High Efficiency APPT for LEO SSC control applications

N. Antropov, G. Diakonov, N. Lyubinskaya, M. Orlov, G. Popov, P.Trubnikov, V. Tyutin, V. Yakovlev

Research Institute of Applied Mechanics and Electrodynamics,
4, Volokolamskoye shosse, Moscow, 125810, Russia
riame@sokol.ru

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Introduction

During several past years RIAME MAI has managed to obtain thrust efficiency for Teflon ablative PPT of rail geometry that do not yield to the efficiency of low-power EP of stationary action, which are designed for providing orbit correction for low-orbit SSC (small spacecraft).

In view of design, technologic, functional simplicity and low cost, distinguishing it advantageously from electric propulsions of other designs, such APPT can be considered as one of the most perspective thrusters to be used as a part of SSC orbit correction propulsion system within the broad range of required total pulses. So, highly efficient APPT-150 (with 150 J of stored energy), thrust efficiency of which comprises 40 % at least currently, is capable to solve efficiently many orbit control tasks for a SSC of up to 500 kg in mass requiring total thrust impulses of up to 10×10^4 Ns per a thruster.

APPT-20 with the thrust efficiency of ~ 17 % has good prospects to be used as a part of orbit control propulsion system of a SSC with the mass of up to 100 kg, as well as a part of attitude control systems for heavier SSC. Maximum total impulse of such thruster is ~ 1.5×10^4 ns.

APPT-50 with thrust efficiency of up to 25 % may be considered as a universal orbit correction thruster for a SSC with the mass from 50 kg to 300 kg requiring total thrust pulses of up to 3×10^4 Ns.

Some results of research, development, and refinement of a highly efficient APPT, obtained in 2003-2004 mainly, are presented in the report.

APPT Progress at RIAME MAI

1992 – recommencement of work under APPT that was interrupted at the end of 70-ies;

1992 – 1998 – design-experiment studies aimed at the determination of ways for increasing efficiency of APPT operating process;

1999 – 2001 – development, investigation and refinement of APPT models within the range of energy consumption of (20-100-150) J with the thrust efficiency of (12–25-35) %, respectively.

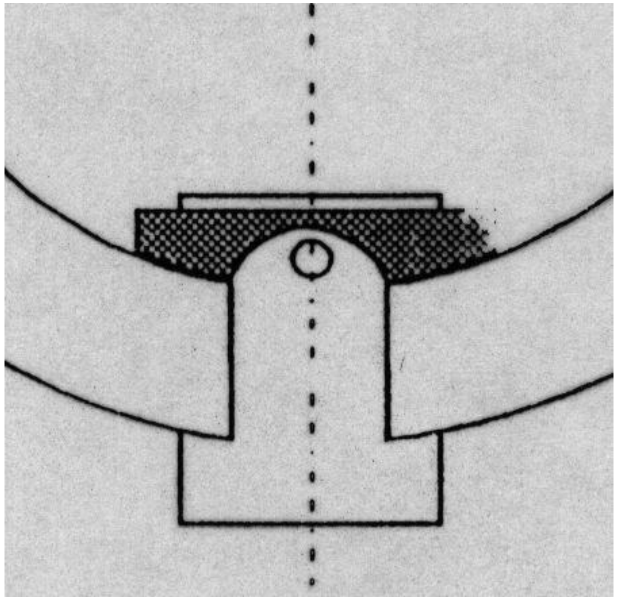
2003 – 2004 – development of APPT models with the efficiency of (17 – 35) % within the energy range of (20 – 100) J.

2004 – start of development for the APPT-50 flight model (with the energy of 50 J) with the aim of its flight test in 2006 on board SSC of "Vulkan" type developed by NIIEM, located in Istra.

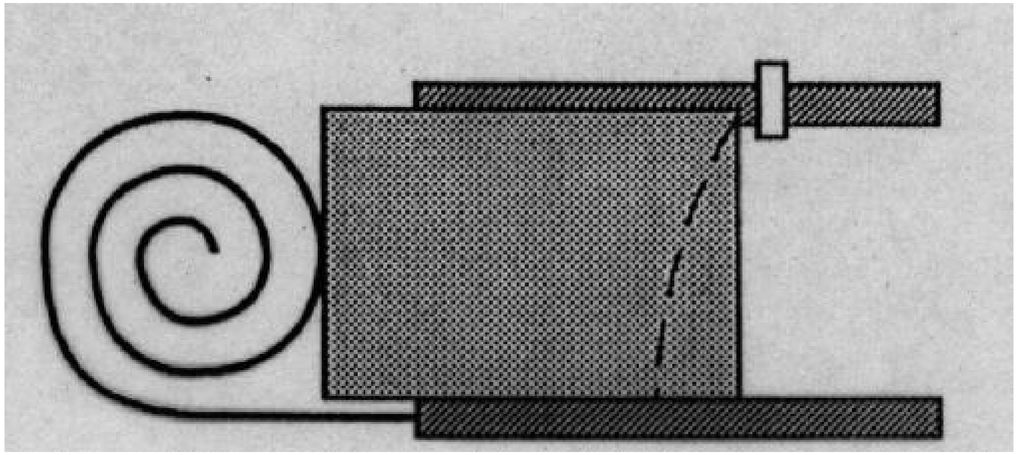
2004 – start of development for the propulsion system comprising APPT-50 designed for orbit correction for a constellation of SSC of "Vulkan" type and similar.

2008 – start of deployment for "Vulkan" constellation equipped with APPT-50 based correction propulsion system.

Scheme of APPT with side feed of propellant



Scheme of APPT with back feed of propellant



Choice of APPT scheme.

APPT schemes with rectangular discharge channel:

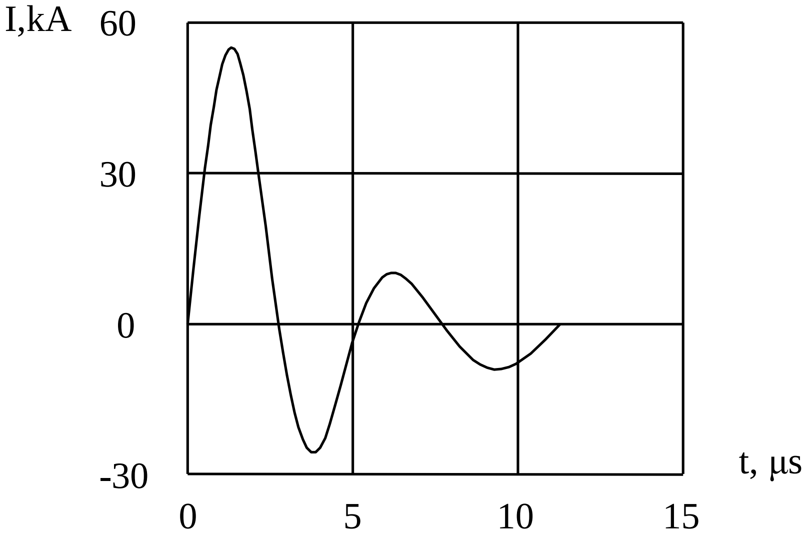
- **with the side system for propellant feed into the channel;**
- **with the back feed system.**

Advantages of APPT with side propellant feed:

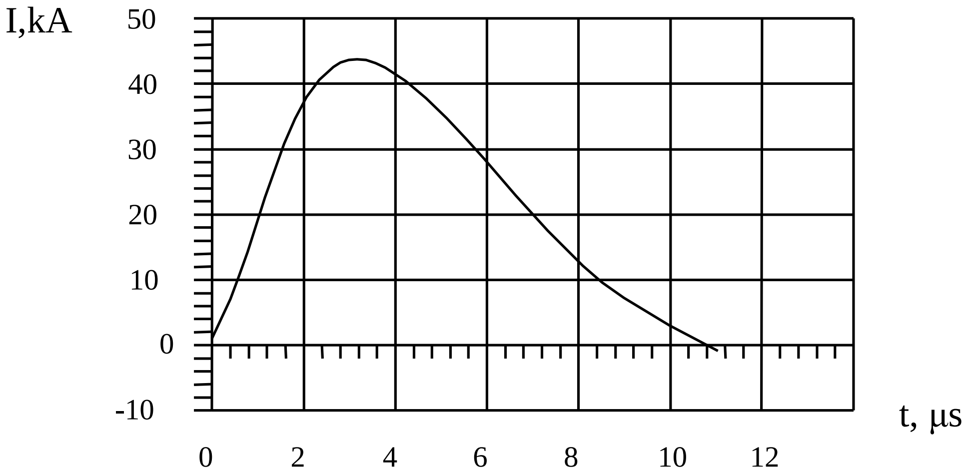
- **possibility to realize advantages of quasi-aperiodic discharge;**
- **high thrust impulse bit (P_{bit}).**

The problem that frequently prevents the use of scheme with side feed – carbon deposition on the operating surfaces of bars. According to our experience, it is possible to solve this problem.

Discharge Current for the Typical and Highly Efficient APPT



Discharge current of the typical APPT



Discharge current of the high efficiency APPT

Positive effect in the highly efficient APPT is reached due to a better matching of the circuit parameters. Basic obvious difference between the thrusters of various generations is the transfer from oscillatory discharge to the quasi-aperiodic that leads to a number of important consequences:

1. Considerable mass reduction for the propellant fed into the channel.

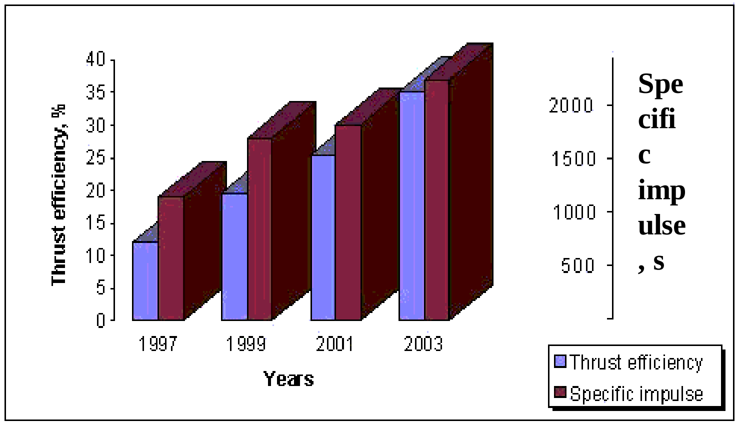
2. Acceleration of substantially larger part of propellant by bulk electromagnetic force.

3. Considerable reduction of capacitor load – increase in lifetime and reliability.

Progress in the (20 – 100) J APPT Characteristics
APPT-100 Parameters Diagram

Stored energy, J	20			50			100		
Years	1999	2001	2003	1999	2001	2003	1999	2001	2003
Impulse bit, mNs	0.3	0.4	0.7	0.8	1.1	1.4	1.9	2,6	3.2
Specific imp., s	750	800	900	1100	1300	1750	1300	1850	2200
Thrust efficiency	0.6	0.8	0.16	0.9	0.14	0.24	0.12	0.24	0.35

APPT-100 parameters diagram



New considerable growth in the APPT characteristics was achieved by RIAME in 2003 that was verified by test within the range of discharge energy of (20 – 100) J.
Data on the thruster characteristics at different values of stored energy are presented in the Table. Growth of APPT thrust efficiency during 5 years is close to 300 %.

Some Results of APPT Study in 2003
(for APPT-100 as an object under study)

Parameter		Basic variant	1	2
Initial data	L_{k}, H	40×10^{-9}	40×10^{-9}	40×10^{-9}
	R, Ohm	4×10^{-3}	6×10^{-3}	4×10^{-4}
Design values	Thrust efficiency	26.5	19.0	32.0
Test values	Thrust efficiency	25.5	17.0	37.0

Calculation studies for the APPT operating process allowed assessment for the influence of the outer circuit resistance that is mainly concentrated in the energy storage upon the APPT thrust efficiency. Results of such assessments showed that it is necessary to aim at the reduction of the storage ohmic resistance.

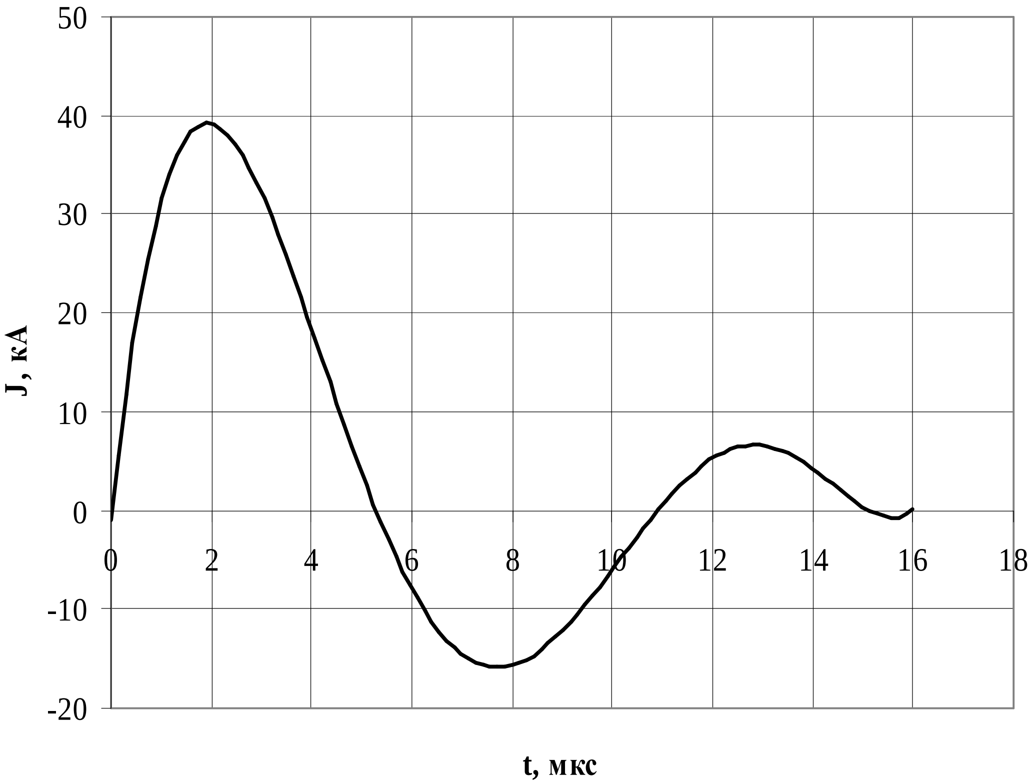
RIAME has developed an energy storage with the internal resistance of $(4 - 6)\times10^{-4}$ Ohm instead of $(2–3)\times10^{-3}$ Ohm typical for the storages used earlier. Total active resistance of external circuit was reduced down to $\sim 1.5\times10^{-3}$ Ohm from $(3 - 4)\times10^{-3}$ Ohm and appeared to be close to the resistance of current leads.

Test values of thrust efficiency are presented in the same Table.

Similar results were obtained for the low-resistance energy storages with other rated values.

Some Results of APPT Study in 2003 (2)

Energy storage with R_{Ohm} < 1 MOhm allowed to increase APPT thrust impulse bit by 15 – 20 %, and its thrust efficiency by 20 – 40 % (sheet 5). As not more than 5% of the stored energy is dissipated in the storage, a real possibility was obtained to increase cycling frequency up to 2 Hz and may be higher.



Discharge current of the modern APPT-50

It is interesting that in the case of APPT-50, high characteristics take place at oscillatory discharge. Basic reason for the appearance of current oscillations is associated with the following:

- **reduction of the circuit active resistance;**
- **plasma acceleration even in the 2nd half-period may be electromagnetic to a considerable degree, because of insignificant quantity of propellant.**

This statement will be verified by test in the nearest future.

Shape of the current curve witnesses of the possibility for further thruster efficiency increase at better matching of impedances for the parts of its circuit.

Results obtained allowed to attract greater attention of Russian SSC developers and space agency to APPT. Work was started under the preparation of APPT demonstration flight tests to be performed in 2006.

Analysis for the Characteristics of PS Comprising Thrusters of Different Types, which were Considered as Basic for the PS of “Vulkan” SSC (mass of ~ 300 kg). Maximum PS power is 100 W, P_{tot}=21.3 kNs, mass - 15 kg.

PS type	Cold gas Thruster	Ammonium thruster without heating	Ammonium thruster with heating	Hydrazine thermoca-talytic thruster	SPT-30	APPT-100	APPT-50
Power, W	10	60	100	10	100	8 frequency 0.8	100 frequency 2
Specific impulse, s	64	100	165	220	1000	2200	1700
Impulse bit, Ns	$5\cdot10^{-2}$	$5\cdot10^{-2}$	$5\cdot10^{-2}$	5	$5\cdot10^{-3}$	$3\cdot10^{-3}$	$1.5\cdot10^{-3}$
Thrust, N	$5\cdot10^{-2}$	$5\cdot10^{-2}$	$5\cdot10^{-2}$	5	$5\cdot10^{-3}$	$2.4\cdot10^{-3}$	$3\cdot10^{-3}$
Propellant mass, kg	33.3	21.3	12.9	9.7	2.1	~1	1.3
PS mass, kg	80	28	22	22	12	10	8

Characteristics of correction PS based on the thrusters of different types are presented.

PS based on SPT-30 and APPT-100 meet all requirements. SSC developer (Research Institute of Electromechanics) took an option of APPT-based PS because it has lower mass, is substantially more simple and easier to manufacture. Economic factor had profound effect upon the PS selection. Production cost for the APPT-100 based propulsion system is (3–4) times lower than that of the SPT-30 based PS (according to NIIEM specialists). APPT thrust efficiency growth allowed APPT-100 replacement by APPT-50. APPT-50 characteristics are presented in the Table.

Results of Modern APPT Test-Bench Refinement (1)

Thruster model bench test was made in 2004 within the frames of work under the development of propulsion system flight prototype comprising APPT-50.

Aims of test-bench refinement:

1. APPT preliminary tests for the lifetime of 2×10^6 cycles inclusive at the operation frequency of 2 Hz providing control for the temperature of capacitors, Teflon bars, electrodes and for the surface state (monitoring for the bar shape and carbon presence).

2. Obtaining of basic integral characteristics of the thruster with the stored energy of 50 j and their stability monitoring during tests.

3. Study for electromagnetic pickup produced by the thruster.

4. Assessment for the SSC surface contamination by carbon and contamination forecast for the case of long-term operation.

Refinement results:

1. 2×10^6 cycles at the frequency of 2 Hz; energy storage, discharge channel and discharge initiation system operated well. Temperature of APPT-50 capacitors:

– in the bottom part of the body ~ 25^0 C;

– in its top part (near the bus mounting points) – $(30 – 35)^0$ C, i.e. more than twice lower than earlier.

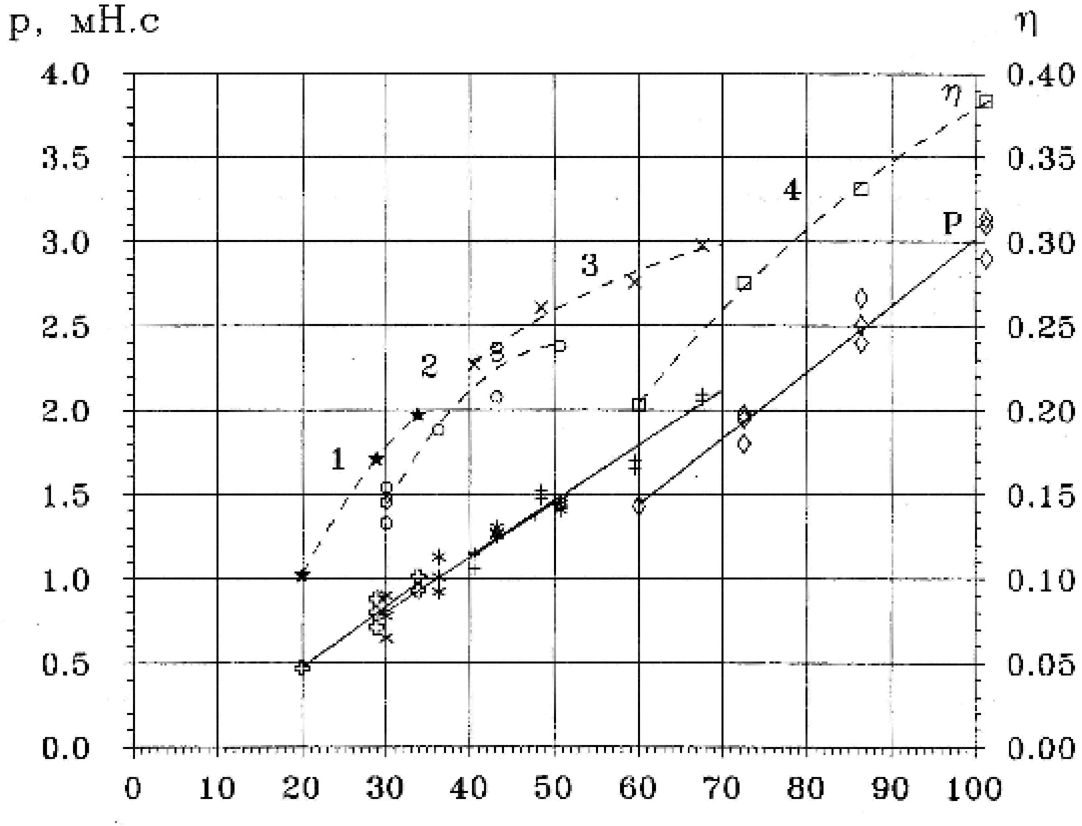
2. Integral characteristics corresponded to expected ones and were stable.

3. Carbon on the bar operating surfaces was absent.

4. Ablation of igniter electrodes and basic electrodes allows prediction for their lifetime with 1×10^7 thruster operations at least.

5. Basic integral characteristics of modern APPT are presented in transparency 6. They are noticeably higher than the obtained earlier.

Results of Modern APPT (2) Test Refinement, APPT Characteristics within the Energy Range of (20-100) J



Reduction in the slope for η_T curves at the discharge energy growth witnesses of the necessity to increase the number of capacitors in the energy storage.

Results of Modern APPT Test-Bench Refinement (3)

Tests were made under the study of influence of plasma electromagnetic radiation and carbon films formed during the APPT operation upon the radio equipment and SSC optic surfaces.

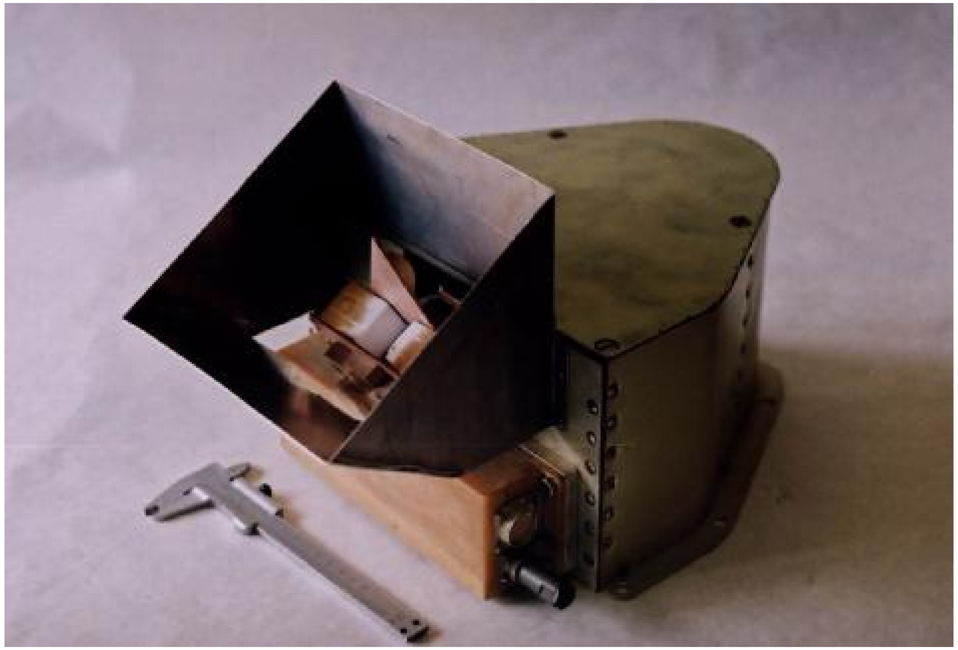
Tests were made inside the vacuum chamber of 1 m^3 in volume under the conditions of oilless vacuum of 10^{-5} torr.

In general, electromagnetic interference has low-frequency spectrum: (0.1 – 1.0) MHz. Oscillations of the field magnetic component with the amplitude of not more than 3 A/m are registered at a distance of 1 m from APPT. Fields generated by magnetic system of gyros unloading that is mounted on board the "Vulkan" SSC are considerably more intense.

Study for the problem of carbon deposition revealed the following:

- **At the discharge current the plume of modern APPT is focused rather well with the double divergence angle in the vertical plane of not more than 30^0;**
- **After the discharge, about 20 % of total propellant mass flows uniformly out of the channel into the half-space at the thermal and subthermal velocities;**
- **Considerable (the most dangerous from the point of view of possible variation of SSC surface properties) part of the carbon mass propagating at large angles to the discharge channel axis can be trapped by a screen mounted around the discharge channel;**
- **Forecast for the SSC optic surfaces contamination by carbon for the operation period of 7 years, based on test data, showed that their degradation as a result of space factors will be considerably higher.**

Preparation for APPT-50 Flight Tests



Engineering model of APPT-50 flight prototype

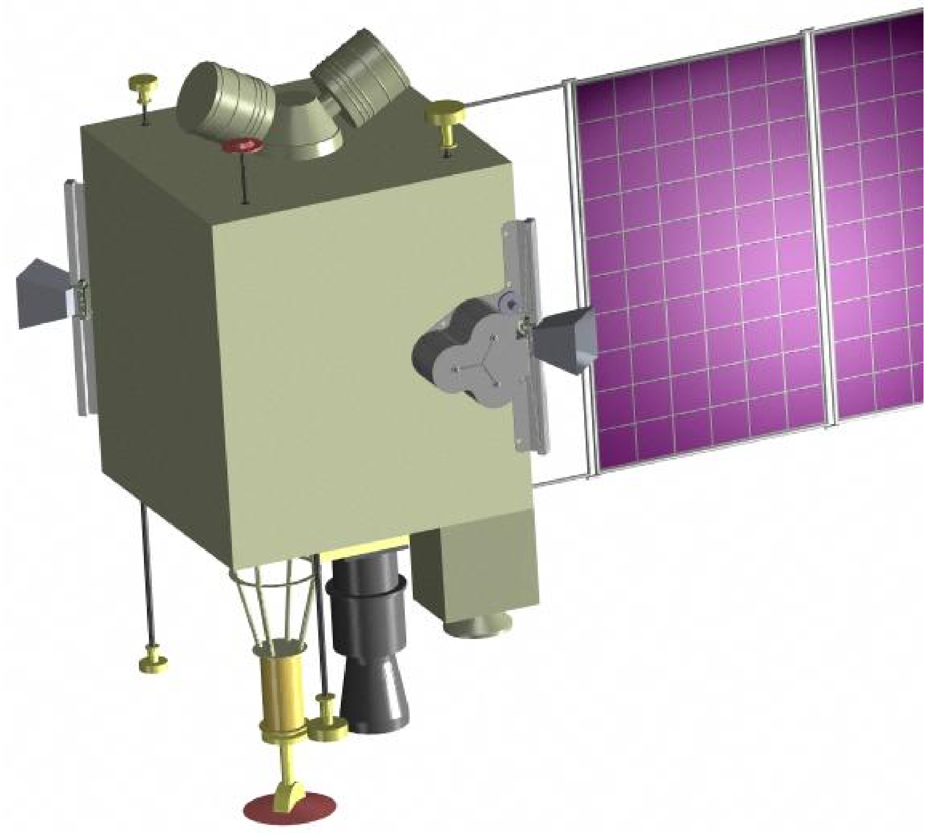
A decision was made in 2004 on the preparation and fulfillment of test for the APPT-50 based propulsion system flight prototype on board the experimental SSC of “Vulcan” type that is developed by NIIEM located in Istra. Launch is planned for 2006. Propulsion system flight prototype will be produced by RIAME, ground tests will be made at RIAME and NIIEM. External appearance of the APPT-50 engineering model developed by RIAME is presented in the figure.

Test aims:

1. To verify APPT operability under space conditions.
2. To verify basic thruster characteristics.
3. To secure SSC orbital parameters keeping.

Option of Arrangement for the Propulsion System Comprising Two Thrusters of APPT-50 Type on Board “Vulkan” SSC

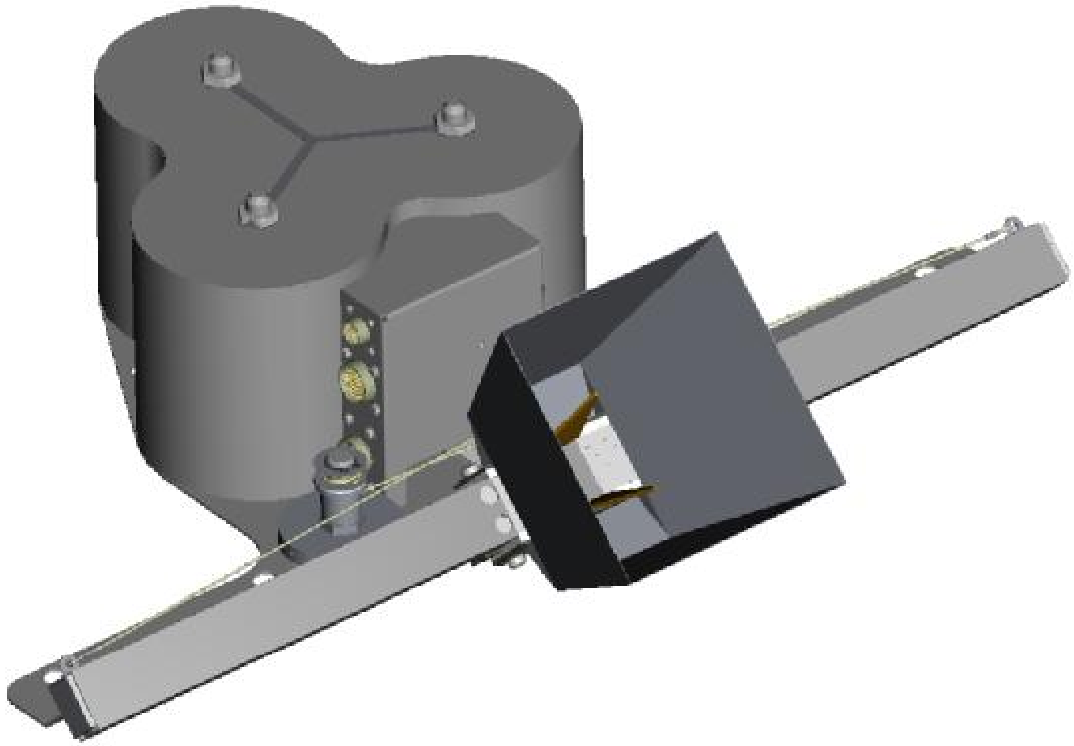
(M_{SC} = 280 kg, H_{orb} = 550 km)



Appearance of "Vulkan" SSC with APPT-50 thrusters

Successful test-bench tests that verified possibility for APPT-50 operation with the frequency of 2 Hz allow to start development of APPT-50 based propulsion system (PS) as of the standard PS for “Vulkan” SSC. APPT-100 replacement by APPT-50 will allow PS mass and cost reduction. PS being designed differs by the discharge channel inclination at an angle of 45^0 to the energy storage plane. PS will consist of two completely independent thrusters of APPT-50 type mounted on the opposite ribs of SSC body. PPU is common for two thrusters. Total mass of such propulsion system is about 14 kg.

Development of APPT Flight Models

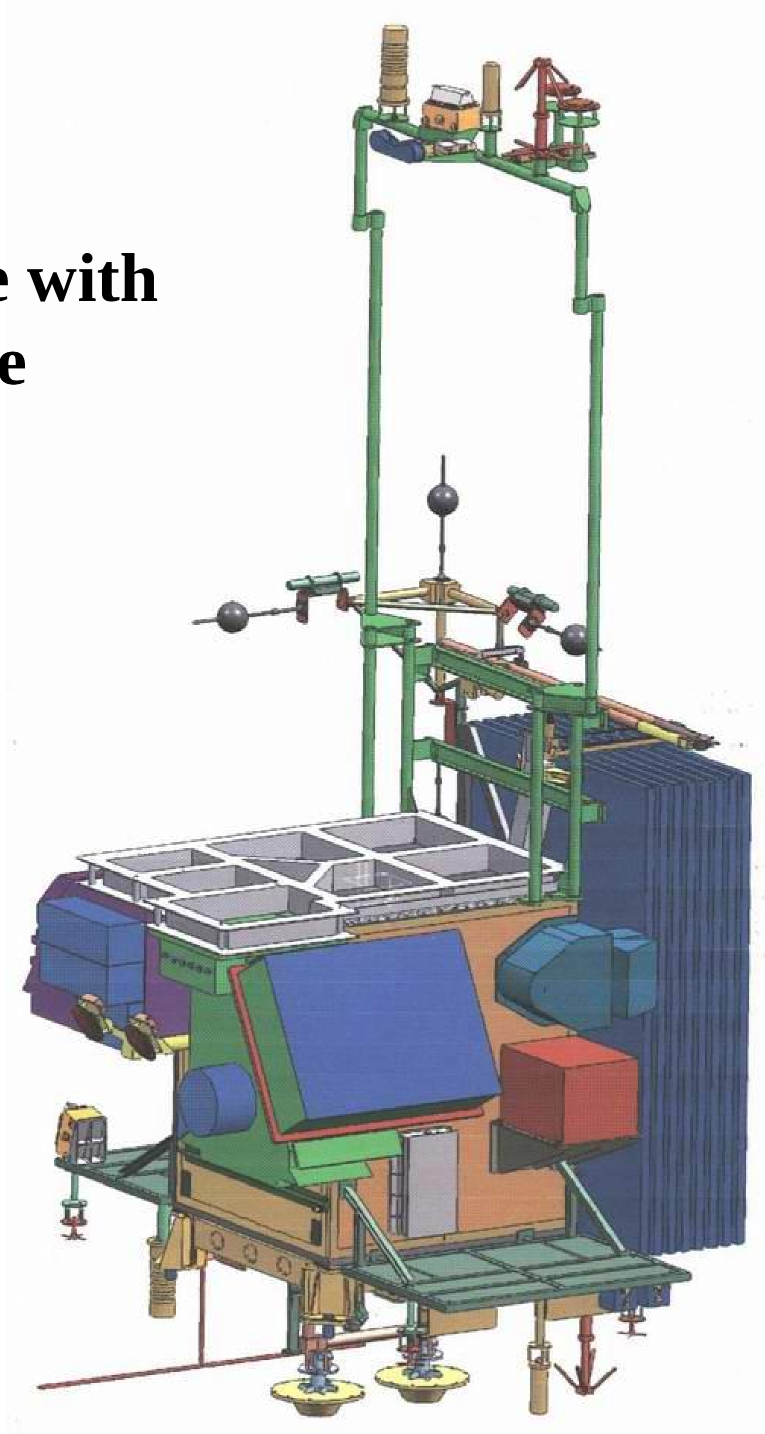


APPT -50 appearance

A number of low-orbit SSC (navigational, remote sensing, communications) are currently being developed in Russia. Typical SSC mass is from 60 kg to 400 kg. Many tasks of orbital control for the mentioned spacecraft can be solved by modern APPT-50. APPT-50 is capable to operate with the frequency of 2 Hz (and even higher) during a long time. At that, its thrust characteristics practically exceed the characteristics of APPT-100 thrusters of earlier modifications, maximum cycling frequency of which at durable operation was not higher than 0.7 Hz. That allowed to choose APPT-50 as a propulsion system thruster for the “Vulkan” universal space platform. One of the options of APPT-50 based propulsion system is presented in the figure.

Distinctions of propulsion system arrangement on board SSC define some design peculiarities of the thruster.

SSC "Vulkan" Type with Flight Prototype Appearance



Conclusion

Highly efficient APPT of next generation is developed, characteristics of which are higher considerably than those of the known analogues.

Thrust efficiency of APPT-50 and APPT-100 thrusters of new generation comprises 25 % and ~ 35%, respectively, that is not lower than the efficiency of small electric propulsions of stationary action.

Energy storage is developed with a low level of ohmic losses that allows APPT-50 thruster to operate during unlimited period at the cycling frequency of 2 Hz and probably higher.

Engineering model of APPT-50 based propulsion system was developed and tested. It was approved by NIIEM (Istra) as a correcting propulsion system for "Vulkan" SSC (M_{SSC}= 270 kg, H_{orb} = 550 km, $P_{å}$ = 21.5×10^4 Ns).

Demonstration tests for the flight model of APPT-50 based PS are planned for 2006 – 2007.

Highly-efficient APPT keep all known advantages of the "traditional" thrusters of such scheme: design, technologic and functional simplicity and low cost of production and operation; they are characterized by high competitiveness for solving control tasks for a SSC with the mass from 50 to 500 kg.