Victor Khrabrov – Pioneer of the First Space Electric Propulsion System Development and Space Tests

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Abstract: Paper presents a review of professor Victor Khrabrov (1931-2009) works on Ablative Pulsed Plasma Thrusters (APPT), which are a reflection of his outstanding contribution to the research, development and space tests of the first electric propulsion system (EPS) in the world. Development of APPT-based EPS in 60-ies of the past century was realized by a relatively small team on the basis of pioneer investigations made by A.M. Andrianov and V.A. Khrabrov from the Kurchatov Institute and L.A. Pets and A.I. Simonov from the Russian Space Corporation "Energiya". EPS passed numerous ground tests, and then it was integrated on board "Zond-2" spacecraft. EPS comprised 6 APPTs designed to control orientation of solar panels. On November 30, 1964, "Zond-2" SC was launched from the earth parking orbit to Mars in order to test operation of onboard systems and carry scientific investigations out. A.M. Andrianov and V.A. Khrabrov were undoubtedly the key persons in those pioneer developments.

I. Introduction. Beginning of Works on PPT in the USSR

BY the beginning of 60-ies the EP history overcame the semicentennial threshold and was marked by a large number of theoretical and a number experimental works. The epoch of R&D diversification began[1]. That period was subsequently called as the "Space boom" in space studies. Characteristics of that time period from the point of view of the history of space studies in general and EP studies are shown in Fig. 1. During that period the attention of researchers and developers was mainly concentrated on electric propulsions based on electrostatic method of propellant acceleration. In many projects EPS was still considered as one of the systems of manned spacecraft equipped with nuclear power plant. But it became obvious that the real prospect for the development of high-power nuclear propulsion system moved away for indefinite period of time. And in the very beginning of 60-ies systems, which were planned to be the executive devices of flight control system designed for a spacecraft with rather moderate onboard power provided by solar panels, came out to the level of priority goals of EP development.

In the USSR the experimental design bureau OKB-1 (later – Russian Space Corporation "Energiya") that was the developer and producer of the first artificial Earth satellite, automatic stations launched to the Moon, Venus,

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Mars, manned spacecrafts and orbital stations, was the main enterprise of the Russian rocket-and-space industry, at which high intellectual and engineering potential was concentrated.

In 1957 S.P. Korolev, Chief Designer of OKB-1, applied to I.V. Kurchatov with request and proposal to start investigations aimed at the development of EP of different types, power and purpose at the Institute of Atomic Energy.

Pilot PPT studies have been conducted at the Institute since 1959:

- plasma acceleration process was modeled with use of computer,
- variations of different key parameters were studied – plasma forming propellant (gases, metals, dielectrics),
- geometric and electric parameters of acceleration channels.

Several tens of thruster models were studied altogether.

During one of tests with gas PPT Teflon was used as a separating insulator. A surprising thruster behavior was discovered – the discharge oscillogram did not practically depend on the mode of operation of the gas feed valve. A.M. Andrianov, the Head of the Laboratory, guessed right immediately that the reason was in the intense pulsed evaporation of Teflon insulator. Having analyzed current and voltage oscillograms, he proposed to use pulsed evaporation of insulator as the fast-acting pulsed valve for propellant feed. And so the first experimental model of Teflon PPT appeared. Subsequently, works in the field of PPT at the Kurchatov Institute were mainly concentrated on the models with dielectric propellants.

The PPT team was formed, and V.A. Khrabrov became its member. Before that he was studying physical processes in Z-pinches and was an experienced investigator of pulsed electric discharges in gases already. Very soon he became the leader of PPT team.

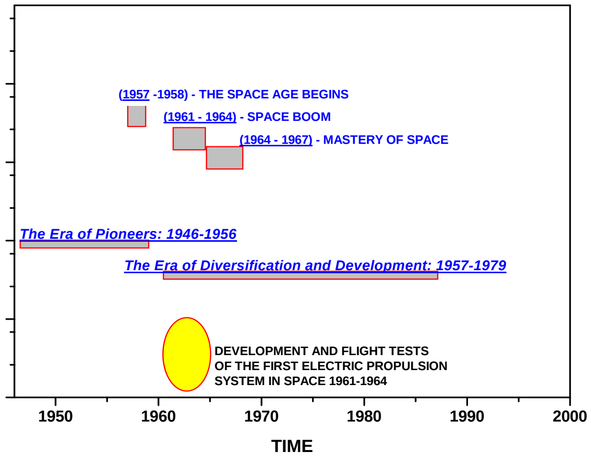

Figure 1. Characteristics of the time period of PPT work beginning from the point of view of the history of space studies in general and EP studies.

II. First Space Electric Propulsion System Development and Space Tests

A. EPS Development Task

In 1959 on the initiative of S.P. Korolev, General Designer of OKB-1 (subsequently – Russian Space Corporation "Energiya"), requirements specification was formulated for the development of EPS that could be used for the stabilization system of "Zond", "Mars" and "Venus" spacecrafts, launches of which were planned for 1962-1966[2]. Computational and theoretical studies for the EP use as a part of SC attitude control system have been actively realized under the leadership of B.V. Raushenbakh by that time and prospectivity for their use was substantiated. Technical specifications were stated for the first EP-based attitude control system. That system comprised 6 thrusters:

- two pairs for the attitude control in pitch and one pair in roll,
- total mass of the first attitude control system should not exceed 30 kg,
- impulse bit was to be as high as P ~ $2 \bullet 10^{-3}$ Ns at the capacitor energy of 60 J,
- total number of pulses should not be less than $5 \bullet 10^{5}$,
- acceptable impulse bit reduction at the lifetime end should not exceed 10%.

It was required that the design of the first EP-based attitude control system be characterized by high reliability, relative simplicity and stability in relation to the influence of space factors, absence of radio interference and harmful effect on the structural elements of the spacecraft.

B. First experiments

A.M. Andrianov and V.A. Khrabrov proceeded to experiments with the first model of ablation PPT – coaxial electrodynamic plasma gun. L.A. Pets and A.I. Simonov, experienced specialists of the OKB-1, became the members of R&D team also.

During the first two years pilot studies followed accurate scheme: next design of EP model – investigation – analysis of results – disappointment and frustration of hopes.

In was shown by the middle of 1962 that APPT was the most efficient way to solve the task stated. First successful lifetime tests (350 000 firings) of electromagnetic APPT operating with Teflon were made during the period of March 27 – April 16, 1962. Photo of electrodynamic APPT (without external electrode) is presented in Fig, 3. The thruster was operating in the pronounced electrodynamic mode, and the plasma flow had high average rate. The thrust of 1 g was obtained at the average power consumption of 1 kW. But for the first space test it was necessary to have power-to-thrust ratio of about 250 W/g.

Pilot studies and heated discussions of their results continued with renewed vigour. Electrothermal APPT with coaxial insulator was finally invented and produced that met requirements of the OKB-1. Such APPT operating in the mode of electrothermal acceleration is shown in Fig. 4.

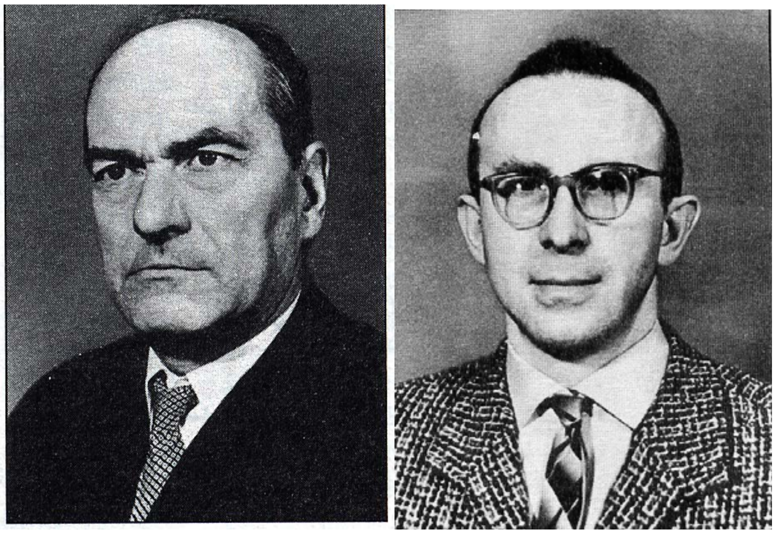

Figure 2. Professor A.M. Andrianov and research fellow V.A. Khrabrov, inventors and investigators of the first APPT.

A circular cathode and an initiating device were inserted into the cylinder of dielectric (polyethylene, Teflon, sulphur, alundum, etc.) from one side. An ignition effect was used for initiation; such effect takes place when the current of one auxiliary capacitor flows through the carborundum-copper boundary. Accelerator was connected to the capacitor bank by low-inductance wires. During those tests the capacitance of capacitor bank was from 50 to 5000 µF, operating voltage was from 0.3 to 5 kV.

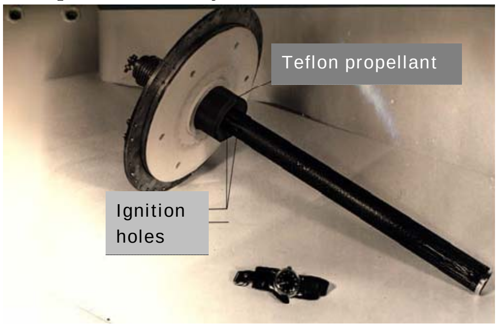

Figure 3. The first APPT model

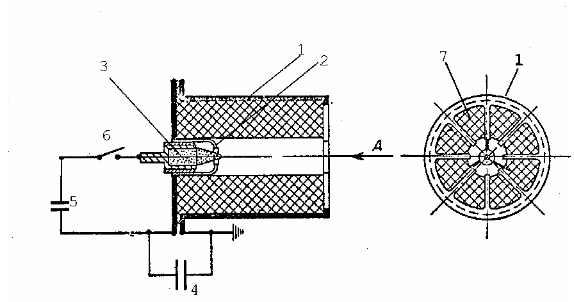

Figure 4. Electrothermal APPT: 1,2 electrodes; 3-carborundum, 4- primary discharge capacitor bank, 5-discharge initiation capacitor, 6 -switch, 7 - propellant.

During the period of about 1 µs a discharge was formed with the resistance of about 10^{-2} Ohm. The discharge was of aperiodic nature, and during the first half-period about 50% of energy initially stored in the capacitor bank was transferred into it. Average plasma density (100 µF, 1 kV) was about 10^{17} cm/s at the efflux rate at the channel outlet of $7 \cdot 10^{5}$ cm/s. Average temperature was about 2 eV. Thickness of skin-layer at t = 1 µs was approximately equal to the chamber diameter. Gas-kinetic pressure exceeded magnetic by more than an order of magnitude, and gas-kinetic plasma acceleration at its motion in the channel was realized in the discharge. Results of studies for the physical processes in such thruster and of numerical modeling were published subsequently [3, 4, 5]. Photo of the designed electrothermal APPT is presented in Fig. 5.

Electrothermal APPTs with considerably lower power-to-thrust ratio of 85 W/g were developed later. The APPT principle was protected by the inventors' certificate with the priority as of December 4, 1962. The authors of invention — A.M. Andrianov, L.A. Pets, A.I. Simonov, V.A. Khrabrov.

Figure 5. Photo of electrothermal APPT

Table 1. Performance data of APPT being a part of plasma attitude control system

Capacitor	**100 µF**
Charging voltage	**1000 V**
Operation frequency	**1 Hz**
Thrust	**20 mN**
Average power	**50 W**
Power-to-thrust ratio	**25 kW/N**
Discharge current amplitude	**20 kA**
Propellant consumption	**0.5 mg/s**
Efficiency	**10%**
Lifetime	**10^6 pulses**

C. Flight model

Victor Khrabrov called the next stage of work as the «Race against time». Installation of a real flight plasma attitude control system (PACS) on board a spacecraft was to be the result of that race.

It is impossible even to list stages of experimental-design work fulfilled to develop onboard standard PACS model in a short publication. Everything was difficult, everything was made for the first time and on a very tight schedule. Performance data of flight model are presented in Table 1.

After successful lifetime tests of "flight" electrothermal APPT models the Kurchatov Institute and OKB-1 started joint R&D work aimed at the development of flight model of the attitude control and stabilization system. An interagency commission was formed of the representatives of different ministries, committees and departments for the detailed insight into the state and level of investigations made.

In March, 1963, parts of the attitude control system were demonstrated to the commission: two pairs of PPT on the torsion pendulum. Commission approved investigation results in full and recommended to accelerate R&D works in order to use plasma attitude control system on board the spacecrafts of "Mars-Venus" and "Zond" types.

Experimental plasma attitude control system of "Zond" spacecraft comprised six PPT nozzles as actuating devices: two pairs — for the attitude control and stabilization in roll, and a pair — in pitch. Total system mass was 28.5 kg. As soon as plasma thrusters were produced professor A.M. Andrianov brought them personally to the customer. APPT-based EPS of "Zond-2" spacecraft is shown in Fig. 6.

Unfortunately, on November 11, 1963, the spacecraft did not reach predetermined trajectory. Nowhere was reported about that. Work on the preparation of EP launches was to be continued. After the first failure S.P. Korolev ordered to prepare three PPT sets simultaneously, which were produced by November, 1964.

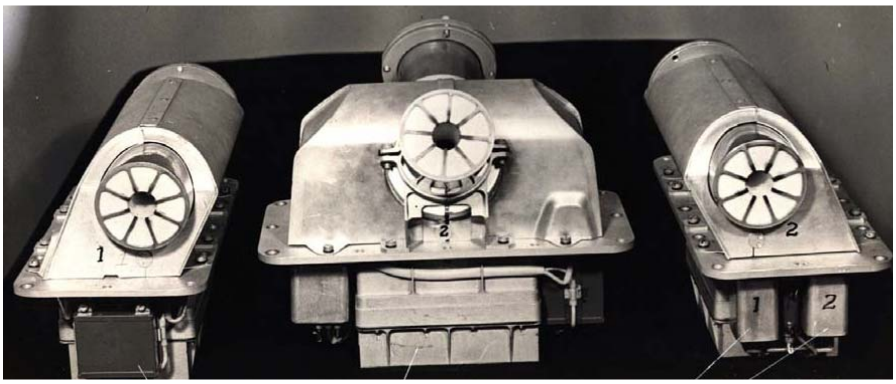

Figure 6. EPS of "Zond-2" spacecraft.

D. Tests of PPT-based EPS on board the "Zond-2" spacecraft

"Zond-2" was successfully launched on November 30, 1964. Unfortunately, one half only of "Zond-2" solar panels deployed in space; that is why power supply for the systems was twice less than standard …

December 14, 1964, Monday. Regular communication session of "Zond-2" with the Earth began; by that moment the spacecraft was at the distance of 5 370 000 km from Earth already. A permit for operation of plasma thrusters is given. Standard attitude control system of "Zond-2" is disabled. During the entire communication session of about 70 minutes in duration six plasma thrusters successfully provided attitude control for "Zond" in space, so that the plane of its solar panels was perpendicular to direction of sun rays. Plasma started its work in space.

On December 19, 1964, TASS informed the world about the birth of new direction in space engineering — "electric rockets". And in the New Year issue of "Pravda" (January 1, 1965) an article "The space open" was published by professor K.Sergeev (pen-name of S.P. Korolev), in which high estimate was given to the first tests of electric propulsions in space: "For the first time in space engineering a plasma thruster was tested successfully for the attitude control purposes, and this is of great interest for interplanetary flights".

After the successful launch and space test an interest to the investigation and development of different EP types increased substantially. A variety of organizations and a large number of specialists were involved in that work.

Pulsed plasma thrusters have realized their role 40 years ago having laid a road to space for electric propulsions, and their history is not finished yet. PPTs are operating successfully on board US spacecrafts, new designs of up to 100 W in power are being developed for small satellites. Pulsed plasma thrusters will operate on board Russian spacecrafts again also. But then, 40 years ago, the time of stationary plasma thrusters (SPT) came, first models of which were already tested at test benches of Kurchatov Institute.

III. After space tests.

A. APPT-based EPS "Globus"

"Further works on the PPT development were transferred from the Kurchatov Institute of Atomic Energy to the Experimental Design Bureau "Fakel". Doctor V.A. Khrabrov provided scientific management for the project. First experience of the EPS development as of the space engineering product was obtained at "Fakel" during the development of pulsed plasma propulsion system "Globus" [6,7] (Fig. 7) for the pitch attitude control of one of spacecrafts developed by the M.F. Reshetnev NPO (Scientific and Production Association). That system was developed jointly with scientists from the Kurchatov Institute of Atomic Energy just after the first PPT tests in space. EPS performance data are presented in Table 2.

Figure 7. Space propulsion system "Globus" with pulsed plasma thrusters produced by the Experimental Design Bureau "Fakel", Kaliningrad – Kurchatov Institute of Atomic Energy, Moscow – NPO PM, Krasnoyarsk

Spacecraft with pulsed plasma propulsion system "Globus" was launched on June 5, 1968. And again, as during the first launch of "Zond" spacecraft, the satellite did not reach intended orbit. Space tests of that system were made in 1974 only during the successful realization of a series of geophysical experiments "Ariel" by scientists and engineers of Moscow Aviation Institute under the supervision of Garri A. Popov.

Table 2. Performance data of APPT-based EPS "Globus"

Power consumption	200 W
Thrust cost	5…10 kW/N
Voltage	1000 V
Pulse frequency	2 Hz
Propellant	BiJ3
Capacitor	200/4 μF, 0.04 kg/J
Lifetime:	>100000 pulses

B. Solution for the thrust increase problem. Assembly consisting of 9 APPTs

In 1966 the laboratory team was ordered to develop PPT with the thrust of 0.1 N. A.M. Andrianov and

V.A. Khrabrov, as well as the team of laboratory as a whole, had vast experience in this line of activities. The system differed substantially from previous developments, had large mass and required powerful vacuum pumping.

Conditions close to space ones were created at a test bench developed for APPT testing. Vacuum chamber of 6 m in length and 1.5 m in diameter was the primary element of the test bench. The thruster assembly together with capacitor bank and switching unit was suspended on the torsion pendulum boom inside that chamber. Total pumping rate provided by vacuum pumps was $5•10^4$ l/s at the pressure of $5•10^{-4}$ mm Hg. The APPT mockup was made in the form of an assembly of 9 independent thrusters connected to a capacitor bank with the capacitance of 1 000 µF (V =1.5 kV) that in the course of operation was discharging to each thruster. The mockup mass was about 400 kg. The assembly diagram in shown in Fig. 8. Basis geometric dimensions of each thruster were the following: insulator length: 7 cm; electrode radii: R = 2 cm, R = 9 cm; length of internal and external electrodes: 10 cm. At the capacitor bank voltage of 1.5 kV the discharge current amplitude was 95 kA. Teflon was used as an operating insulator. A carborundum pair (carborundum contact with metal) was used for the primary discharge initiation. The following parameters were measured while testing the assembly: thrust (accuracy of about 1%) generated by the APPT assembly, propellant consumption, discharge current and electrode voltage, as well as temperature in different assembly points.

Thrust of 0.1 N was registered in the quasi-stationary mode of operation at the operation frequency of 6 Hz and power consumption of about 5 kW. Maximum duration of test was 6 hours. Plasma efflux velocity was 30 km/s, thrust efficiency η=0.125, power-to-thrust ratio W= 0.5 kW/g. Temperature of electrodes and operating insulator was as high as 160-180°C, temperature of capacitors was 35°C. At the forced operation conditions a thrust of 0.27 N was registered during about an hour; electrode temperature increased with that up to 270°C, and operating insulator temperature increased up to 200°C. According to estimations, a thrust of 0.3 N was quite achievable with that assembly at the electric power consumption of ~12 kW and plasma efflux velocities of ~ 60 km/s.

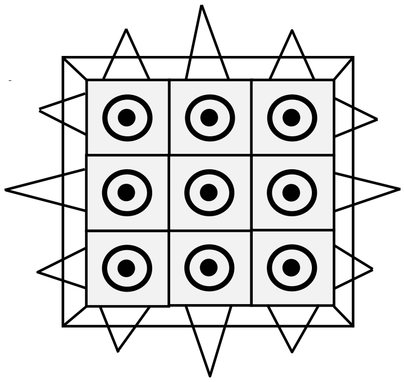

Figure 8. APPT assembly (end view)

IV. Magistral activity and EP popularization

In 1968 Victor Khrabrov started his scientific-magistral activity at the department “Plasma physics” of the Moscow Engineering-Physical Institute. He was a professor of that University since 1983. He educated and trained students and postgraduates, who subsequently worked actively for the benefit of science at the domestic and foreign scientific organizations. Victor Khrabrov has written a number of educational books. He was the founder of the course “Space Electric Rocket Propulsions”. Besides, a number of popular publications on EP was initiated by him also [8, 9, 10, 11].

During the last year of his life he worked at the book “Starprobe vehicles are born on the Earth” about different types of space propulsions, development of space resources, asteroid hazard.

V. Conclusion

V.A. Khrabrov jointly with A.M. Andrianov were the founders of scientific discipline “Physics and technology of high-power pulsed ablation discharges”, the most manifest application of which was the development and space test of the first electric propulsion system in the world.

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