Development and Qualification Test of a SPT Electric Propulsion System for "GALS" Spacecraft

A. Bober, K. Kozubsky, G. Komarow, N. Maslennikov,
FAKEL, Kaliningrad Region, Russia

A. Kozlov, A. Romashko,
NPO PM, Krasnoyarsk 26, Russia

ABSTRACT

In 1992 in Russia there was completed the development and qualification of the propulsion system for S/C "GALS," the first Russian satellite with "North-South" orbit correction system. On S/C "GALS," produced by NPO PM, stationary plasma thrusters SPT-100 of FAKEL production were used for S/C orbit in "North-South" and "East-West" direction, as well as thermal catalytic thrusters K-10 for S/C attitude maintenance and station-keeping during all stages of S/C functioning after the deployment. It is planned also to qualify SPT-100 for the usage on western S/C. When developing the propulsion system, FAKEL was basing on its 10-year experience of electrical thrusters (SPT-70) utilization on Russian geostationary communication satellites "Kosmos," "Lutch" of NPO PM production. This paper presents main characteristics of the "GALS" propulsion system, as well as description of thrusters' design, propellant storage and management assembly. Also are discussed problems of EPS integration on S/C, main results of qualification tests, including tests as part of S/C "GALS."

INTRODUCTION

In 1991 Experimental Design Bureau FAKEL designed, manufactured and qualified an electrical propulsion system for S/C "GALS" under contract with Scientific Production Association of Applied Mechanics (NPO PM).

FAKEL and NPO PM have been conducting joint works on the EP application on spacecrafts since 1965.

EPSs based on SPT-70 have been successfully utilized, beginning in 1982, on NPO PM spacecrafts to perform initial maneuvers on S/C insertion into the required point as well as for attitude maintenance in "East-West" direction.

Experience, obtained during the development and usage of these thrusters, was used when producing the EPS with SPT-100 for S/C "GALS," on which it is being planned to utilize these thrusters for "North-South" orbit control for the first time.

In 1966...1968 the first "full" EPS with pulsed plasma thrusters of thrust 2-4 g and power 200 W was developed and launched to LEO as part of S/C. Thereafter this propulsion system was used by RIAME for active geophysical experiments [1].

In 1968 FAKEL and NPO PM started the development of a propulsion system for communication geostationary spacecrafts. In 1975 FAKEL completed the development of EPS, based on electrothermal ammonia thrusters of thrust 0.8 N at power up to 1.5 kW and thrust of 0.02 N at power 67 W for orbit control. During this period, the first propulsion systems "EOL" with stationary plasma thrusters, developed by FAKEL under the scientific direction of A. Morozov (IAE) and participation of RIAME MAI, were successfully carried out [2,3].

Design simplicity, effective operation on inert gases, small number of secondary power sources at relatively low voltages motivated the selection of SPT for usage on Russian geostationary spacecrafts "Kosmos," "Lutch" of NPO PM production [4]. For these spacecrafts FAKEL developed SPT-70 [5].

Following are main results of SPT-100 EPS development and testing as well as problems of the EPS integration on S/C "GALS."

DESIGN AND TECHNICAL CHARACTERISTICS

Telecommunication geostationary S/C "GALS" has a long lifetime and high power capability as compared with those S/Cs on which SPT was used earlier.

For this S/C FAKEL developed a new, more powerful thruster SPT-100, which conceptual design corresponds to SPT-70. Acceleration channel diameter of the thruster was increased from 70 mm to 100 mm.

In 1991 the SPT-100 was demonstrated in the USA. In the same year FAKEL carried out SPT-100 tests with the participation of US experts [6].
Technical Characteristics

- Number of thrusters – 8, including 4 for "North-South" and 4 for "East-West" orbit correction.
- Thrust – 83 mN at BOL and not less than 70 mN at EOL.
- Propellant – xenon.
- Thrust vector deviation from the thruster geometrical axis not more than 45°.
- Thruster lifetime – not less than 1400 hours.
- Thruster power consumption at voltage 300 V – not more than 1350 W, for the EPS, as a whole, with 2 thrusters, operating simultaneously – not more than 3.1 kW.
- Total thrust impulse – not less than 750 kN·s.
- EPS "dry" mass – 76 kg. Xe mass – 52 kg. EPS total mass – 128 kg.
- EPS control is performed from the ground-station and on-board computer by 35 commands, including 14 commands for heaters' control. For the transfer of information on the EPS operation 39 telemetric parameters are used, including 19 for thermal modes' control.

EPS COMPLETE SET

"GALS" EPS comprises 7 units: 4 double propulsion units, 1 propellant management assembly (PMA), 2 propellant storage assemblies (PSA). All assemblies are mounted on the external surface of S/C body in a plane, passing through center of mass. PPU is placed inside S/C body, filled with nitrogen. The EPS design scheme is presented in Fig. 1.

The EPS design, based on self-contained units, provides minimal work scope during EPS integration on the S/C. All electrical and pneumatic connections between units are demountable and are performed by inter-unit pipelines and electrical cables.

PROPULSION UNITS

Each of the 4 propulsion units consists of 2 SPT-100s and 2 Xe flow controllers (XFC). Thruster alignment is made when manufacturing the units, taking into account the results of the control of thrust vector position relative to the thruster geometrical axis. To distribute and control xenon flow to SPT anode and cathode, in the XFC there are used 4 electromagnetic valves, 6 mechanical throttles and 2 thermal throttles. Total flow rate to the thruster is controlled by means of heating the thermal throttle by a discharge current sensor in the PPU.

Thermal mode of the unit components are provided by heaters, controlled by central on-board computer by temperature sensors. Restriction of flows through or from the thruster is provided by two radiators and titanium thermal "bridges." XFC thermal mode is determined by S/C mounting plates' temperature. The propulsion unit scheme is presented in Fig. 2.

XENON STORAGE ASSEMBLY

Each Xenon Storage Assembly comprises a titanium tank of 15.5 l with operation pressure up to 350 atm, two pyrovalves, connected in parallel, and a filling valve. The assembly general view is presented in Fig. 3.

All the components were earlier used in space as part of "cold" gas propulsion systems.

PROPELLANT MANAGEMENT ASSEMBLY

The PMA comprises two pressure relief valves with latch valves, 2 intermediate volumes of 1000 cm³ each for Xe pressure reducing up to 3–7 kg/cm², 4 solenoid valves, 3 pressure transducers and a plenum tank for electromechanical pressure stabilization within a range of 2.4...2.6 kg/cm² at the propulsion unit inlet.

On the assembly there are special connectors for propellant pipelines checking after EPS integration on S/C. The scheme is presented in Fig. 4.
Fig 2. Schematic of Double SPT-100 Unit

Fig 3. Propellant Storage Assembly

Fig 4. Schematic of Propellant Management Assembly

QUALIFICATION TESTS

The EPS test program envisages different debugging tests, aimed at the selection of the units' schemes and design prior to the EPS manufacturing in flight configuration. Upon the debugging tests, the qualification tests were conducted to confirm normal operation after applying loads, connected with ground operation, launch overloads as part of S/C "GALS" and simulation of space environment. The tests were carried out at rated and extreme parameters of power sources and thermal control system. The EPS components were approved for assembly at higher level after their own qualification tests. However, final
qualification of these components was carried out, basing on test results as part of the EPS and for the EPS—as part of S/C. "GALS" EPS Test Plan is presented in Fig. 5.

MECHANICAL AND CLIMATIC TESTS

The EPS units and components were subjected to the following tests:
1) accelerated tests of humidity and temperature cycles' effects during storage and preflight tests;
2) accelerated tests of transportation loads, simulated on a shock stand;
3) tests of strength when applying loads, acting at launch stage, simulated by sine vibrations;
4) tests of shocks and linear loads.

Besides the EPS was subjected to additional vibration tests within a scope corresponding to ground tests as part of "GALS" flight model. Tests on space radiation affects were conducted with the components, critical to these effects. Namely, these tests were conducted with SPT-100. Mechanical and climatic tests of "GALS" EPS were completed in May 1991.

THERMAL VACUUM TESTS

The EPS thermovacuum tests at units' level were carried out at FAKEI facility with the thrusters operating in marginal conditions, except solar radiation. The scheme of the propulsion unit arrangement in the vacuum chamber is shown in Fig. 6.

LIFETIME TESTS

"Fire" lifetime tests were conducted in FAKEI vacuum chamber with diffusion pumps at the inlet of which were placed traps, cooled by liquid nitrogen. During self-contained tests of the thrusters there were used the facility power sources, and during lifetime tests of the EPS units - flight power sources. Basing on the results of the first 400 hours of thrusters and EPS units' testing, FAKEI started manufacturing the EPS flight models. To confirm the specification requirements, the tests with 20% margin by lifetime were conducted. During qualification test stage, lifetime test was carried out with four SPT-100s, including two thrusters as part of the propulsion unit with two xenon flow controllers. During the whole development period, eight thrusters were subjected to "fire" tests with total accumulation of 17000 hrs., including 8000 hrs. at qualification tests. Maximal lifetime of a single thruster - 4005 hrs. at 2744 starts without affecting the normal operation was obtained in 1991. The picture of this thruster after the life test is shown in Fig. 7.

Fig 5. Testing Flow Diagram
The S/C test procedure, adopted in NPO PM, does not envisage electrical tests in the vacuum chamber. All on-board systems are checked for functioning in regular environmental conditions. Peculiarities of SPT-100 physical processes do not allow thruster ignition during S/C ground testing. Therefore, there were developed and used special electric simulators of the EPS, giving a possibility to connect PPU to loads, close to real, as well as to check functioning of flight sequencing. Simulation of anode circuit main load is performed by means of a gas discharge lamp, having the same current-voltage characteristics. Control commands' generating, designed modes' testing, telemetric data collection and processing, test results' presenting are all automated. During integration electrical checks in NPO PM, there was conducted the check of EPS/PPU compatibility by electrical parameters as well as their compatibility with Automatic Information System (AIS), including functional components' adjustment, control commands, and telemetric parameters. It was checked the EPS functioning together with the PPU, using EPS simulators at all flight modes, abnormal modes and marginal conditions. Test procedures were tested with AIS, test software was debugged, test documentation was checked.

During functional checks and tests as part of S/C, the comprehensive refinement of flight functional sequencing and abnormal situations, using thruster simulators and flight on-board software. The EPS interaction with other S/C systems was also updated.

During incoming control and self-contained tests of flight sets, there were checked PPU electrical circuits, tightness and electrical circuits in the EPS. S/C self-contained tests were performed, EPS/PPU operation ability and readiness for integration on the first S/C flight model was confirmed.

During S/C preparation at technical site, there are performed self-contained filling of xenon storage assemblies, inspection of joints’ leakage and checking of electrical connections, comprehensive tests in S/C modes, and final steps on the EPA preparation for operation in orbit. The completion of the EPS qualification tests is planned for the initial stage of S/C orbit functioning, prior to putting it into the end use operation.

**SPT-100 EPS INTEGRATION ON S/C "GALS"**

When developing "GALS," SPT-100 EPA peculiarities were taken into account with regards to their influence on design and operation of on-board systems and S/C as a whole.

S/C parameters and operation are influenced mostly by:

- thrust and accuracy of its maintenance in magnitude and direction; EPS total thrust impulse and its distribution over different modes; thruster specific impulse;
— thrust cost, characteristic of power consumption level;
— thruster total lifetime by impulse (time) and number of starts; composition and arrangement of the EPS units on S/C;
— influence of plasma jet on S/C instruments;
— electromagnetic effects, including interference over power circuits, setting and information circuits of other on-board systems, influence on charging of S/C external surfaces, influence on radio line;
— the EPS functioning logic, diagnostics and control.

Here below is shown the impact of all mentioned factors.

**THRUST**

SPT-100 thrust level, selected on the basis of on-board power availability, permit to perform orbit correction both in "East-West" and "North-South" direction within a long period of time, through from the standpoint of reducing time, necessary for the initial stages of S/C deployment, it is desirable to have higher thrust level. Partially this task is solved by simultaneous operation of two thrusters, as long as the power, intended for on-board equipment, can be used for the second thruster operation in the same direction.

Thrust value accuracy is necessary to calculate thruster operation time when performing correction maneuver. For thrust stabilization Xe flow rate control by discharge current with accuracy ±1% is introduced. In real conditions, actual thrust values are constantly clarified by orbit parameters measurements, performed by self-contained on-board navigation system, also during the thruster operation. This control logic permits to reduce impact of thrust change as lifetime is being accumulated.

Stability of thrust vector direction is necessary to reduce disturbing moments on S/C and decrease hydrazine quantity for attitude maintenance thrusters.

**TOTAL THRUST IMPULSE, NO. OF IGNITIONS**

Significant energy expenditures, required for orbit correction maneuver in "North-South" direction, predetermined EPS choice for "GALS."

The EPS, based on SPT-100, has a mass 5-7 times less than a chemical propulsion system for the same conditions. Thrust impulse in "North-South" direction is by an order of magnitude greater, than in "East-West" direction. And this defines the requirements to the thruster lifetime and reliability. With "GALS" mass being 2500 kg and active lifetime of 5 years, EPS total impulse must be not less than 7500 kN*s.

Number of ignitions was chosen, basing on starting cyclorama—once a day in "South" direction.

**SPECIFIC IMPULSE**

Main SPT-100 EPS advantage is a high specific impulse, which decreases amount of propellant and, correspondingly, tanks' mass for its storage. For "GALS" a special filling procedure was developed for maximal Xe density in tanks: two tanks of 15.5 l each are filled up to 62 kg.

**THRUST COST**

SPT-100 thrust cost amounts to 16–19 W/mN and limits upper thrust value, because power consumption of 1.5 kW with one SPT-100 in operation is significant for the S/C, having total power range of 2.5...4 kW. With the functioning payload, it is allowed to have one SPT-100 in operation. In order to keep total positive energy balance of the spacecraft, limitations for thrusters ignition time are defined for shadowed parts of the orbit.

**LIFETIME**

Lifetime requirements for the SPT are mission dependent. SPT-70 has lifetime of 700 hrs., which is enough for "East-West" correction at the beginning of flight and within 5 years. To perform "North-South" correction for "GALS" by means of SPT-100, it is required to have lifetime up to 1500 hrs. and to provide 10-year life it is needed more than 2500 hrs. and 4000 starts.

**EPS ARRANGEMENT ON S/C**

The EPS units arrangement zones are determined by their functional purpose and their impact on S/C parameters. "GALS" general view is shown in Fig. 8.
Four propulsion units, each comprising two STP-100s, are mounted on “GALS” in “North-South” and “East-West” direction with angle deviation of thrust vector of not more than 5°. The value of this deviation is determined by presence of two thrusters in each unit, positioned along S/C axes. Compensation of the moments, occurring with SPT operation, is provided by thermal catalytic thrusters, developed by FAKEL for attitude maintenance systems of NPO PM spacecrafts.

Propellant tanks are placed symmetric about center of mass to provide its minimal changing with the propellant exhausting. To exclude propellant leaking between separate storage assemblies, their temperature difference shall be minimal. Storage assemblies provide convenient mounting/dismounting process for the self-contained filling in a special constant-temperature cabinet to obtain the designed density of the propellant.

The EPS power supply and control are performed by electronic Power Processing Unit (PPU). Separate functional EPS units are connected between each other and the PPU by electrical cables. The EPS control, diagnostics and operation logic are provided by the PPU and special on-board computer software.

The PPU is placed in a pressurized instruments' unit of the spacecraft, with due regard for minimal length of the cables, which resistance shall not exceed designed values.

**PLASMA JET INFLUENCE**

Physical properties and three-dimensional model of the thruster jet are one of the most critical factors when analyzing S/C design and packaging scheme.

In the general case, while developing S/C with EPS there shall be defined the results of plasma jet interaction with other S/C components, including:
- force interaction with S/C body, antennas, solar arrays, thermal control radiators with calculation of thrust loss and disturbing moments produced;
- thermal impact on solar array photo converters with evaluation of energy characteristics degradation;
- mechanical, thermal and electrical impact on thermal control coatings;
- electromagnetic interference of the plasma jet with operation and parameters of S/C radio-technical equipment at different radio wavelength;
- impact of the jet illumination, intrinsic and due to solar radiation dissipation, on optic-electronic astroinstruments;
- changing of S/C inherent external environment;
- impact on electrostatic charge distribution over S/C surface, due to generating a conducting plasma formation around S/C.

It should be noted that on S/Cs “Kosmos-1366” and “Lutch” there existed free semi-spheres for plasma jets, because thrusters were mounted in “East-West” direction only. Therefore, many interaction types were not critical and not studied.

Taking into consideration the increase of thrusters' number on “GALS” and other future spacecrafts, their free arrangement in four direction appears to be difficult, and all types of plasma jet interaction with S/C components are subject to investigation, analysis and estimation.

For “GALS” force interaction calculations were made; available experimental data for other types of interaction were considered; maximal possible spatial decouplings of the jet core with structural components were implemented during S/C packaging; special methods of wires and electrical connectors' shielding were used; evaluation procedures of EPS interference with S/C in-orbit operation were developed, as well as redundant functioning algorithms.

**POWER SUPPLY AND ELECTROMAGNETIC EFFECTS**

The EPS power supply affects significantly S/C total energy balance in different operation modes, including stand-by mode, thruster operation, abnormal situations. The operating SPT is a rather powerful (up to 1.5 kW per thruster) load, which could change Power Supply System operation mode, when storage battery is being connected, due to lack of power from solar array. Switching of such a great load affects significantly the noise situation over S/C equipment power circuits. Therefore, the noise situation was studied during
Despite the fact that the EPS is reasonably self-contained, it affects other S/C systems greatly.

Types and levels of on-board systems’ interaction are taken into account during the development stage and are clarified during flight tests.

**CONCLUSION**

In Russia there was completed the development and qualification of the first electric propulsion system with a stationary plasma thruster for “North-South” orbit correction system of S/C “GALS.” The EPS main components and their protoflights (SPT-70) are flight qualified on Russian S/C “Kosmos,” “Lutch,” “Meteor.” Environmental tests, including climatic, mechanical and thermovacuum, were conducted in compliance with Russian standards.

Life tests were conducted with eight SPT-100 thrusters with total accumulation of 17000 hrs., including 4000 hrs., accumulated with one thruster. The EPS comprehensive tests as part of "GALS" have been completed. Flight test is planned for the end of 1993.

**REFERENCES**