Development of High Power Magnetoplasmadynamic Thrusters in the USSR

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O.A. Gorshkov*, V.N. Shutov**
Keldysh Research Center, Moscow, 125438, Russia

K.N. Kozubsky¶
EDB "Fakel", Kaliningrad, Russia

V.G. Ostrovsky§
RSC "Energia", 141070, Russia

V.A. Obukhov†
RIAME MAI, Moscow, 125871, Russia

Abstract: The paper presents a retrospective review of Russian high (up to 1 MW) and average (~10-100 kW) power magnetoplasmadynamic (MPD) thrusters developments performed in USSR from 60th to 80th years of the last century. Numerous designs of thrusters of this type, using various kinds of propellant and operating at different power ranges were developed during this period of time. The most typical design schemes and their operation parameters are presented in the paper.

Nomenclature

F_L	= Lorentz's force
$F_{L,Z}$	= component of Lorentz's force parallel to thruster axis
$F_{L,R}$	= component of Lorentz's force normal to thruster axis
Z	= direction along thruster axis
R	= direction along thruster radius
r_a	= anode average radius
r_c	= cathode average radius
E	= electric field strength
B_φ	= azimuth magnetic induction
F_{em}	= electromagnetic component of thrust
F_g	= gas-dynamics component of thrust
F_l	= Hall's component of thrust
μ	= magnetic conductivity
I	= discharge current

* - Head of Department, Department for Electrophysics, kercgor@dol.ru
** - Principal engineer, Department for Electrophysics, kercgor@dol.ru
¶ - Chief Designer, EDB "Fakel", fakel@gazinter.net
§- Senior staff scientist, RSC "Energia", v.tuganenko@mail.ru
† - Deputy Director, RIAME MAI, riame@sokol.ru

P_C = pressure in near-cathode zone
j_{φ} = Hall current
B_r = radial magnetic induction
dv = elementary plasma volume
B_0 = external magnetic induction on the cathode exit
$\omega_e\tau_e$ = electron hall parameter
F_h' = electromagnetic force component caused by plasma rotation in crossed electric and magnetic fields
r_{ab},r_{ae} = initial and exit anode radii
r = distance from a deposition sensor to the thruster exit
τ = test time
S_k = front surface of cathode
Δm = mass of vaporized cathode material
g = mass flow rate to cathode front surface ratio
A_0 = magnetic pressure to gas-dynamic pressure ratio
a_0 = sound velocity
B_a = magnetic induction at anode exit
D_a = anode diameter
T_c = cathode temperature
η = efficiency
I_{sp} = specific impulse, s
α = nozzle divergence angle
m = propellant mass flow rate

I. Introduction

Since the beginning of 50-th, capability of space exploration by humanity became obvious. In connection with this, spacecraft engineers were searching for opportunities of new propulsion methods development. These new methods were to provide significantly higher specific impulse if compared with liquid propulsion existed to date.

The problem was formulated not only as exploration of the nearest space but also as exploration of solar system planets. Proposals of how to perform propellant acceleration by means of electric energy appeared as well as first concepts of electric propulsion (EP).

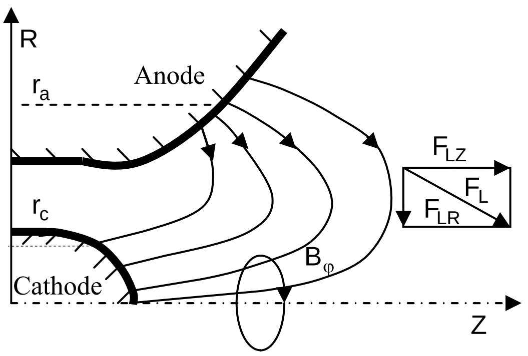

Figure 1. Self-field MPD principle of operation

Self-field magnetoplasmadynamic thruster scheme (SF-MPD), which is a predecessor of a wider class of magnetoplasmodynamic thrusters (MPD), was proposed in 1955 by Maecker. The scheme was the most suitable for EP thrusters, capable transforming high electric power (up to 1 MW and greater) into directional motion of accelerated (up to velocity of 50 km/s and greater) plasma plume. Broad outlooks were brought into light by this proposal from solving transportation tasks like space tug operation to manned mars mission.

SF-MPD principle of operation is shown in Fig. 1. In this thruster electromagnetic force component F_{LZ} is directed along thruster axis Z and accelerates plasma along this axis. Another component, F_{LR}, compresses plasma towards Z axis. The latter force may be converted into thrust since it contributes to paraxial plasma heating and subsequently accelerates it along Z axis. At presence of applied external magnetic field Hall's component force caused by interaction of hall current with radial component of the applied field appears.

MPD thrusters have several advantages over other electric thrusters. For instance, they provide the highest thrust per unit surface of plume section (~ 0.1 -1.0 N/cm^2) of all electric thrusters. Low discharge voltage allows direct connection of the thrusters to low-volt on-board power sources. They can utilize different propellants (gases, alkali metals et al.), function in a wide range of operation modes (different mass flow rates, powers etc.). MPD thruster discharge ignition may be performed by propellant injection. The thrusters are capable providing high propellant outflow velocities (up to ~50 km/s and greater) at that having relatively high efficiency (up to~ 60 %).

The listed MPDT features caused interest for their intense development at the beginning of electric propulsion era. In the late 50th – early 60th studies in this field were opened in the USSR. The studies were held in Keldysh Research Center (that time "Scientific-Research Institute of Thermal Processes"), RSC "Energia" (that time "TsKBM", later NPO "Energia"), EBD "Fakel" (that time a branch of NPO "Zaria"), TsNIIMASh, MAI and in other organizations. The chief developers of MPD thrusters in these organizations were: A.A. Porotnikov (KeRC), S.A. Bakanov (EBD "Fakel"), M.V. Melnikov (RSC "Energia") and V.B. Tikhonov (MAI). The general direction on the MPD thrusters development activities in USSR was performed by Corresponding Member of USSR Academy of Sciences V.M. Ievlev (KeRC).

On the first stage of activities the emphasis was made on a design scheme of high-current MPD thruster with coaxial geometry of electrodes. However, a short time later it was shown by tests of such thrusters that front geometry (the geometry where length of the central electrode is much less that outer one) is a more promising design of a thruster discharge chamber. Therefore, subsequent efforts were concentrated on this line. As a result the so-called self-field MPD (SF-MPD) thrusters appeared. At a later time, in connection with a switch to studies of medium-power MPD thrusters, the main attention was paid to the thrusters with applied solenoidal magnetic field, named applied-field MPD (AF-MPD) thrusters.

Initially the studies of MPD thrusters were launched at KeRC, later other organizations joined to this work. It should be mentioned that not only the organizations listed above, but a number of others were involved into the activities and activities of some of these organizations resulted in space flight testing (SFT).

The researches included wide range of subjects both experimental and theoretical. In fact, a foundation was laid to a new direction in plasma physics straightly intended for electric thruster development.

A wide variety of theoretical studies, connected with development of high-efficient MPDT included
- study of plasma motion in a self-field thruster channel,
- MPDT integral performance definition,
- discharge cavity geometry optimization,
- studies of near-electrode and near-wall processes.

Experimental studies were not behind the theoretical ones and sometime were even ahead them. Multiple self- and applied magnetic field MPDT designs were created and studied at the observed period. Different substances such as Hydrogen, Lithium, Potassium, Argon and others were used as propellants. The thrusters operated in quasi-stationary and continuous modes at various discharge power. Numerous types of electrodes units, insulators and magnetic systems were subject of the research. In the initial period most of the research results remained unpublished. Only in 70th the first printed works on this topic started to appear.

Due to complexity of cooling of the most heat intense MPDT units, on the early stage of research the studied thruster models operated at quasi-stationary modes as the thrusters were designed for such conditions. Later, when the solution of cooling problem was achieved, steady-state operating thrusters became subjects of the study. Using alkali metals as propellant played an important role in solving this problem.

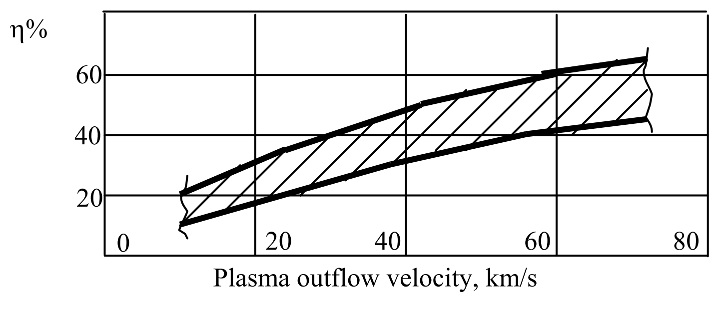

Figure 2. Lithium MPDT efficiency as a function of outflow velocity

Alkali metals have low ionization potential, they may be absorbed on electrode surfaces and are space-saving when stored onboard a spacecraft (SC). The main disadvantage of such propellants is their precipitation on different SC surfaces. This problem was also studied during the works on MPDT.

The best MPDT performance: 60 % efficiency and outflow velocity over 50 km/s, was achieved while using Lithium as propellant (Fig.2).

The theoretical researches were helpful not only as a basis for MPDT development but also for understanding of physical processes in other electric thrusters. A lot of interesting and useful data was obtained[2, 3, 5].

Since mid. 70th, according to different reasons (decline of interest to Mars mission, absence of powerful onboard power source, etc.), the development of high power plasma thrusters lost its actuality. The research in this field was reoriented towards development of medium power MPDT. At that the emphasis was made on more detailed theoretical studies of physical processes in the thrusters as well as on optimization of their operation mode. The problem of influence of alkali metal electric propulsion on spacecraft operability was also studied.

This paper represents some results of MPDT development and research obtained in the USSR. Authors did not consider that their task is informing about all types of MPD thrusters studied during the observed period of time but to present the typical and the most interesting results.

II. Keldysh Research Centre

In the period from the end of 50th to the year 1975 different MPD thruster models with power up to 1 MW, utilizing different propellants, including Lithium were studied at KeRC.[1,3-9].

Different designs of electrode units and magnetic systems were proposed during this period. KeRC developed methodology for MPDT characterization and developed basics for MPD thruster theory. A wide variety of propellants was studied, such as different gases (Hydrogen and other), alkali metals (Li, K, Na, Cs), their alloys and Bismuth. Both solid-state thermoemission cathodes and liquid metal cathodes, with forced cooling and without, were used. The unique for that time experimental facilities were created. It allowed performing continuous firing tests of thrusters with discharge current up to 100 kA

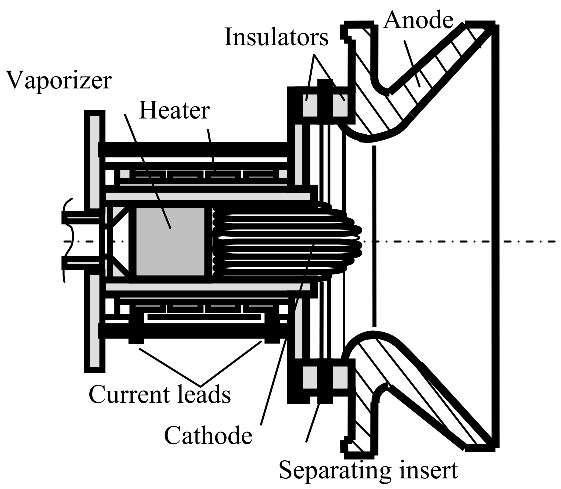

Figure 3. ~500 kW power level SF-MPD

The scheme of a ~500 kW Lithium SF-MPD thruster is presented in Fig. 3. The cathode design is multi-rod type (also known as multi-channel hollow cathode) with propellant passing through gaps between the rods. A thermoemission cathode with no forced cooling was used here. The described design allows operating at high current density when cathode temperature is ~3000ºC due to precipitation of self-regenerating alkali metal film having low work function on the emitter's surface.

Usage of a Tungsten anode with radiation cooling eliminated need of forced cooling. Thruster startup was performed by propellant injection that allowed avoiding application of electric commutation devices for the discharge circuit. Thruster shutdown was performed in a similar way – by turning mass flow rate off.

The thruster demonstrated thrust of a several tens of Newton level at exit flow velocities up to 80 km/s and efficiency up to 50%.

KeRC studied some sorts of quite original self-field MPDTs, among which a thruster with liquid metal cathode[1]. In this thruster the discharge plasma contacts with a thin layer of liquid metal covering Tungsten parts of cathode. At that the discharge heat and partly vaporizes metal that serves as propellant. Another fraction of liquid metal cools the cathode. The erosion problem is solved here by means of continuous renewal of the liquid metal (Lithium) layer. The thruster operated at power up to 500 kW, current up to 8 kA and with thrust of up to 20 N.

Life tests (duration - 1000 hours) were held out on a ~5 kW Potassium MPDT[8]. The cathode was partly made of poly- and partly of monocrystalline Tungsten. The tests demonstrated that the monocrystalline tungsten is less subject to erosion. Modified models of the thruster were used during space flight test of "Kren" system onboard "Cosmos-728" and "Cosmos-760" SCs[9].

Big attention was also paid at KeRC to theoretical studies. For example, a 2D numerical model of plasma flow in a MPDT channel was developed at KeRC. An iterational method was used[3]. The model helped to improve understanding of self-field and applied-field MPDT physics.

The contemporary systematic knowledge on plasma acceleration mechanisms in different types of MPDT operating at various levels of power can be described by the following brief overview.

Thrust of MPDT is defined by electromagnetic force which has one of its component accelerates plasma while another compresses it towards the plume axis. The overall thrust value is a sum of electromagnetic and gas-dynamic forces. The electromagnetic force can be calculated with help of the following expression:

$$F_{em} = \mu \cdot I^2 (\xi + \ln r_a / r_c) / 4\pi \qquad (1)$$

where μ is magnetic conductivity, I is the discharge current, r_a and r_c are effective anode and cathode radii respectively, ξ is the dimensionless numeric parameter varying in range between 1/2 and 2/3.

The gas-dynamic force is mainly formed by the cathode plume. It can be calculated as

$$F_g = \pi r_c^2 P_c$$

where P_c is the pressure in near-cathode zone. For AF-MPD thrusters overall thrust can be found as a following sum of forces:

$$F = F_{em} + F_g + F_1$$

where F1 component is calculated as:

$$F_1 = k \cdot I \cdot B_0 \cdot r_a$$

where B_0 is applied magnetic field at the cathode end, k is a coefficient depending on operation mode, particularly it is a function of $\omega_e \tau_e$.

At $\omega_e \tau_e << 1$ in the main acceleration zone (that corresponds to dense plasma with low B) plasma is rotating under action of crossed E and B fields. This effect can be converted in the exit region into acceleration of the plasma along the thruster axis. In this case equation for k is following:

$$k = r_{ai} \cdot \left(1 - r_c^2 / 2r_{ai}^2\right)\left[(1 - r_{ai}^2 / 2r^2{}_{ae}) / 2\right]^{1/2} \qquad (2)$$

where r_{ai} and r_{ae} are initial and end radii of anode respectively.

In the extreme case, at $r_{ai}^2 << r^2{}_{ae}$ value of the coefficient may be as much as 0.7. At that equation for F1 may be written as follows:

$$F_1 = 0{,}7 \cdot I \cdot B_0 \cdot r_a$$

At $\omega_e \tau_e > 1$ (that corresponds to rarified plasma in relatively high B) an azimuthal Hall current appears. As a result, of interaction between this current and radial magnetic field a force occurs. This force accelerates plasma in the axial direction. This acceleration mechanism in its purest form is realized in Hall-effect thrusters. With some simplifications, an estimation can be made for $k \sim 0.5$ and, therefore,

$$F_1 = 0{,}5 \cdot I \cdot B_0 \cdot r_a.$$

More than satisfactory performance was achieved at medium discharge power of about 10 kW and less by applying MPD thruster scheme, in which a gas-dynamic acceleration mechanism becomes sufficient. At moderate plasma temperatures of ~2eV, outflow velocities were achieved within the range from ~ 10 km/s to ~ 20 km/s and even more.

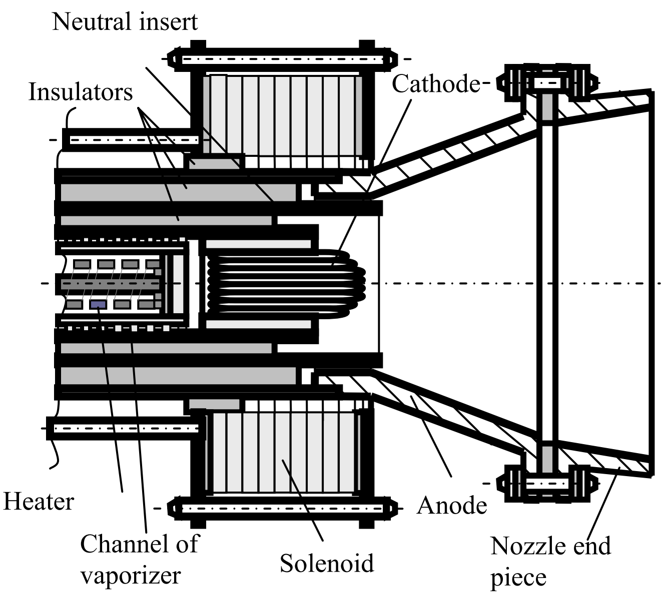

Figure 4. Medium-power Hybrid MPDT schematics

A hybrid scheme of such a type is presented in Fig. 4. It was used in a Lithium MPDT of medium power (20…30 kW) developed and studied at KeRC. In the described case the anode is fitted with an insulated orifice. Expansion angle of tested anodes varied from 50 to 90 degrees. Magnetic field near cathode varied from B = 0.05 to 0.09 Tesla, Lithium mass flow rate - from m = 0.02 to 0.03 g/s, discharge current - from I = 400 A to I = 1100A.

The dependences of this thruster efficiency on specific impulse at different anode expansion angles and flow rates are presented in Fig.5. At lower values of specific impulse (~ 1000 - 2000 s) higher efficiency corresponds to operation modes and geometry of the studied MPDT in which it is similar to a common arcjet. A shift to operation in a mode with sufficient magnetic acceleration was observed at specific impulse values of ~ 2200 - 2800 s. In the latter operation mode the efficiency is higher. At that the optimal performance was observed in an operation point where inclination of discharge volt-ampere characteristic changes from moderate to almost vertical.

A lot of attention was paid at KeRC to another problem – influence of an alkali electric thruster on a SC. Laboratory research was performed in this field as well as space experiments. In 1975 space flight tests were performed on board of "Cosmos" series SC. During this test there were firstly performed measurements of precipitating alkali metal film thickness and rate of its deposition on elements of a SC[11].

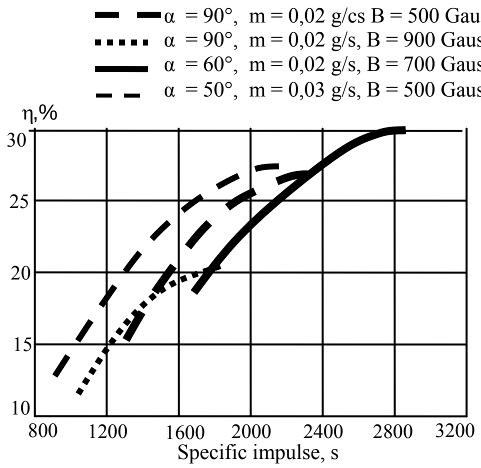

Figure 5. Relationship between the efficiency and specific impulse at different magnetic fields and anode expansion angles

AF-MPD thrusters developed at KeRC were used for the experiment. The thrusters had following operation parameters: power ~3 kW, mass flow rate - (1 - 5) × 10^{-3} g/s, outflow velocity – 15- 20 km/s. Potassium was used as a propellant. The precipitation sensor of quartz microbalance type was used. It was placed in the rear hemisphere relatively to plasma plume. In 13 minutes of thruster operation thickness of precipitation layer became equal to 0.1 μm.

Another experiment with a plasma source was performed in 1990 on a "Progress M-4" spacecraft. These experiments allowed an intensified effect of alkali metal plasma plume on a SC. The experimental propulsion system for the "Progress M-4" spacecraft with an autonomous power source was developed and produced by KeRC. Two types of plasma sources (PS) were studied. The first used a composite propellant consisting of Sodium, Potassium and Cesium. It operated at mass flow rate ~ 0.1 – 0.5 g/s, current ~ 600 A and power ~ 6 kW. Another one used Cesium with a mass flow rate ~ 0.1 g/s, current ~ 200 A and power ~ 2 kW. The PS operation was separated into three sessions. A single 6-kW PS operated during the first session and two 2-kW PS operated during each of other two sessions. Duration of each session was 230 s.

The experiment scheme is shown in Fig. 6. Quartz microbalance sensor was used as a precipitation sensor. It was placed on a distance of r = 0.3 m (first session), r = 0.16 m (second session) and r = 0.17 m (third session) from the anode exit of PS, in the rear hemisphere relatively to plasma plumes of each source.

Maximal alkali metal precipitation was observed after the second session, when the plume axis was directed with an angle of 45° from the spacecraft axis. The layer thickness was 1.17 μm. Almost complete evaporation of the layer from the sensor surface occurred before the third session. The thickness after the third session was about 0.02 μm.

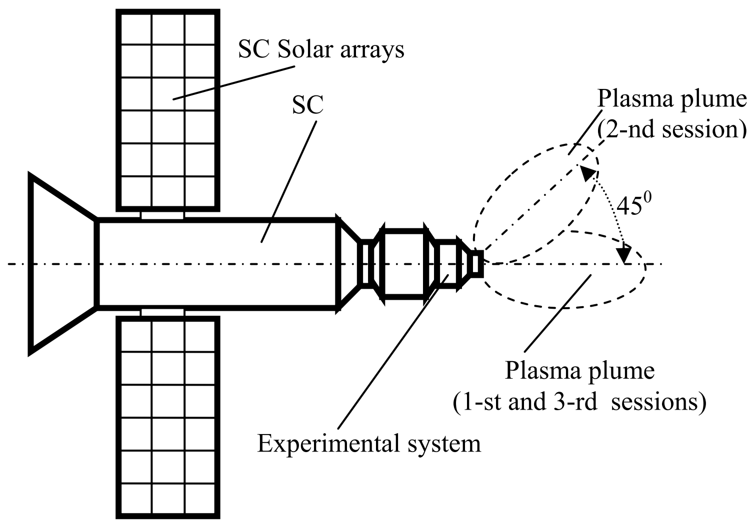

Figure 6. "Progress M-4 " experiment schematics

Computations made according to the results that were obtained from the "Progress M-4" experiments allowed estimating the influence of Cesium precipitation onto solar array functioning. It was defined that 4000 hours of PS continuous operation in the mode of the third session would cause complete degradation of "Progress M-4" solar cell.

In the conclusion of the section we shall note the basic achievements of KeRC in the field of MPDT development:

1. In the shortest terms MPD thrusters were developed which capable operating at advanced power levels (up to 1 MW). Various designs of electrode units and magnetic systems were studied experimentally.
2. The Research Centre became the first initiator of wide application of alkaline metals, including Lithium, as MPDT propellants.
3. Foundations were laid for basic theories of working processes in MPDT of both high and average levels of power. Numerical models were created allowing calculation of the main performance of different MPD thrusters (SF-MPD and AF-MPD). The models were based on a number of simplifying assumptions. It was shown that at average powers a significant contribution to thrust is made by gas-dynamic force.
4. First 1000-hour life tests of a 5-kW alkali metal MPD thruster were held out in mid. 70th.
5. Much attention was given to a problem of influence of electric thrusters using alkali metal propellants onto a spacecraft. Flight experiments of low-power MPDT were performed on "Cosmos - 728 " and "Cosmos - 760 " SCs, as well as a space experiment on "Progress M-4" SC, when intensified effect of a plasma jet of alkaline metal onto a SC was studied.

III. NPO "Energia"

Researches for creation of electric thrusters were started at NPO "Energia" in 1958 under direction of professor M.V.Melnikov at support of academician S.P. Koroliov.

Big attention was paid in NPO "Energia" to a problem of cathode lifetime. As a result, a multiple-cavity design was proposed. A cathode of such design consists of a package of Tungsten rods pressed into a shell. Gaseous or vapor-like propellant is injected through this pipe. The cathode operation mode is selected so that discharge plasma fills most of the cathode internal cavities and almost complete propellant ionization takes place inside them.

It was observed, that a decrease of Lithium flow rate below some limiting value terminates ionization process inside the cathode cavities. At that the discharge shifts towards the cathode end, temperature increases substantially and the cathode potential grows. Researches have shown, that erosion of a multiple-cavity cathode occurs is caused mainly by cathode material evaporation and "blowing" of the evaporated Tungsten by the propellant flow.

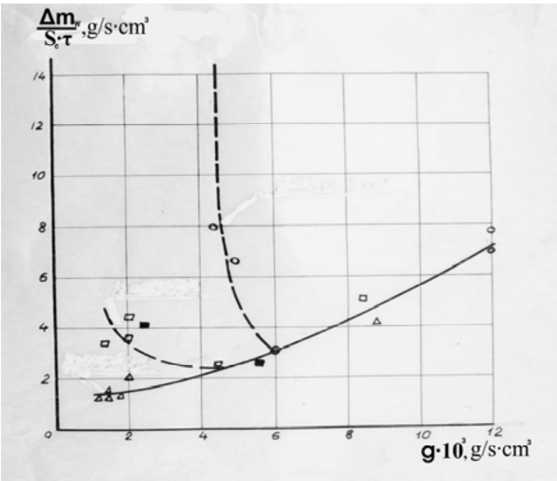

Figure 7. The dependence of specific ablation speed of tungsten from anode on lithium mass flow rate to cathode surface ratio: Δ - current density 100 A/cm², □ - current density 160 A/cm² at 500 A current, O - current density 160 A/cm² at 5000 A current, ■ - 240A/cm² at 5000 A current.

Fig. 7 shows dependences of cathode material specific ablation speed on Lithium flow to cathode area ratio at different cathode current densities. When the cathode functions in a multiple-cavity mode the ablation is low due to low cathode potential drop. At that the ablation speed is ~ 10^{-6} g /s·cm² and increases with growing flow rate (firm line in fig. 7). When the cathode operates in a mode in which the discharge is shifted from the cavities to the rod ends, the ablation speed increases at decreasing flow rate due to growth of cathode potential drop and temperature (left dashed line on fig. 7). Intensive Tungsten erosion drastically limits its lifetime. The increase of a current up to 5 - 10 кA complicates processes on the cathode because of plasma pressure increase and redistribution of the propellant flow through cavities of the cathode (dashed line on the right).

Variants of multichannel cathodes have been developed and tested on NPO "Energia". However there were no successful solutions aimed to lower temperature of the cathode. Cathodes made of Tungsten alloy wires with activating additives gave only short-term effect. The problem has been solved by installation of an ampoule with batcher containing Barium-based additive into the internal cavity of a cathode[13, 14].

In such a cathode Barium evaporated from its surface is renewed by the additive stored in the ampoule. Measured Barium evaporation rate was 0.1 - 0.5 % of Lithium flow rate. Use of Barium-based activating additive in MPDT cathodes allowed decreasing cathode temperature by ~1300 K. At that the erosion rate decreased in several orders.

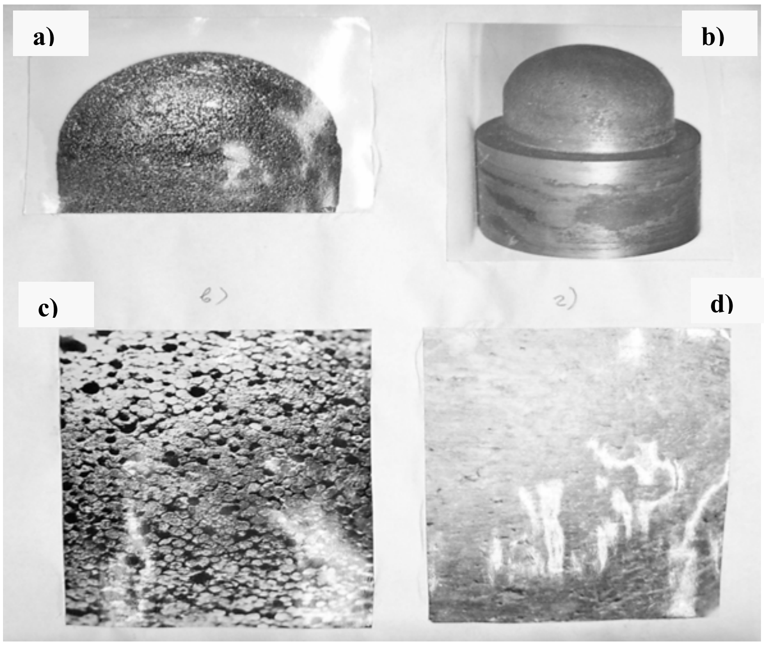

Figure 8. The photos of hole cathodes after long-term work at 500 A current (a, б); cathode surface fragments (c, d).

Fig. 8 presents photographs of porous cathodes. The cathodes are 18 mm in diameter: the left one have been tested for 40 hours at discharge current density ~100 A⁄cm^2 without activating additive, the right one, with Barium-based activating additive, have been operated for 133 hours at the same current density. The lower two photos show fragments of each cathode surface with 10 times magnification. The cathode with no additives (left picture) surface has traces of fragmentary melting that is typical for cathodes operating at extremely high temperatures. The appearance of the cathode having activating additive (right picture) demonstrates no melted fragments of the surface. The lower right picture shows that even pore opening does not occur at temperatures of 1730 – 1750 K.

A lot of attention was also paid to anode processes studies. NPO "Energia" carried out studies of anode profile influence onto MPD thruster performance. Earlier experiments revealed that small changes of anode profile cannot influence MPDT performance greatly. For that reason, the studies were performed on principally different anode shapes such as monotonously expanding anode, narrowing anode, anode with a nozzle throat similar to a Laval nozzle, cylindrical anode.

It was observed that each type of anode has some advantages, disadvantages and a preferable field of application. At the same discharge current the highest thrust is provided by a monotonously expanding anode, the lowest - by Laval nozzle anode. The opposite tendency was observed for the specific impulse: the former anode provided the worst specific impulse, the latter – the best.

NPO "Energia" also studied the so-called “anode crisis” in MPDT[13]. It was detected that the discharge current may be increased by means of additional injection of ionized propellant into the near-anode zone[14]. Tests of MPDTs with powers up to 100 kW demonstrated that by means of additional propellant injection through the anode the discharge current may be increased by 10-20% at some increase of thrust and specific impulse. However such effect makes too small benefit to performance and requires complex design changes to be made for its realization. For this reason application of such effect is scarcely worth-while.

There was also proposed an efficient protective measure needed to prevent discharge binding to the exit extremity of MPDT anode by placing a solenoid creating radial magnetic field near the anode exit plane. At that a zone where the most discharge current connects to the anode surface becomes wide enough and no discharge binding is observed on the anode extremity. A glowing strip in central part of anode was observed during tests of MPDT operating at currents ~ 10 kA in which most of the discharge current connects to the anode surface.

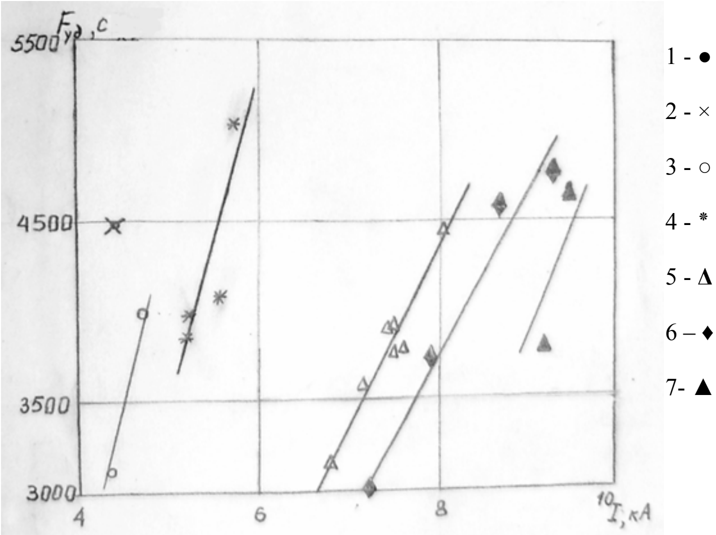

Figure 9. MPDT specific impulse as a function of discharge current at Lithium mass flow rates: 1 – 0.026 g/s; 2 – 0.08 g/s; 3 – 0.10 g/s; 4 – 0.13 g/s; 5 – 0.24 -0.26 g/s; 6 – 0.28-0.30 g/s; 7 – 0.33-0.36 g/s

The experience gained by NPO “Energia” in field of MPDT development and optimization allowed creation of a high-power MPDT design. The thruster could use gases and metallic vapours as propellants. Tests of the thruster performed on facilities of NPO "Energia" and related organizations. The thruster operation time was equal to several seconds at power of 900-1000 kW. Thruster also operated for tens and even hundreds of hours at powers in range 500-600 kW. Maximal values of specific impulse and thrust efficiency observed during the tests were 5000 s and 60% respectively[14]. A diagram of specific impulse of the thruster as a function of discharge current is presented in fig. 9.

A Lithium MPDT for stationary operation at powers 500 – 600 kW was designed for life tests with application of many of the technologies mentioned above aimed to improve its performance and lifetime (Fig. 10). The life test duration was ~500 hours at the lasting of which the thruster operated at power in range of 450 – 500 kW.

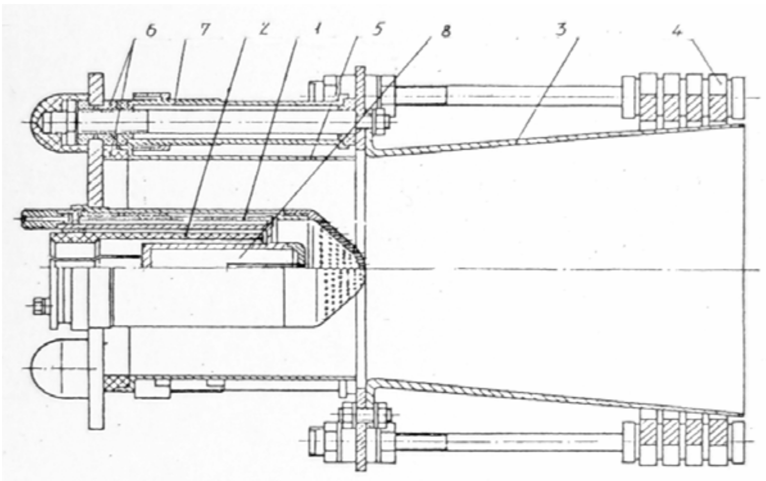

Figure 10. 500 kW MPDT design

Figure 11. Lithium MPDT operating at ~17 kW

In order to study MPDT influence onto SC systems a flight test was performed. A MPDT (Fig. 11) with power of 17 kW and discharge current of 700 A was produced. The system was equipped with accumulator batteries to provide power for in-flight operation lasting for several minutes. A multiple-cavity cathode was connected by a pressurized interface to a capacity containing porous insert made of metal with high melting temperature. The insert was impregnated by 9 grams of Lithium that have been used as a propellant. The space experiment proved reliability of startup and stability of operation of MPDT onboard a SC. It was demonstrated that such a thruster has good compatibility with other SC systems.

Main results of NPO “Energia” in the field of MPDT have been:

1. For the first time in the USSR, already in the middle of the seventies, 500-hour tests of the lithium ~ 0.5 MW power MPDT were conducted.
2. The experimental investigation of the effect of anode geometry and character of propellant supply (to cathode, anode) on MPDT characteristics was performed.
3. A MPDT schematic was proposed, where there is an additional external magnetic field near the anode exit edge, that makes it possible to increase the uniformity of the current distribution over the anode surface (i.e. to increase the discharge current and MPDT power).
4. Various variants of multihollow cathode were experimentally studied from the viewpoint of ensuring its long-term operation. A variant of the cathode with placing an ampoule with barium within it was proposed which has provided a long-term service life of the great-power (~0.5 MW) MPDT.
5. A space experiment with the MPDT of a mean power (17 kW) was performed. It has verified the compatibility of MPDT with SC.

IV. EBD "Fakel"

In the 60th-70th of the last century EBD "Fakel" in collaboration with other organizations (NPO "Energia", KeRC, MAI) carried out active work on MPDT working on alkali metals[15, 16].

For the manned space expedition to Mars according to the project of S.P. Korolev and M.K. Tichonravov in the EDB “Fakel” in collaboration with the RSC “Energia the high-current coaxial and SF-MPD thrusters with self-magnetic field and power of several hundred kilowatts were developed. The created prototype models of such thrusters with lithium propellant had worked a hundreds hours on the EDB “Fakel” test facilities. The photos of the first coaxial and SF-MPD thruster laboratory models are presented on the Figs 12 and 13.

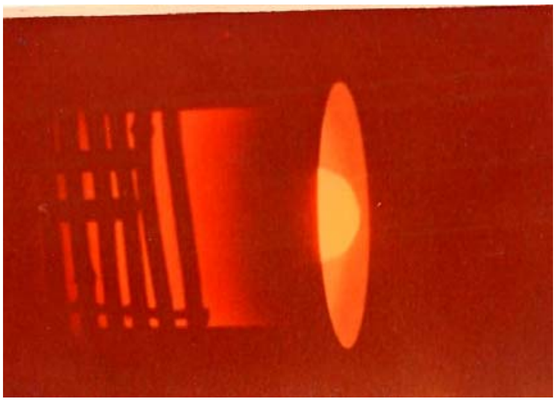

Figure 12. Coaxial high-current MPT thruster. Picture taken in 1964.

Figure 13. SF-MPD thruster. Picture taken in 1964

Figure. 14. MPD thruster in work. Picture taken in 1962.

The first facility intended for tests of high-power MPDT was put into operation in the EDB “Fakel” as early as 1962. Figure 14 presents the photo of the lithium plasma jet of such thruster at this facility.

First high-power thrusters with power up to 300 kW with uncooled electrodes operated in the mode of short pulses (5 - 10 s). For the first time in the USSR the MPDT worked uninterruptedly for 1 hour at EDB “Fakel” in 1965. The thruster operated at the discharge current of 7 kA, with lithium propellant

In the late sixties – early seventies several modifications of BST and EHT of mid and high power were developed. It was in particular discovered that the cathode life time highly depends on its operation as an element of the liquid-metal feed system. The cathode operation frequently was broken due to contaminations incoming together with lithium.

Also investigations of microwave radiation and oscillations in lithium plasma of BST were conducted for the first time [17]. Already by this time rather good characteristics were achieved. For example the BST "K-100" had the following operation characteristics at the power ~ 150 kW: specific impulse of 3750 s, efficiency of 35%. In the middle seventies a high power MPDT was developed and manufactured in the RSC "Energia. The performance tests of this thruster were conducted in the EDB "Fakel".

Later high power MPDT investigations were conducted in Moscow Aviation Institute. In EDB "Fakel" the development of lithium arcjet with power from 2 to 30 kW was started. The flight model of the electric propulsion system with thruster "Micron" was developed for space tests in 1966-1968. It had the following characteristics: thrust – 2 gram-force, power – not higher than 2.2 kW, mass – not higher than 25 kg. The photo of the arcjet "Micron" flight model which is presently kept in the museum of EDB "Fakel" is shown in Fig. 15.

The design efforts for liquid metal propellant feed systems (FS) of the electric propulsion conducted in one's time in EDB "Fakel" are worth to notice separately.

A facility for the electric propulsion testing with alkali metals: lithium, potassium, natrium, cesium was worked-off in seventies. This complex was developed on basis of the conduction-type pumps[18] which were the primary elements of the feed systems. The peculiarity of these FS is capabilities of very small flow rate providing (10^{-10}-10^{-6} m^3/s). These FS distinguish by simplicity of design, a long operation lifetime, and absence of the moving mechanical details. They enable usage of the low pressure tanks and have a wide control range and high stability of flow rate. Stable operation of these FS is achieved owing to use of throttle devices with high throttle factor of $(1\text{-}100)\cdot 10^{11}$ pascal×s/m^3.

Figure 15. A flight model of "Micron" Lithium thruster

In-depth study of the FS characteristics including examination of the corrosive action of molten metals on the FS operation has conducted[19]. It was clarified that the main corrosion processes are isothermal and thermal mass transfer and also the diffusion of molten metal into hard material. At that the significant increase of the life time can be achieved if the temperature gradient is positive in the line of moving of molten metal and the temperature no more than 400° C (for the couple stainless steel – lithium). Subsequently the results of investigations were confirmed in the course of tests of magnetohydrodynamic distribution devices with life time up to 6000 hours. In addition the evaluation magnetohydrodynamic FS units were developed in EDB "Fakel", and both the autonomous life tests during 5000 hours and 1000-hours tests consisting of propulsion system were conducted.

The flight test of FS with alkali metals consisting of propulsion system was conducted on basis of low power MPD thruster. The test was conducted jointly with Keldysh Center (installation "Kren"). The feed system included a tank with propellant, electromagnetic pump, steam generator and housing. Potassium storage 50 gram, consumed power 150 W.

Further the experience of work with alkali metals was employed during the creation of cesium plasma source at Soviet-French geophysics experiment "ARACS" for the investigation of the interaction of plasma with the ionosphere.

Following works for MPDT of the EDB "Fakel" are worth to note:

1. Experimental facility, allowing long tests of MPDT with a power up to 0.5 MW was created. Different tests of models of MPDT with different power consumption ranges were conducted at this facility.

2. Feed systems for liquid metal propellant on the basis of conductive type electromagnetic pumps were successfully employed at ground and on-board tests of different types of electric propulsion.

V. MAI

Researches into MPDT physical processes were conducted at MAI most actively at a period from 1964 to 1985. At this period calculation procedures were developed and researches of thruster integral characteristics on a basis of one dimensional models were fulfilled [20]. An analysis of mathematical expressions defining the MPD thrust revealed that the dependence:

$$F_I = \left(1{,}33 + 1/2A_0^{\;2}\right)\cdot 10^{-7}\cdot I^2$$

agrees best with experimental results.

Here $A_0 = 0{,}883\cdot 10^{-7}\cdot I^2/ma_0$ - the ratio of the magnetic pressure to gas dynamic, m – the mass flow rate, I - the discharge current, a_0 - sonic speed.

An expression for the Hall component of the thrust F_h was obtained for the MPDT operating in the range from 25 to 150 kW:

$$F_x = 0{,}1\cdot B_a D_a \cdot I\ ,$$

where B_a - the magnetic field at the anode exit, D_a - the anode diameter.

Relevant designed dependences for determination of volt-ampere characteristics of AF-MPDT were also obtained (Ref. 21).

In the seventies particular emphasis was placed on problems associated with the AF-MPDT lifetime, that is in the main controlled by cathode erosion. Thermoemission Tungsten cathodes even with additions of Thorium, Lanthan, Yttrium, cannot provide a necessary life (8 to 10 thousand of hours). Use of the Barium (Ba) addition to propellant-Llithium – is the most promise for EHT. Preliminary qualitative estimates of the life of such cathodes revealed that they are capable of continuous operation during 8 - 10 thousands of hours[22]. Results of life experiments of the lithium 30 kW thruster with operational cycles 3 hours each and a total on-duty time of 100 hours demonstrated a principal possibility to ensure the cathode life as 8 to 10 thousand of hours at continuous operation and the current density up to 150 A/cm^2.

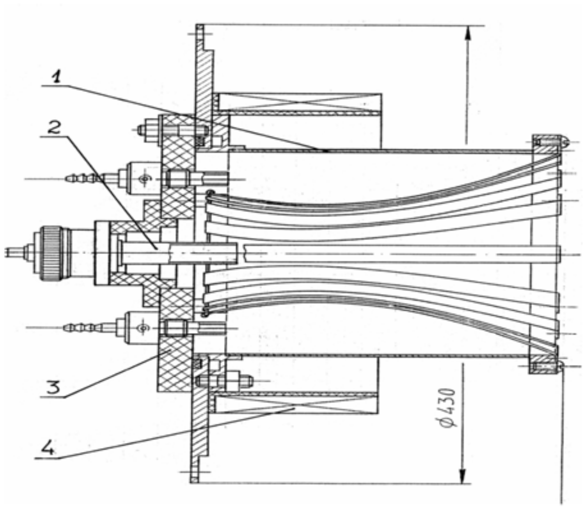

Figure 16. Quasi-stationary MPDT for working on gaseous propellant

A phenomenon of the anode current "crisis" was also subjected to a thorough research. A designed technique was developed, which allows evaluating values of the current density at the anode surface of an actual MPDT with an accuracy sufficient for preventing it from its failure on reaching limiting modes[23] .

Experiments were mostly conducted on MPDTs of average power (10 to 200 kW). In experimental researches it has been ascertained[24,25] :

- Barium supply to the EHT results in a decrease in T_C by 400°C and voltage by 3 to 4 V,
- with the supply of ionized propellant to the anode, a reduction in temperature of the anode edge near transient parts of the volt-ampere characteristics by ~ 400 °C can be evident,
- for a lot of MPDT models it has been obtained - up to 40 % , I_{sp} ~ 2000 - 2500 s.

These researches allowed it to formulate a complex of recommendations on creation of the efficient average-power MPDT. Experimental and theoretical researches of stationary AF-MPD thrusters (Ref. 25–27) have demonstrated a possibility to develop the thrusters with the specific impulse from 35 to 45 km/s at the efficiency of ~ 45% and with power 130 to 150 kW.

In the nineties a laboratory model of the hybrid MPDT meant for experimental research in quasi-stationary mode at discharge duration of ~ 1000 μs and power of ~ 1MW was developed. The scheme of the model is shown in Fig. 16. The model consists of the anode unit 1, cathode unit 2, interelectrode insulator 3 and coil 4 of the external magnetic field.

The anode unit incorporates the cylindrical case and 8 plates (copper). Anode unit plates are formed along lines of the external magnetic field. The cathode unit 2 incorporates electromagnetic pulsed gas valve and cylindrical hollow cathode (copper). The consumption of gas (argon or nitrogen) through the valve comprises from 10^{-6} to 10^{-5} kg/pulse. The coil 4 is fastened on the anode unit case. The magnetic induction in the accelerating channel: B=0.03-0.04. The thruster can operate both with the switch of the coil 4 (as AF-MPDT), and without external magnetic field (as SF-MPDT).

Conclusion

Thus, in the sixties – eighties years of the last century, a necessary scientific and engineering work was done in the USSR for the purpose of development of high-power MPD thrusters. Knowledge and experience gained thereat preserve their urgency at the present time too when the manned Mars mission has become again to acquire outlines of a practicable project.

References

[1]Koroteev A.S., Utkin Y.A., "Magnitoplasmodynamic thrusters. Past and Future," *J. Polet* № 3. 2002, p. 2. (in Russian).

[2]Morozov A.I. "Physical bases of space electric propulsion thrusters," Moscow. Atomisdat. 1978. (in Russian).

[3]Grishin S.D., Leskov L.V., Kozlov N.P., "Electric propulsion thrusters," Moscow. Mashinostroenie. 1975. (in Russian).

[4]Porotnikov A.A. "Stationary high current plasma accelerators," *Plasma accelerators*. Moscow. Mashinostroenie. 1973. p. 105. (in Russian).

[5]Porotnikov A.A., Petrosov V.A., Ostretsov I.N. "Near-electrode processes," *Physics and application of plasma accelerators*. Ed. Morozov A.I. Minsk. Nauka i tehnika. 1974. (in Russian).

[6]Porotnikov A.A., Ostretsov I.N. et.al. "On the influence of the individual fields of ions on the emissive characteristics of thermocathodes," *Technical Physics*. 1973. V. 4. Iss. 8. p. 1708. (in Russian).

[7]Koroteev A.S., Utkin Y.A. "Electric propulsion in space research missions," *4th Symposium on space nuclear energy.* USA. Albuquerque, 1990.

[8]Zhurin V.V., Porotnikov A.A. et al. "Recent development in electric propulsion in the USSR," AIAA.83-1397. 1983.

[9]Koroteev A.S., Shutov V.N. "High Efficiency Arcjet Thrusters," AIAA 93-1786, *29th International Joint Propulsion Conference*. 1993.

[10]Zhurin V.V., Porotnikov A.A., Shadov V.P., et al. "Active Experiments in Space Using MPD Accelerators," AIAA Paper 79-2070. 1979.

[11]Brukhty V., Smirnov A. Shutov V., et al. "Effect of alkali metal electric rocket engines on spacecraft," *23th International Electric Propulsion Conference*, IEPC-93-149. Moscow. 1993.

[12]Encyclopedia of the low-temperature plasma // Ion and plasma thrusters. V. 4. Moscow. Nauka. 2000. p. 318.

[13]Ageev V.P., Ostrovskiy V.G. "Lithium high power continues action MPD thruster," *Proceedings of the Academy of Sciences // Energy*. № 3. 2007. (In Russian).

[14]Branch of the institute for thrusters. Kaliningrad department for thruster laboratory of the USSR Academy of science // Nesterenko A.N. Ed. Murashko V.M. Kaliningrad. 2005. 240 P. (In Russian).

[15]Murashko V., Kozubskiy K. "New Russian space technologies: Space propulsion systems in space. Urgent problems of aviation and aerospace systems." Iss. 1. (21). V. 11. 2006. Daytona Beach.

[16]Zaikina A., Kemov V., Kirdyashev K., et al. "Investigation of the microwave radiation and oscillations in the lithium electric propulsion." *Proc. 3rd Conference on the investigation and engineering of mid-power electric propulsion thrusters*. Kharkov. 1975. (In Russian).

[17]Vinogradov V., Petrov K., Snarsky R. "Application of MPD-pumps in feed systems of electric propulsion." *Proc. 3rd Conference on the investigation and engineering of mid-power electric propulsion thrusters*. Kharkov. 1975. (In Russian).

[18]Vinogradov V., Petrov K., Snarsky R. "Investigation of corrosion influence of liquid metals on the MPD0-pump feed system characteristics." *Proc. 3rd Conference on the investigation and engineering of mid-power electric propulsion thrusters.* Kharkov. 1975. (In Russian).

[19]Kvasnikov L.A., Latyshev L.A., Sevruk D.D., Tikhonov V.B. "Theory and calculation of the energy-power facility for space vehicles." Moscow. Mashinostroenie. 1984. 331 P. (In Russian).

[20]Tikhonov V.B., Semenikhin S.A. et al. "Research of Plasma Acceleration Process in Self-Field and Applied Magnetic Field Thrusters." *23rd International Electric Propulsion Conference*. IEPC-93-076. Seattle. WA. USA.

[21]Semenikhin S.A., Sysoev D.V. "Determination of the minimum essential consumption of barium additive in the cathode of the MPD Thruster." *4th International conference "Aviation and Space-2005"*. Moscow. 2005.

[22]Smolin G.G. "Current constraint at extreme modes of operation of the MPD thruster." *Physics and techniques of plasma systems*. Moscow. MAI. 1985 (in Russian).

[23] Tikhonov V., Semenikhin S.et al. "Technology Requirements for High-power Lithium Lorentz Force Accelerators." *Space Technology and Applications International Forum*. Albuquerque. 1997.

[24]Tikhonov V.B., Semenikhin S.A., Polk J.E. "Preliminary tests of the 30kW lithium MPD thruster with barium additive." IEPC-99-178, *26th International Electric Propulsion Conference*, 1999.

[25]Tikhonov V.B., Semenikhin S.A., Polk J.E., Brophy J.R. "The experimental performance of the 100kW Li thruster with external magnetic field." IEPC-95-105 *24th International Electric Propulsion Conference,* 1995.

[26]Tikhonov V.B., Semenikhin S.A., Polk J.E., Brophy J.R. "Performance of 130kW MPD thruster with an external magnetic field and Li as a propellant." IEPC-97-117, *25th International Electric Propulsion Conference,* 1997.