thruster schemes are under evaluation – one stage SPT and TAL, two stages SPT and TAL.

Introduction

The paper presents joined materials contributed by leading Russian spacecraft manufacturers using different types of electric propulsion (EP), as well as organizations dealing with research, design and production of EP systems, thrusters and plasma devices.

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Scientific and Production Association of Applied Mechanic (NPO PM, Krasnoyarsk)

Application of electric propulsion at NPO PM has been started by launch of spacecraft (SC) “Potok” May 18, 1982. Four stationary plasma thrusters SPT-70 have been used for north-south and east-west orbit correction. In total 15 SC of Potok and Luch series with 4 SPT-70 onboard of each one have been launched in 1982…1999 year time frame. In 1994 first SC Gals with SPT -100 developed by EDB “Fakel” has been successfully launched. Since 1994 11 SC of GALS, EXPRESS and SESAT series have been equipped by SPT-100 thrusters using Xenon as a propellant.

For the first EXPRESS and GALS satellites the propellant mass was one of the key parameters limiting SC design lifetime. Mass of xenon carried in the SC tanks for the first EXPRESS and GALS satellites was selected based on 5-year lifetime design requirement. But later on an experience obtained during exploitation of these SC allowed to improve the algorithms of EP system operation and minimize the EP firing time. That, in turn, allowed to expand SC lifetime up to 7 year. Last satellites EXPRESS series have 12.5 year lifetime. It should be note, that progress in SC lifetime has been achieved taking into account detailed study of interaction between EP and SC subsystems.

Interaction and potential influence of SPT thrusters and plasma plumes on a SC always are in a focus of NPO PM efforts during development and exploitation of EP onboard their satellites. Special measurements performed during operation of all satellites allowed to get proven data and verify computer model developed in MAI for calculation of plasma beam interaction with solar panels and corresponding appearance of mechanical torques.

Two spacecrafts namely EXPRESS-#2 and #3 launched in 2003 have been equipped by set of probes to measure parameters of plasma flow generating by EP thrusters. These probes allow to measure ion energy and flow density. Two probes were installed near satellite payload and another two one were attached to solar arrays. The arrays rotate relatively to SC and EP thrusters, and attached probes provide data about angular distribution of the plasma beam parameters.

Besides that, measurements of electric field in several points on a surface of EXPRESS-A #2 and #3 has been performed without and with EP operation.

For future programs NPO PM considers several potential EP manufactures and supports several activities aimed on development of a Hall thruster with specific impulse (Isp) higher than one for modern SPT-100. New thruster KM-5 (T-120) developed by Keldysh Research Center now is in use onboard of EXPRESS-A4 for north-south correction. Higher Isp will allow to minimize mass of xenon propellant for satellites with increased lifetime. Next generation of thrusters with improved and expanded range of operating parameters are now under development at EDB “Fakel”, Keldysh Research Center and TsNIIMASH in accordance with NPO PM specification.
All-Russia Scientific and Research Institute of Electro-Mechanic (VNIIEM)

Scientific and production enterprise VNIIEM is actually the first SC manufacturer in the world tested SPT-type thrusters (EOL-1) in space onboard of METEOR satellite in 1972 [2]. The successful flight tests were performed in 1974…1976 and provided unique database and knowledge in regard to EP system parameters, compatibility with SC subsystems, optimized algorithms of low thrust systems operation. The total accumulated firing time of the EP system was about 1000 hour, and it is important to note, that no failures or incorrect operation of the system were observed.

Exploitation of the SPT thrusters was combined with unique research program performed with help of scientific probes installed on the SC [2]. Most remarkable results of this study can be summarized as following:
1) variation of the spacecraft own atmosphere was identified during operation of EP system – density of the particles reached up to \(10^{-5} \text{cm}^{-3}\) (for orbit 900 km), ion energy = up to 30 eV, and SC floating potential was about 10 V.
2) there is a dependence of the plume propagation on its orientation relatively to Earth magnetic field,
3) electromagnetic emission with frequency ranges 5…20 kHz and 0,8…1,5 MHz accompanying the EP system operation were found;
4) mechanical torque from plasma beam impinging solar arrays was identified and measured for different relative orientation of the beam and the solar panels,
5) no degradation of the solar arrays output characteristics were found, and survivability of the arrays under interaction with plasma beam was demonstrated.

After successful tests of SPT a new GEO meteorological SC “ELECTRO” utilizing monopropellant ammonia resistojet has been developed at VNIIEM. The satellite has been launched and successfully operated in a period 1988…1994. The used ammonia thrusters are able to provide thrust 0,15 N and total impulse 130 Ns, EP system consisted of 12 thrusters and provided orbit correction and orientation of the SC. Important aspects of the SC own atmosphere variations, potential condensation of the product from jet exhaust plume were studied.

As a result of flight tests of different EP systems possibility of their application has been proven.

Now VNIIEM is under design process of a new small Earth observing satellite KANOPUS with low power SPT onboard. General view of the SC is shown on the Figure 2. Specific of the satellite and propulsion system is the operation at 200 W only. Propulsion system based on SPT-50 type thruster from EDB “Fakel” has been selected for this mission. The propulsion system has to provide orbit correction, maneuvering and SC orientation with total impulse 50 000 Ns. Thruster block with two SPT is designed to perform all mentioned functions, it is intended to provide thrust vector control by variation of SC orientation.

Fig. 2 General view of KANOPUS spacecraft.

Khrunichev Space Center

Since 90-th years Khrunichev Space Center is developed family of small SC based on unified spacecraft platform YAHT. Main design solution utilized in the YAHT propulsion system is application only stationary plasma thrusters for several tasks:
- Orbit insertion,
- Orbit correction,
- Periodical unload of gyroscopic orientation system and/or SC orientation

The unified SC platform YAHT is designed to be used for different purposes on low and geostationary orbits. For LEO missions relatively new solution is the SPT application on Earth observing SC realized in the
design of MONITOR spacecraft. This satellite has been launched and operated in 2005–2006 on 500 km orbit. To minimize number of thrusters necessary to generate thrust in several directions the SPTs have been installed on special gimbals allowing $\pm 45^\circ$ thrust vector control. Composite 35-litre xenon tanks with nominal pressure 31MPa also have been implemented to minimize total mass of propulsion system. As a result total dry weight of propulsion system has been reduced up to 43 kg, total propellant mass is 70 kg.

General view of the Monitor SC is shown on Figure 3.

Figure 3. General view and photo of the Monitor SC before launch [1]

Example of GEO derivative of YAHT platform is KAZSAT spacecraft successfully launched and operated now on geostationary orbit.

Khrunichev Space Center is permanently working with propulsion system component suppliers on an improvement of the main components of the system. Under order of Khrunichev Space Center the EDB “Fakel” performs a program aimed on essential increasing of SPT-70 lifetime. Special design of electronic equipment based on reliable and well proven elements from one side and redundancy of critical one allowed to develop a reliable and light electronic blocks operating in vacuum during 10 years and more in open space environment.

In addition to innovative design of propulsion system necessary monitoring system is used on board the YAHT-family satellites to monitor parameters of the EP system and own SC atmosphere. The monitoring allowed to optimize EP operation algorithms and, in particular, to get enough precise data in regard to of xenon mass flow, stored/spend mass of xenon. Accuracy of these measurements is about 7%.

Rocket and Space Corporation “Energia”

EP activity has been started at RSC “Energia” in 1958 under leadership of Prof. M.V. Melnikov. First project of nuclear electric propulsion system with total electric power 2200 kW has been developed in 1965. The EP system was based on MPD thrusters with lithium as a propellant. Unique MPD with specific impulse 4000 s, 14N of thrust, power consumption 500 kW has been developed and tested in support of this project.

At the end of 70-th a new project of 500 kW “electric tug” based on stationary plasma thrusters and anode layer thrusters was in a focus of activity. Two stage bismuth thruster known as TAL-200 has been developed and tested together with TSNIIMASH. TAL-200 has demonstrated outstanding parameters: power consumption 35 kW, specific impulse more than 5000 s, thrust efficiency about 70%. It should be note, that it was the first bismuth thruster with radiation cooling.

In 1993 development of a family of YAMAL communication satellites has been started at RSC “Energia” under commercial order of JSC “Gazcom”. The first satellites of this family – YAMAL 100 – have been launched in 1999. In year 2003 next two satellites – YAMAL-200 - have been launched into GEO. The satellites have 8 SPT-70 thrusters providing orbit insertion, orbit keeping, orientation and deorbiting of the SC. On board of YAMAL-100 SC the stationary plasma thrusters (SPT-70) was first time used for orbit insertion, it operated about 50 days to insert the SC into GEO operation point.
For the beginning of 2007 total operation time of the thrusters on YAMAL-200 satellites have reached value of 6000 hours with 12 000 ON/OFF cycles.

YAMAL 300 series is under development and manufacturing now.

Based on obtained experience RSC “Energia” intends to expand areas of EP application. More powerful EP systems are under consideration. In parallel to development activity multipurpose space experiment with Hall plasma accelerator is planned onboard International Space Station in cooperation with TsNIIMASH.

**Design Bureau “Arsenal”**

A lot of projects of interplanetary missions with electric propulsion and nuclear reactor as a power source have been developed in a world. But Design Bureau “Arsenal” is the only organization collected REAL experience of design and exploitation of EP systems powered from nuclear reactor.
At the end of 80-th two satellites “Cosmos 1818” and “Cosmos 1867” with nuclear reactor “TOPAZ” and SPT based experimental propulsion system manufactured by EDB “Fakel” have been launched and tested in space. In accordance with test program the propulsion systems operated 150 hours in total with 180 ON/OFF cycles. Successful tests have confirmed compatibility of the EP and nuclear systems, all design parameters and results of ground test have been confirmed and verified during these flight tests. This result provides us a “bridge” to future interplanetary missions to Mars and far planets of Solar system with powerful nuclear power source and effective electric propulsion system.

Today DB “Arsenal” is working on a new small multipurpose satellite with EP system.

**Scientific and Production Association of Machine Building (NPO MASH)**

Under development of satellite RUSLAN Scientific and Production Association of Machine Building (NPO MASH) is considering implementation of electric propulsion. RUSLAN is a relatively small SC for operation on geostationary orbit.

Parameters of the RUSLAN spacecraft are given in the Table:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft mass on GEO, kg</td>
<td>640</td>
</tr>
<tr>
<td>Electric power, W</td>
<td>6000</td>
</tr>
<tr>
<td>Time of orbit transfer, days</td>
<td>150</td>
</tr>
<tr>
<td>Lifetime</td>
<td>10 – 12 years</td>
</tr>
<tr>
<td>Launch rocked</td>
<td>«Strela» + booster</td>
</tr>
</tbody>
</table>

Specific of the RUSLAN project is usage of former military rocket and solid booster for SC launch into transient orbit (\(H_\pi = 244\) km, \(H_\alpha = 24320\) km, \(i = 52^\circ\)). Further insertion has to be performed by electric propulsion system.

The planned maneuvers are illustrated by scheme on the Figure 6:

![Figure 7. Scheme of the RUSLAN orbit transfer](Image)

RUSLAN electric propulsion system is designed to provide:
- Orbit transfer and insertion,
- Orbit keep and SC orientation,
- Deorbiting,

thus SC electric propulsion system includes two types of SPT thrusters from EDB “Fakel”:
- One SPT-140 for orbit transfer and S/C insertion,
- Four SPT-70 for orbit keeping.

For today development process of RUSLAN S/C is in progress
**Experimental Design Bureau “Fakel”**

EDB “Fakel” is a unique enterprise specializing on low thrust propulsion systems. Production of this organization – stationary plasma thrusters - is well known all over the world and supplied to all main SC manufacturers in Russia. During last years EDB “Fakel” has provided thrusters and propulsion systems for several satellites: GLOBUS, EXPRESS-AM33, EXPRESS-AM44, EXPRESS-MD, KAZSAT-1.

List of SC now in service with SPT-type thrusters is given in the Table:

<table>
<thead>
<tr>
<th>№</th>
<th>Launch date</th>
<th>SC</th>
<th>Propulsion system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.03.00</td>
<td>EXPRESS-A2</td>
<td>SPT-100</td>
</tr>
<tr>
<td>2</td>
<td>18.04.00</td>
<td>SESAT</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>25.06.00</td>
<td>EXPRESS-A3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>05.07.00</td>
<td>Kosmos-2371</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>24.12.03</td>
<td>YAMAL 201</td>
<td>SPT-70</td>
</tr>
<tr>
<td>6</td>
<td>24.12.03</td>
<td>YAMAL 202</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>28.12.03</td>
<td>EXPRESS-AM22</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>29.10.04</td>
<td>EXPRESS-AMI</td>
<td>SPT-100</td>
</tr>
<tr>
<td>9</td>
<td>29.03.05</td>
<td>EXPRESS-AM2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>24.06.05</td>
<td>EXPRESS-AM3</td>
<td>SPT-100C</td>
</tr>
<tr>
<td>11</td>
<td>26.08.05</td>
<td>MONITOR-9</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>18.06.06</td>
<td>KazSat-1</td>
<td>SPT-70</td>
</tr>
<tr>
<td>13</td>
<td>15.03.04</td>
<td>MBSAT</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>17.06.04</td>
<td>Intelsat-10-02</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>11.03.05</td>
<td>Inmarsat-4 F1</td>
<td>SPT-100U</td>
</tr>
<tr>
<td>16</td>
<td>23.06.05</td>
<td>Intelsat-Americas-IA-8</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>11.08.05</td>
<td>Thaicom4 / iPSTAR-1</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>08.11.05</td>
<td>Inmarsat-4 F2</td>
<td></td>
</tr>
</tbody>
</table>

Successful operation of the SPT-type thrusters onboard of several different satellites stimulates interest of SC manufacturers to this product. It could be even more attractive due to a possibility to expand thruster operation range. The program aimed on increasing of specific impulse of SPT-70 and SPT-100 is undergoing now with support of Russian Space Agency. The following parameters have been demonstrated during tests of the SPT thrusters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SPT-70 type</th>
<th>SPT-100 type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Id (discharge current)</td>
<td>1.80A</td>
<td>2.60A</td>
</tr>
<tr>
<td>Isp (specific impulse)</td>
<td>2200 s</td>
<td>3000 s</td>
</tr>
<tr>
<td>Pd (power)</td>
<td>900W</td>
<td>1950W</td>
</tr>
<tr>
<td>F (thrust)</td>
<td>43mN</td>
<td>77mN</td>
</tr>
<tr>
<td>Ud (discharge voltage)</td>
<td>500V</td>
<td>750V</td>
</tr>
</tbody>
</table>

These thrusters may be considered as good basis for development of EP systems for SC with operating lifetime 15 years. It is planned to complete qualification of such a thrusters in year 2008.
For perspective systems EDB "Fakel" has developed and qualified low weight xenon feed system with the following parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon Inlet Pressure</td>
<td>18.6 MPa maximum</td>
</tr>
<tr>
<td>Xenon Outlet Pressure</td>
<td>0.157…0.186</td>
</tr>
<tr>
<td>Xenon Outlet MEOP</td>
<td>0.69 MPa, no flow</td>
</tr>
<tr>
<td>Proof Pressure/MEOP</td>
<td>1.5:1</td>
</tr>
<tr>
<td>Burst Pressure/MEOP</td>
<td>&gt;4.0:1 tubing, fittings</td>
</tr>
<tr>
<td>Xenon Purity</td>
<td>not less than 99.997%</td>
</tr>
<tr>
<td>Temperature</td>
<td>-15 to 40°C</td>
</tr>
<tr>
<td>Flow rate</td>
<td>2-35 mg/sec</td>
</tr>
<tr>
<td>Voltage, Input</td>
<td>est 23.5 to 30.5 VDC</td>
</tr>
<tr>
<td>Valve electric resistance, Ohm</td>
<td>210 ± 5</td>
</tr>
<tr>
<td>Valve opening voltage, V</td>
<td>24 … 34</td>
</tr>
<tr>
<td>Valve retention voltage, V</td>
<td>10 ± 2</td>
</tr>
<tr>
<td>Lifetime</td>
<td>15.0 years minimum operation after 5 years storage,</td>
</tr>
<tr>
<td>Operational cycles</td>
<td>4500 min.</td>
</tr>
<tr>
<td>Reliability (Ps)</td>
<td>0.9979 or greater</td>
</tr>
<tr>
<td>Mass</td>
<td>maximum 3.05 Kg</td>
</tr>
<tr>
<td>Leakage</td>
<td>0.060 l*micrometer of Hg/s</td>
</tr>
</tbody>
</table>

For small satellites with limited electric power onboard low power - 200 W- Hall system is under development with a goal to qualify it in 2009.

Research activity in a field of EP.

Russian plasma and EP scientific society has an outstanding physical background supporting new development and improvements of EP technique currently in use. Good coordination between practical needs and scientific efforts is the feature of modern period of scientific research in electric propulsion in Russia. Several directions may be considered as a primary one for today:

- Development of an increased Isp (3000 sec and higher), long lifetime Hall thrusters for application on commercial and scientific satellites. The new thrusters have to offer optimized complex of parameters - low angular beam distribution, low electromagnetic noise and etc;
- Low power EP development for small and micro satellites;
- Experimental apparatus and computer modeling allowing to prove compatibility of different EP systems with a SC;
- Very high Isp (up to 10 000 sec) and high power (about $10^2$ kW) propulsion systems for future interplanetary missions.

Actually these directions are not a new one, a lot of progress has been achieved also and remarkable results demonstrated previously. But specific of modern period is a consideration of entire combination of parameters necessary for effective application in practice.

Research Institute of Applied Mechanic and Electrodynamics (RIAME)

Hall thrusters

New stationary plasma thrusters SPT-100 scale are under study and development at RIAME with a goal to provide at one and the same time high thrust efficiency, high Isp and high lifetime. Combination of these characteristics arise the problem, because an increase of Isp requires discharge voltage increase, but growing of power consumption leads to lifetime decreasing, and to keep its value at the acceptable level propellant mass flow needs to be reduced. The later, in turn, leads to losses of efficiency. So, some compromise has to be found. The developed new thruster demonstrates attractive parameters in a tested range of discharge voltage up to 1100V. Experimental dependencies of thrust efficiency, specific impulse are shown on Figures 8,9 below.
100-hour erosion tests of the thruster have been performed to get data for lifetime prediction. The tests have been done at power levels 1.5 and 1.9 kW with discharge voltages 700 V and 850 V. It is important, that thruster lifetime at these regimes estimated with help of erosion test result is not less that 5000 hour. Thus the possibility of SPT operating range expansion is demonstrated [7].

![Figure 8. Specific impulse versus discharge voltage for different xenon flow rates.](image)

![Figure 9. Thrust efficiency versus discharge voltage for different xenon flow rates.](image)

**Pulsed Plasma Thrusters**

To satisfy needs of small SC manufacturers Teflon pulsed plasma thruster (PPT) with outstanding parameters have been developed [8-12]. Demonstrated efficiency is about 15…40 % for discharge energy range 20…150 J.

General view of the PPT with two discharge channels is shown on the Figure 10. The thruster is developed for discharge energy 35 J with a goal to be used onboard of 200-kg spacecraft.
Figure 10. General view of PPT-35 two channel propulsion system

For micro satellites PPT with discharge energy 1…10 J is under development also. Photo Figure 11 shows Teflon bars from such a thruster after 5·10^4 pulses performed with 2…20 Hz frequency. It is important, that no carbon fraction harmful for SC surfaces appeared in this PPT.

Figure 11. Teflon propellant bars after PPT testing

Combination of achieved parameter allows effective application of the micro PPT for control of 50-kg class SC.

For today one of important but still uncertain parameters of PPT is electromagnetic noise generating by pulsed discharge. Study of this aspect requires special technique. Based on collected experience [13, 14] and new equipment now available study of the PPT radio emission has been performed. The PPT operated in vacuum chamber 2 m and 1 m in diameter. One of the chamber walls were made from plastic material transparent for radio waves. Receiving antenna allowing to measure emission in a range of 30 MHz…18 GHz was installed outside of the chamber near the transparent wall.

Typical measured data is shown on the Figure 12. The upper curve represents the emission from the thruster discharge, and the bottom one shows the background noise. Most intensive oscillations are in a band of 30MHz …1 GHz. Wide range of oscillations indicates significant role of plasma processes in the noise generation. It may be assumed, that cyclotron oscillations in the discharge plasma occurring in presence of significant magnetic field inducted by discharge current pulse as well as oscillations nearby plasma boundary are the physical origin of the wide spectrum of the observed radio emission.
MIREA team basing on deep study of plasma discharge physics continues their efforts aimed on optimization of working processes in Hall thruster discharge and development of new schemes of stationary plasma thrusters. It was identified, that in order to get efficient thruster operation several conditions have to be satisfied:

- particles backflow from the thruster exit plane have to be less than flux of eroded material from thruster channel walls;
- exhaust plasma beam should not interact with chamber walls; the ideal case is the one with a beam interacting only with gaseous “trap” (target).

Based on these driving ideas new generation of SPT has been proposed and developed. These thrusters include as well as one stage SPT- ATON as two stage SPT-MAG.

Scheme of SPT-MAG is shown on the Figure 13.

Two stage scheme allows to get almost fully ionized propellant in the first stage and, as a result, effective acceleration in the second stage with very narrow ion energy spectrum, good beam focusing preventing discharge channel erosion. Experimental study of the SPT-MAG shows that efficiency of such a thruster is high and practically constant in a range of discharge voltage 300…1000 V. It is important, that thruster size did not affect the efficiency and voltage operating range. This fact allows creating a family of thrusters covering a range from very low up to very high power consumption (100…150 kW).

The new SPT-MAG ion generator demonstrates several important features:

- An ability to utilize different propellant including gases with small (relatively to Xenon) atomic mass like Kr, Ar, N₂, CO₂, CH₄, NH₃ which can be found also in a atmosphere of other planets, vaporous of metals (Na, Mg, K, Hg, Pb, Br);
Improved beam focusing;
Less electromagnetic noise as compared with previous thrusters;
Better efficiency and lifetime;
Expanded range of operation.

The SPT-MAG thruster operates in a range up to 3kW, the highest demonstrated efficiency is 68% at 500 V and xenon mass flow into the thruster anode $\dot{m}_a=6.0$ mg/s. Experimental dependencies between thrust and discharge voltage is shown on Figure 14.

![Thrust, G](attachment:image.png)

**Discharge voltage, V**

$\Diamond - \dot{m}_a = 3.0$ mg/c, $\Box - \dot{m}_a = 4.0$ mg/c, $\Delta - \dot{m}_a = 5.0$ mg/c, $\times - \dot{m}_a = 6.0$ mg/c.

Figure 14. SPT-MAG thrust value versus discharge voltage

Table below shows measured SPT-MAG parameters:

<table>
<thead>
<tr>
<th>$\dot{m}_a$, mg/sec</th>
<th>3</th>
<th>3</th>
<th>3</th>
<th>4</th>
<th>4</th>
<th>5</th>
<th>5</th>
<th>6</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge voltage, V</td>
<td>300</td>
<td>500</td>
<td>950</td>
<td>300</td>
<td>750</td>
<td>300</td>
<td>600</td>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>Specific impulse, s</td>
<td>1755</td>
<td>2408</td>
<td>370</td>
<td>0</td>
<td>1825</td>
<td>3260</td>
<td>1930</td>
<td>295</td>
<td>200</td>
</tr>
<tr>
<td>Thrust efficiency $\eta$, %</td>
<td>51</td>
<td>56</td>
<td>66</td>
<td>55</td>
<td>67</td>
<td>59</td>
<td>67</td>
<td>62</td>
<td>68</td>
</tr>
</tbody>
</table>

Volt-ampere dependence is almost linear in a range of discharge voltage between 300 and 1000 V. It allows to assume, that in this voltage range propellant ionization and processes in the discharge do not changes essentially.

Another important feature of the designed thruster is an ability to operate in a pulsed mode. Duration of the pulse can be about 2 ms. Such a regime of Hall propulsion system can be considered for SC with very low (10…100 W) bus power.

Summarizing the obtained result it can be noted, that developed approach to new generation of SPT-type thrusters elaboration has been verified and its fruitfulness for further study has been confirmed.
Keldysh Research Center

Keldysh Research Center is one of the leading organizations of Russian Space Agency responsible for coordination of activity in a field of propulsion.

Own research activity is concentrated mostly on Hall thrusters. The first KM-5 experimental thruster is successfully operating onboard EXPRESS-A4 since 2002. Ground qualification of KM-50 thruster for a new EXPRESS-1000 bus is in progress now.

Mission analysis for potential EP application has shown essential benefit - in 1.5...2.7 times - for SC payload in case of usage of EP for orbit insertion. Considered duration of such an orbit maneuvering is up to several months with EP system of 10kW-class with level of specific impulse about 1500...3000 sec (Ref. www.kerc.ru)

Central research Institute of Machine Building (TsNIIMASH)

TsNIIMAS is a leading scientific organization of Russian Space Agency dealing with numerous aspects of rocket and spacecraft systems development, tests and exploitation. Electric propulsion as a one of key technologies of modern and future SC is under analysis and development also. During last time experimental efforts have been concentrated on three directions:

- Elaboration of Hall thruster with variable operation mode and increased specific impulse (up to 3500 sec), namely Anode Layer Thruster D-80, operating on xenon in power range 1...5 kW;
- Design, manufacturing and test of Very High Specific Impulse Anode Layer Thruster (VHITAL-160) using Bismuth propellant for deep space missions under Contract with Jet Propulsion Laboratory, NASA;
- Computer modeling and experimental study of physical processes responsible for compatibility SC and EP systems.

Driving factor for such a selection is practical needs of SC manufacturers and support of internal and international programs involving EP application.

It should be noted, that as well as development of a TAL with increased Isp as the computer modeling is performed in a teaming with EDB “Fakel”, Moscow aviation Institute and RIAME.

Multi-Mode D-80 thruster

Several modifications of two stage multimode D-80 anode layer thruster were experimentally studied previously at different electrical schemes and operating modes. Effective operating of one and the same hardware in one- and two stage regimes in a wide operating envelope was demonstrated:

- Thrust regulation range: 5...25 G;
- Specific Impulse regulation range: 1200...3200 s;
- Power regulation range: 600...4500 W.

These results have been reported in Ref. [15,16,17,18,19,20]. Several erosion tests of the multi-mode thruster had been carried out at NASA GRC and TsNIIMASH. Construction elements erosion rates of several thruster modifications with different discharge channel length operating in different modes were obtained.

Current research activity is aimed on continuation of thruster parameters optimization. Thruster design with very short accelerating channel based on External Anode Layer technology was implemented to minimize erosion rate of thruster elements. Thus in the frames of joint development program new test series of multi-mode TAL D-80 samples (Figure 15) have been carried out at TsNIIMASH and EDB "FAKEL" facilities. Erosion in both thruster stages - discharge (first stage) and accelerating one (second stage) was studied.

Experimental research goals:

- Multi-mode TAL D-80 testing at EDB "FAKEL" test-qualified facility with cryogenic pumping. Comparison of D-80 characteristics measured in one- and two-stage schemes.
- Erosion testing of D-80 modification with near-zero discharge channel length, including first stage cathode erosion analysis with help of spectroscopy method developed at TsNIIMASH by Dr. Karabadzhak.

Performance mapping and study of exhaust plasma beam angular distribution confirms that at in the regimes with increased specific impulse two stage scheme provides better efficiency, lower discharge current oscillations and more focused plasma beam as compared with the ones for one stage operation.

Nonlinear dependences of erosion rate on operating voltage value have been identified. The results of the erosion tests for fist and second thruster stages are given in the Figures 16, 17.

It is important, that D-80 modification with shorted discharge channel has demonstrated erosion reduction up to acceptable level without influence on the thruster efficiency and operating range.
Figure 15. D-80 prepared for testing at EDB "FAKEL" facility.

Figure 16. Erosion rate of the thruster second (accelerating) stage versus summary voltage

Figure 17. Erosion rate of the thruster first (discharge) stage versus discharge voltage

**VHITAL-160**

The VHITAL thruster has been designed based on existing D-160 bismuth thruster developed and tested in 70-th under leadership of Prof. Zharinov. As well as VHITAL-160 the D-160 was developed under programs aimed on deep space interplanetary missions.

The general view of a new VHITAL-160 thruster with integrated Bismuth tank is shown on the Figure 18. Figure 19 shows VHITAL thruster in operation. In a difference to the prototype the VHITAL-160 uses only radiation cooling and adjusted to operate with power consumption 25…36 kW.

The obtained thruster performances are the following:

<table>
<thead>
<tr>
<th>25 kW operation mode</th>
<th>Designed</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power, W</td>
<td>25000</td>
<td>25240</td>
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<tr>
<td>Specific impulse $I_{sp}$, sec</td>
<td>6000</td>
<td>5375</td>
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<tr>
<td>Discharge voltage $U_d$, B</td>
<td>150</td>
<td>130</td>
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<tr>
<td>Discharge current $I_d$, A</td>
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<td>5.85</td>
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<tr>
<td>Accelerating voltage $U_a$, B</td>
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<td>4800</td>
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<tr>
<td>Accelerating current $I_a$, A</td>
<td>5.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Bismuth flow rate $m$, mg/s</td>
<td>11</td>
<td>9.8</td>
</tr>
<tr>
<td>Thrust, $F$, mN</td>
<td>650</td>
<td>527</td>
</tr>
<tr>
<td>Thrust efficiency, $\eta$</td>
<td>0.78</td>
<td>0.56</td>
</tr>
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</table>

The 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007
<table>
<thead>
<tr>
<th></th>
<th>Designed</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power, W</td>
<td>36000</td>
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<td>Specific impulse $I_{sp}$, sec</td>
<td>8000</td>
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<td>Discharge voltage $U_d$, В</td>
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<td>Discharge current $I_d$, А</td>
<td>5</td>
<td>4.85</td>
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<tr>
<td>Accelerating voltage $U_a$, В</td>
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<tr>
<td>Accelerating current $I_a$, А</td>
<td>4.2</td>
<td>4.25</td>
</tr>
<tr>
<td>Bismuth flow rate $m$, mg/s</td>
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<td>8</td>
</tr>
<tr>
<td>Thrust, $F$, mN</td>
<td>710</td>
<td>618</td>
</tr>
<tr>
<td>Thrust efficiency, $\eta$</td>
<td>0.79</td>
<td>0.63</td>
</tr>
</tbody>
</table>

The thruster is delivered to JPL for detailed study.

Figure 18. The external view of the VHITAL-160.

Figure 19. VHITAL-160 in operation, preheating (left) and acceleration (right) modes.
Computer modeling and experimental study of physical processes responsible for S/C and EP systems compatibility.

Several effects such an bombardment of solar panels by accelerated ions, appearance of currents in SC body generating by flux of charged particles from plasma exhaust plume, variation of density and charge of SC own atmosphere accompany operation of EP systems onboard of a SC.

Results of resent research performed at TsNIIMASH indicated that there is a significant difference in the processes in space and the one studied in vacuum chamber during EP ground tests. More other, combination of several processes can be a reason of much stronger effect than a simple summarizing of influence from each process considered separately. All these effects cannot be modeled in the modern test facility. So that, importance of space experiments for physical model improvements and computer code verification has been realized. As a result experimental program aimed on plasma effects study is carried out at TsNIIMASH. The program is based on maximal use of equipment available on the International Space Station (ISS), in particular, Plasma Contactor Units generating electron flows and xenon plasma similar to one from EP thrusters. The program is named “PLASMA ISS” and performed in cooperation with several of organizations. Future active experiments with special xenon plasma generator are planned also in cooperation wit RSC “Energia” and EDB “Fakel”. The experiment is based on 1 kW-class anode plasma accelerator named PLATON to be delivered and installed on the ISS out surface. Such an accelerator with variable output parameters will allow to generate plasma plumes with different characteristics and to perform direct experimental study of exhaust plume propagation, its influence on the high voltage solar arrays and etc. The design of the PLATON accelerator and entire experimental assembly is in progress.

Conclusion

Application of electric propulsion systems onboard of Russian spacecrafts continues to grow as well as a number of EP performed tasks. The wider application motivates improvements of existing electric thrusters and propulsion systems, as a result active research and development programs are carried out in cooperation between Russian industry and research organizations.

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