The analysis of influence of electrical propulsion characteristics on efficiency of transport maneuvers

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Abstract: The transport operation of a satellite insertion into a geostationary orbit (GEO) is examined. The space transport system on the basis of a launcher “Soyuz 2-1b” is analyzed. Transfer from a low earth orbit into GEO implements by chemical engine of upper stage "Fregat" and by an electric propulsion. Possibility of using of stationary plasma thrusters of type SPT140, possibility of using Hall Thruster Propulsion System (Aerojet-Redmond Operation), and possibility of using of the ionic engines of type XIPS-25 is researched. The purpose is to show, how optimal values of specific impulse of electric propulsion depend on characteristics of space vehicle and characteristics of space maneuver, as well as to show, that optimal values of specific impulse can be rather low.

Nomenclature

$K_{structure}$ = the parameter considering mass of fastening elements of electric propulsion
M_{EP} = the mass of electric propulsion
M_{contr} = the mass of the power supply system and of control system
M_{TU} = the mass of the thrusters unit
M_{tank} = the mass of a xenon tanks (a system of storage and fuel supply)
M_{UXS} = mass of the unit of a xenon supply
M_{Xe} = the mass of a propellant (xenon)
$M_{XeContr}$ = the xenon mass for control of space vehicle moving during its insertion into a working orbit
P_{input} = input electric power of thruster
P_{inputNom} = the nominal value of input electric power
T = thrust of electric propulsion
$T_{\mathrm{thrasterNom}}$ = nominal thrust of electric propulsion

I. Introduction

The present research has arisen under such circumstances. Results of the experimental research conducted in Design Bureau "Fakel" at perfection of stationary plasma thruster SPT-140 have been presented to us. These results gave a possibility to analyze the characteristics of this thruster as function of an anode voltage. It was clear, that developers of the thruster search for rational ways of increase in anode voltage of the thruster to increase specific impulse of the thruster.

Using the presented characteristics of this thruster, we have conducted the analysis of a capability of its using for the insertion of spacecraft (SC) into a geostationary orbit (GEO) for some transport system. The result has appeared the following. At a small insertion time (interesting for many commercial projects) into the geostationary orbit, it has appeared that it is necessary to use minimal anode voltage 250 V and corresponding minimal value of specific impulse. Certainly, it is well-known, that for electric propulsion the optimal value of specific impulse are small at small times of fulfilment of transport operations. Another fact was unexpected. Developers of the engine, improving the engine, make significant efforts for increasing of specific impulse of the thruster, but this increase is inexpedient. On a question why so occurs and also what requirements should be executed at increase of specific impulse that this increase was expedient, we tried to answer in the present activity.

II. Results the earlier conducted researches of transport systems with the electric propulsion

The analysis of the spacecraft insertion into a geostationary orbit with use of electric propulsion, and also the analysis of influence of characteristics of electric propulsion on the main parameters of such projects were carried out in many activities, for example, in activities [1-8].

Many authors researched optimum values of specific impulse of electric propulsion (EP). Results of research of this problem, which we carried out in the past, is well agreed with results of other authors, therefore we shall show some results published by us earlier.

In paper [1] it is considered SC insertion into the GEO using light-class launcher (LV). For example, Rockot or Angara-1.1 LV (payload 1950-2000 kg) provides insertion of SC having final mass 400 kg (500 kg) for 3 months (6 months), Angara-1.2 LV (payload 3700 kg) inserts 700 kg SC for 4 months. So, small telecommunication SC could be delivered into GEO using light-class LV from Plesetsk launch site for reasonable transfer duration.

Figure 1 shows impact of EP specific impulse in final SC mass. It is seen that exists an optimal specific impulse for each given transfer duration of the considering range (90-180 day). Optimal value of specific impulse increases from ~1540 s to ~1880 s when transfer duration increases from 90 days to 180 days (Fig. 2). The maximums of final SC mass is flat enough: EP specific impulse variation ±100 s relatively optimal value leads to final mass decreasing on 0.5-3 kg.

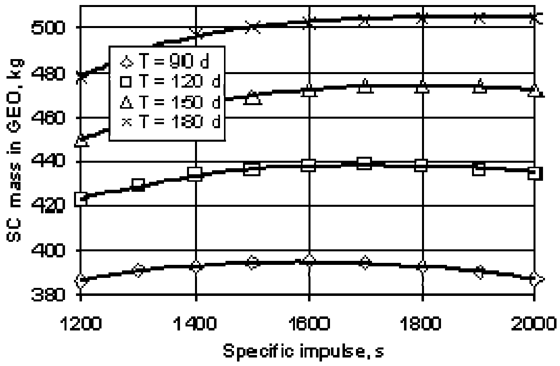


Figure 1. Final SC mass as function of EP specific impulse for different transfer duration (90, 120, 150, 180 days)

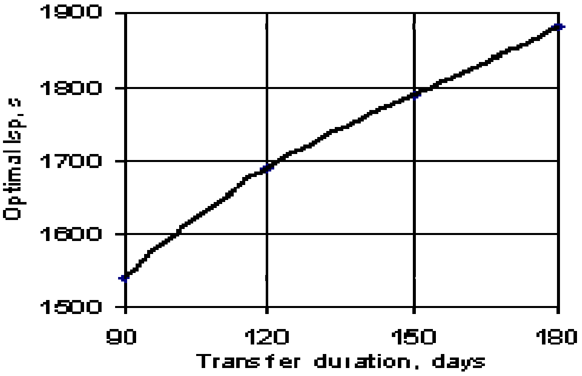


Figure 2. Optimal EP specific impulse as a function of transfer duration

In papers [2, 3] it is considered SC insertion into the GEO using the launcher of middle class. For example, Soyuz-2 (spaceport *"Plesetsk"*, payload 7700 kg) provides insertion of SC having final mass 1400 kg (1700 kg) for 3 months (6 months). It shown that the optimal value of a specific impulse depends on mass delivered into GEO and depends on a value of electrical power of SPT. Minimal transfer duration as a function of SEP specific impulse is shown in Fig. 3 [2]. Case was analyzed, when the input electrical power of a thruster is equal to 10 kW. Three values of a mass injected into a GEO, 1450, 1550 and 1650 kg were considered.

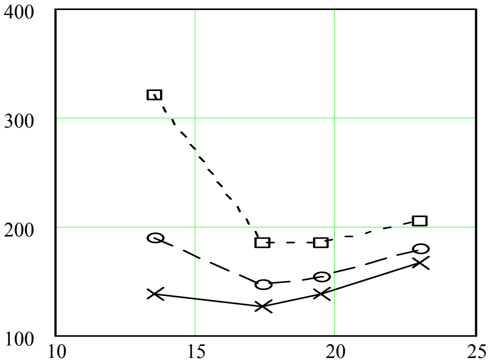


Figure 3. Transfer duration [day] as a function of SEP specific impulse [km/s]

Mass delivered into GEO 1450 kg (the solid line); 1550 kg (the dash line) and 1650 kg (the upper line). Input electric power of SPT 10 kW.

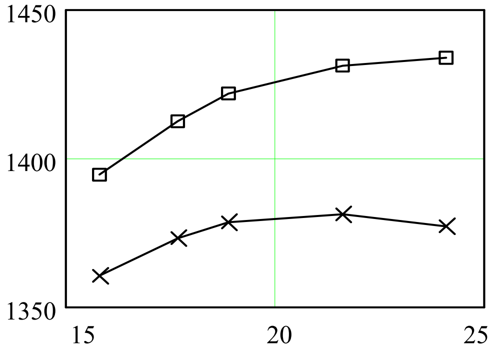


Figure 4. Mass delivered into GEO [kg] as a function of specific impulse of SPT [km/s]

Transfer duration 120 (the lower line) and 150 day (the upper line). Input electric power of SPT 7 kW.

It is visible (Fig. 3) that for all considered cases a minimum of transfer duration corresponds to values of specific impulse 17-19.5 km/s. An optimal specific impulse is being increased with increase of mass delivered into GEO. If mass delivered into GEO is equal to 1450 kg, then optimal specific impulse is equal to 17.4 km/s. If mass delivered into GEO is equal to 1700 kg, then optimal specific impulse is equal to 19.5 km/s. In a considered problem it is not expedient to use large specific impulses (larger 19.5 km/s) and large anode voltage of SPT.

Mass into GEO as a function of specific impulse of SPT is shown at transfer duration 120 and 150 day in Fig. 4 [3] (an input electrical power of SPT 7 kW). The upper line corresponds to transfer duration 150 day. The lower line corresponds to transfer duration 120 day. It is visible, that for a considered case a maximum of SC mass into GEO corresponds to large values of specific impulse (20-24 km/s). Another conclusion of research of information of Fig. 4 an optimum specific impulse is being increased with increase of transfer duration.

The general conclusion of the analysis of the showed results can be such: For transport operation of the insertion into a geostationary orbit the optimum specific impulse of electric propulsion is in a range 15-20 km/s. At small insertion time (60-90 day) and small injected mass it is necessary to use small specific impulses. At increase of an insertion time (increase of the injected mass) the optimum specific impulse grows. It can be more than 20 km/s at insertion times 180-240 day. We shall show below that the conclusions appear a little bit others at use of characteristics of researched thruster SPT-140. We shall try to explain the reasons of this discrepancy

III. The general approach to the analysis of use of electric propulsion for transport operations

Electric propulsion from the point of view of a capability of fulfilment by them of any transport operation (we include in concept of transport operation also operation of maintenance of stability of any orbit of a space vehicle, and operation of stability supply of a space vehicle in the some position on some interval of time) are characterized by following parameters:

- Input electrical power;
- Engine thrust;
- . Specific impulse of the thruster.

Developers of electric propulsion, improving the engines, estimate its quality on a series of the additional parameters. The list of these additional parameters includes: efficiency of the engine, the thrust cost (the relation of input electrical power to engine thrust) and some other parameters.

Obviously, that if developers could change these characteristics in the necessary direction without change of other characteristics it should be made:

- to increase engine thrust;
- to increase specific impulse;
- to increase efficiency of the engine;
- to reduce the cost of engine thrust.

But, unfortunately, for the electric propulsion of any type these characteristics are rigidly connected. Change of one characteristic in the necessary direction often attracts change of other characteristic in an adverse direction. If it is possible, improving the engine to increase its efficiency without deterioration of any other characteristics (for example, without increase in the cost of thrust) it, certainly, should be made. But in practice it almost never occurs: improvement of one characteristic leads to deterioration of other characteristic.

In these conditions the optimal values of characteristics of the thruster should be examined within the limits of research of transport operation for which this engine is supposed to be used. Here, in our opinion, the following three circumstances are important:

- It is necessary to examine a full set of the characteristics describing fulfilment of transport operations, and to choose a characteristic which should be considered as criterion of optimization. At use of electric propulsion this procedure is not trivial.
- For many transport operations expediently use of the combined propulsion systems. Thus the chemical rocket engine (for example, in structure of the chemical upper stage) provides an initial part of transport operation (transfer spacecraft into some intermediate orbit). And then the electric propulsion provides completion of transport operation. In these conditions the optimal performances of the electric propulsion become functions of parameters of a chemical propulsion system.
- It is difficult to assume, that for each transport operation it is possible to develop the optimal thruster. There are a lot of space maneuvers. For each of them the designing of the optimal thruster is not possible. It is necessary to consider the requirement of thruster universality for the some sets of transport operations.

For the majority of transport operations with use of electric propulsion to estimate efficiency of transport operation is possible, analyzing the following two parameters:

- time of fulfilment of transport operation;
- and a mass parameter (for example, mass of the payload, which was delivered into working orbit, at the fixed initial mass of spacecraft).

In our researches we suppose often that an initial mass of spacecraft is known. We suppose that the launcher is known, the characteristics set of a low Earth orbit is known too. Time of fulfilment of transport operation is changed in some range interesting for practice. For each point of this range we determine:

In our researches we believe known initial mass of space vehicle more often. It is equivalent to that research is carried out for the set launcher, for the set characteristics of a base orbit of the ascent and mass of the space vehicle injected into this orbit. Time of fulfilment of transport operation gets over in some range interesting to practice. For each point of this range are searched:

- such scheme of fulfilment of transport operation;
- such chosen characteristics of a chemical propulsion system;
- such characteristics of an electrical rocket propulsion system,

which provide delivery of the maximal mass of a spacecraft (the solution of a transport problem) at fixed time from the investigated time range.

At such statement of a problem it is expedient to analyze and optimize following three characteristics of an electrical rocket propulsion system:

- input electrical power;
- engine thrust;
- specific impulse of the thruster.

In spite of the fact that for each transport operation there is an optimum value of input electrical power, for many transport operations considered now value of input electrical power of electric propulsion is expedient to fix. It is connected with several circumstances:

- Use of electrical power of a spacecraft, which is being injected into a working orbit (of electrical power of a payload of a transported spacecraft) for electrical propulsion during the production of a transport problem, is very expediently. The electrical power of an injected spacecraft always is fixed by those problems for which the spacecraft develops.
- For a solar power installation the developing of such mathematical model which would allow considering the increase of sizes and the moments of inertia of a spacecraft at increase of electric power (from the point of view of dynamic properties of spacecraft) is very difficult. An attempt to use simple models (models, which do not consider a change of dynamic properties of a spacecraft) leads is to unreal greater optimum values of electrical power.
- There is the requirement of universality of electric power installation when this installation can be used for a set of transport operations.

Now the most widespread approach at the analysis of projects of space vehicles with electric propulsion is such approach at which the electrical power used by engines, is fixed or can be varied in some narrow range. Thus the conditions of flight of a space vehicle which influence value of power are being considered. At use of solar power installation such conditions are: distance of a space vehicle from the Sun; eclipse conditions; degradation of solar arrays because of various factors.

IV. Models of analyzed space systems

A. Launcher *"Soyuz"*

The SC mass in low earth orbit (LEO) depends on a spaceport of start-up, launch azimuth and characteristics of LEO. We investigate the project, which at use of a spaceport *"Bykonur"* SC mass in LEO is equal to 8080 kg. The characteristics of LEO: altitude - 200 km; an inclination - 51.6°.

B. Chemical engine installation (type of upper stage *"Fregat"* engine)

Possibility of using of chemical engine installation of upper stage "*Fregat*" is assumed. The main design-ballistic parameters of chemical engine installation are considered following:

* maximum mass of an useful propellant - 5596 kg;
* full mass of an charged propellant (It includes a guarantee reserve of 84 kg and not used remnant of 14 kg) – 5694 kg;
* the mass of a hydrazine used at each engine ignition - 7 kg;
* the mass of a hydrazine used on stabilization of space vehicle - 20 kg;
* the mass of a helium used for a tanks pressurization - 5 kg;
* the mass of a charged chemical propulsion system - 6296 kg;
* the dry mass of a chemical propulsion system - 570 kg;
* terminal mass of chemical engine installation with the adapter and reserve of propellant 668 kg;
* specific thrust - 331 s;
* thrust – 19.613 kN.

C. Model of electric propulsion

1. Structure of the electric propulsion system

Electric propulsion consists of thrusters, converter, control system of propulsion subsystem, as well as xenon tanks with xenon.

The use of four thrusters of a type SPT-140 was supposed. Two from these thrusters were considered as basic thrusters, two others were considered as spare, additional thrusters. It was assumed that two thrusters work simultaneously. A range of admissible values of input electrical power for each thruster is 3.5-3.9 kW.

2. The thruster SPT-140

It is assumed that specific impulse of SPT is constant during transfer trajectory. The value of specific impulse is a function of anode voltage. This function is represented as approximation of experimental data determined by experts of the enterprise Design Bureau "Fakel". Used values of anode voltage and specific impulses are presented in table 1. In the same table we show also the values of engine thrust at input electric power of 3.7 kW.

Table 1

The characteristics of SPT. Input electric power 3.7 kW

Anode voltage	Specific impulse	Thrust	Thrust cost
V	km/s	N	kW/N
250	16.033	0.26048	14.205
300	17.228	0.23543	15.716
350	18.325	0.21388	17.299
450	19.324	0.18128	20.410
550	21.733	0.16268	22.744
600	22.339	0.15863	23.325

3. The mass model of electric propulsion

The mass model of electric propulsion is supposed following:

$$M_{EP} = M_{Xe} + M_{XeContr} + K_{structure.} (M_{TU}+ M_{UXS}+ M_{tank} + M_{contr}).$$

Here

- M_{EP} – the mass of electric propulsion;
- M_{Xe} – the mass of a propellant (xenon);
- $M_{XeContr}$ – the xenon mass for control of space vehicle moving during its insertion into a working orbit ($M_{XeContr} = 0.05\ M_{Xe}$);
- $K_{structure}$ - the parameter considering mass of fastening elements of electric propulsion. We suppose that this parameter equals 1.1;
- M_{TU}– the mass of the thrusters unit. This unit includes 4 thrusters SPT-140 with the control systems of them (40 kg);
- M_{UXS} - mass of the unit of a xenon supply (3 kg);
- M_{tank} – the mass of a xenon tanks (a system of storage and fuel supply) ($M_t = 0.15\ (M_X+ M_{XeContr}$);
- M_{contr} – the mass of the power supply system and of control system. M_{contr} = 5 kg /kW N_{input}. Here N_{input} – the input electric power of the thruster unit.

4. The thrust model of electric propulsion

We suppose that the thrust of each working thruster depends on the input electric power of thruster (N_{input}):

$T = T_{\text{thrasterNom}}\ P_{\text{input}}/\ P_{\text{inputNom}}$.

Here $T_{\text{thrasterNom}}$ – the nominal value of thrust (it has presented in Table 1); P_{inputNom} – the nominal value of input electric power (we suppose it equal 3.7 kW).

We suppose that this relation is correct in a range of electrical powers of 3.5-3.9 kW.

5. Characteristics of the multi-purpose service module

The multi-purpose service module ensures the functioning of the all systems at the spacecraft insertion into a geostationary orbit. Full mass of the multi-purpose service module is equal to 564 kg.

The multi-purpose service module includes the system of electric power supply (300 кг). The main part of this system is the solar electric power installation (205 kg). The solar power installation has electrical power of 10 kW. The area of solar arrays is 56 $м^2$. It uses the silicon photoelectric converters.

The multi-purpose service module includes also: the onboard complex of control system; the onboard service radio complex; the telemeter system; propulsion system of an attitude control system and stabilization; onboard cable grid; system of maintenance of a thermal mode; the adapter with the separation system.

V. The scheme of spacecraft transfer into GEO

For all analyzed projects it is considered, that the launcher injects space vehicle into a low Earth orbit.

Then the chemical engine provides a start of a space vehicle from a low Earth orbit and its transfer into some intermediate orbit. Thus several ignitions of chemical engine are possible. As a rule, three engine ignitions are considered.

The semimajor axis, eccentricity (altitudes of apogee and a perigee), an inclination, a perigee argument and as well as a longitude of an ascending node of an intermediate orbit are the choosing parameters during optimization of the transport mission.

After the spacecraft insertion into an intermediate orbit a chemical propulsion installation is separated from spacecraft. Then the solar arrays of satellite are deployed, and the electric propulsion is activated.

After separation of chemical propulsion installation the electric propulsion provides a over flight of spacecraft into a geostationary orbit. The level of acceleration, which provides the electric propulsion, is rather small; therefore duration of the active segment of trajectory is rather great. A trajectory of spacecraft motion is a multirevolutional spiral with slowly changing osculating elements. In many respects, the trajectory of space vehicle with electric propulsion is determined by values of elements of an intermediate orbit and, in particular, its eccentricity.

Control of spacecraft moving on active segments of transfer trajectory is optimized. Pontrjagin principle of maximum is used as a base method. Difficulties of the solution of a two boundary value problem, to which the maximum principle reduces a problem of optimization of the transfer trajectory, were overcome with use: - of a method of averaging, - of a method of continuation on parameter, - of solutions of some modeling problem. The description of the methodical approach can be found in publications [9-12].

Let's present the main results of the conducted calculation research at the analysis of examined space system.

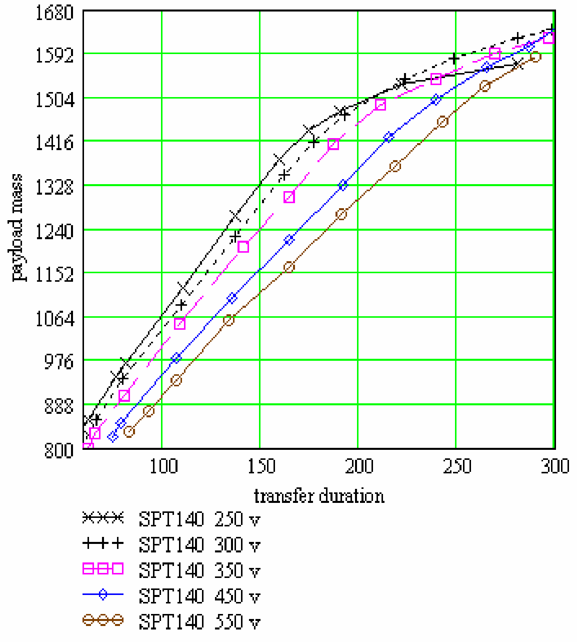
VI. Main results of numerical analysis of SC insertion into GEO

In Fig. 5 the mass of spacecraft payload, which is being inserted into GEO, as a function of transfer duration is shown. In Fig. 6 the spacecraft mass in the moment of insertion into GEO is shown. Various lines correspond to various anode voltages. The most left line corresponds to voltage 250 v. Lines, which lay more to the right correspond to greater anode voltages (300 v, 350 v, 450 v, 550 v). The specific impulses for these voltages are accordingly equal to 16033 m/s (for 250 v), 17228 m/s, 18325 m/s, 20225 m/s, 21733 m/s.

The most important conclusion from the analysis of the shown functions is a following conclusion. For very large range of insertion time the optimum value of specific impulse is equal to the minimal impulse, which corresponds to the minimal anode voltage 250 V. From the point of view of the maximal mass of a payload this range is limited from above by an insertion time of 213.3 day. Thus, the optimum specific impulse is equal to minimal examined impulse (16033 m/s) in a range of insertion time [55 day (minimal transfer duration) … 213.3 day]. The optimal specific impulse is equal to 17228 m/s in a range of insertion time [213.3 day-300 day]. This specific impulse corresponds to anode voltage 300 V.

And only, if the insertion time more than 300 day, the using of higher specific impulses is expedient

Such conclusion contradicts many results of the analysis conducted earlier (in particular, the results, which we have shown above in Fig. 2 and Fig. 4). We shall try to explain this fact below.



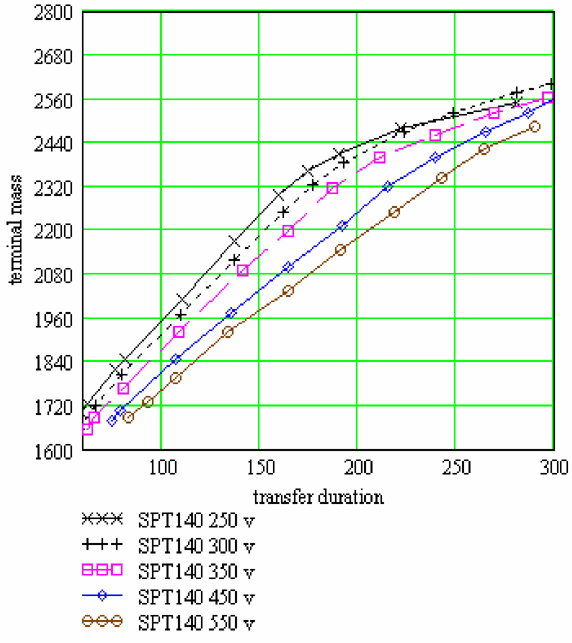


Figure 5. Payload mass [kg] as a function of transfer duration [days] for SPT with different specific impulses

Figure 6. SC mass into GEO [kg] as a function of transfer duration [days] for SPT with different specific impulses

Comparing functions of Fig. 5 and Fig. 6, it is interesting to note, that from the point of view of maximization of final mass of a spacecraft (mass of a spacecraft at the moment of the insert into a geostationary orbit) the minimal specific impulse (16033 m/s) is optimum in even more broad range of insertion time [55 day-243.7 day]. At insertion time of greater 243.7 day it is expedient to increase specific impulse (to increase anode voltage up to 300 V). Change of border of expedient transition from minimal specific impulse to greater specific impulse is explained so: with increase of an insertion time the optimum value of characteristic velocity of a space vehicle with the electric propulsion is being increased. The optimal value of xenon mass is increased too. This fact causes the increasing of mass of a xenon tanks and all structure of an electric propulsion installation. The mass of electric propulsion is included in mass of a spacecraft at the moment of the SC insert into a geostationary orbit. We shall explain this effect more accurately. When an insertion time is equal to 213.3 day then the maximal mass of a payload is equal to 1519.2 kg at use of both anode voltages (250 V and 300 V). But the mass of a spacecraft at the moment of the SC insert into a geostationary orbit is various. It is equal to 2461.7 kg at the minimal anode voltage. At anode voltage 300 V this mass is less - 2444.5 kg because the demanded mass of xenon is decreased for SC transfer. The dry mass of electric propulsion is decreased too. Due to this reason a spacecraft mass at the moment of the insert into a geostationary orbit for examined anode voltages are equal at a greater insertion time - 243.7 day.

The optimal characteristic velocity of a spacecraft with the electric propulsion as a function of an insertion time is shown in a Fig. 7. Various lines of this figure correspond to various values of specific impulse. Monotonous increase of examined function is visible. This function is practically linear at insertion time a little bit greater than minimal time. At increase of specific impulse (for the fixed insertion time) optimal value of characteristic velocity is being decreased.

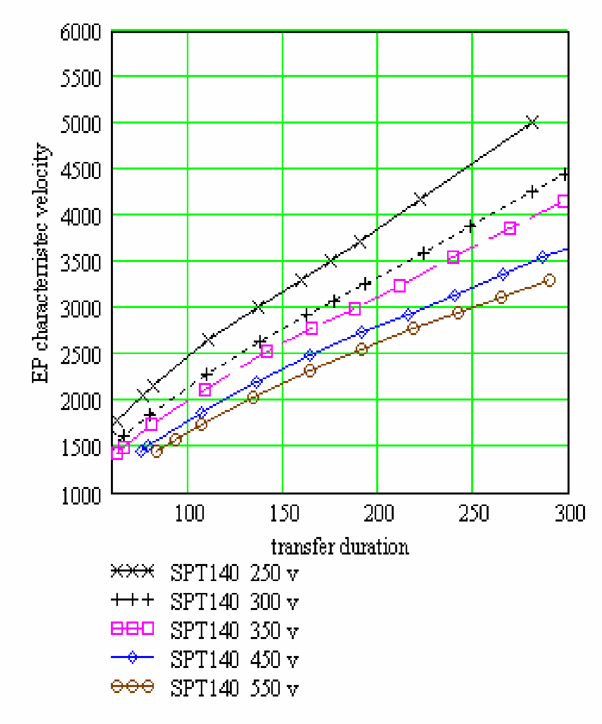


Figure 7. EP characteristic velocity [m/s] as a function of transfer duration[days] for SPT with different specific impulses

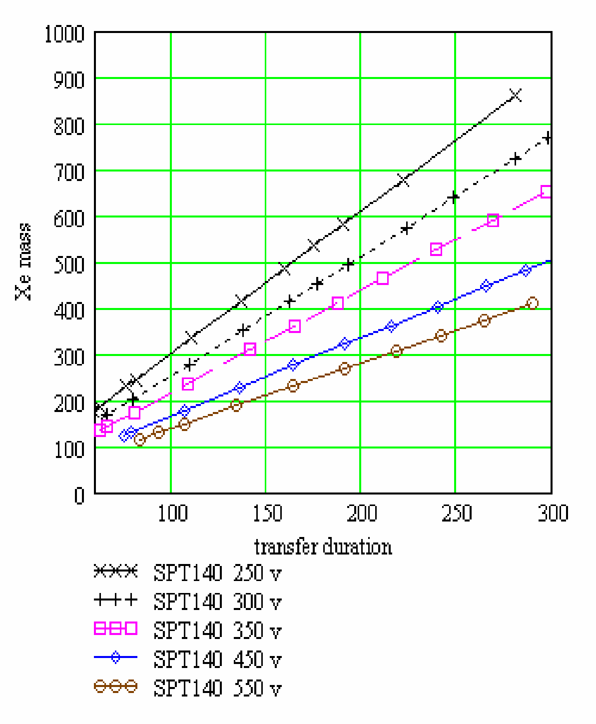
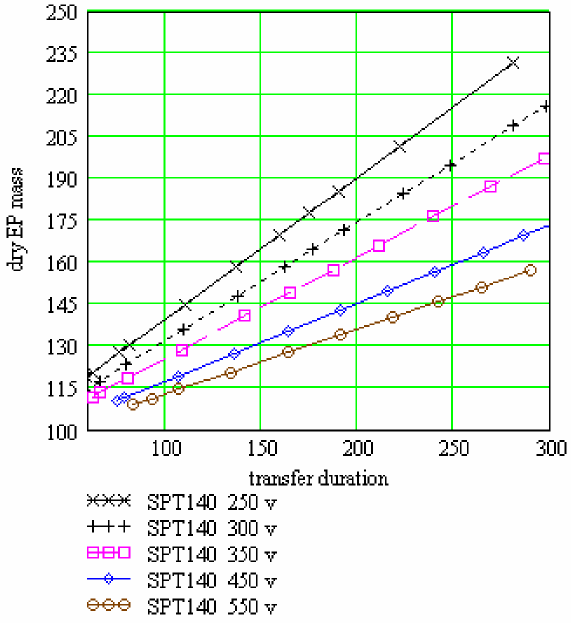


Figure 8. Optimal XE mass [kg] as a function of transfer duration[days] for SPT with different specific impulses

The optimal value of a xenon mass as a function of an insertion time is shown in a Fig. 8. Various lines of this figure correspond to various values of specific impulse. Monotonous practically linear increase of considered function is visible. At increase of specific impulse (at the fixed insertion time) the optimal value of xenon mass is being decreased.

The dry mass (without a xenon mass) of an electric propulsion as a function of an insertion time is shown in a Fig. 9. Mass of the charged electric propulsion installation as a function of an insertion time is shown in a Fig. 10. Various lines of these figures correspond to various values of specific impulse. These functions are practically linear in all examined range of insertion time. Monotonous increase of examined functions is visible. At increase of specific impulse (for the fixed insertion time) the optimal mass of an electric propulsion installation is being decreased.



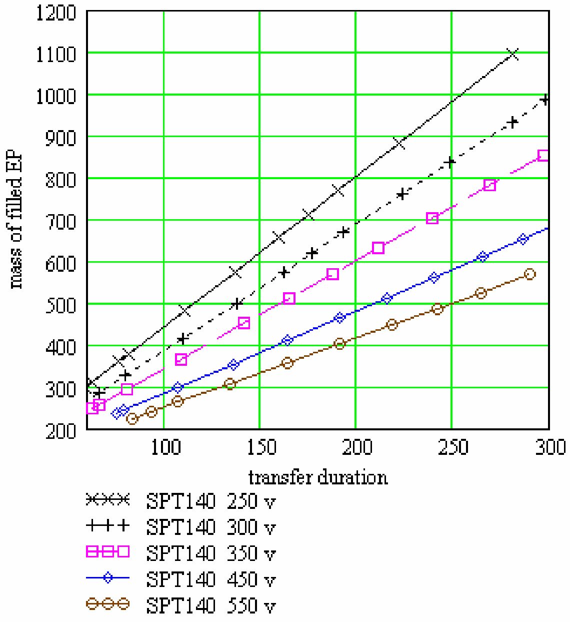


Figure 9. The dry mass of EP [kg] as a function of transfer duration [days] for SPT with different specific impulses

Figure 10. Optimal mass of filled electric propulsion [kg] as a function of transfer duration[days] for SPT with different specific impulses

The optimal value of characteristic velocity of a chemical propulsion installation as a function of an insertion time is presented in a Fig. 11. The optimum propellant mass of a chemical propulsion installation as a function of an insertion time is presented in a Fig. 12. Various lines of these figures correspond to various values of specific impulse. Both optimal characteristic velocity and optimal charging are monotonously decreasing functions of an insertion time. At the fixed value of an insertion time the increase of specific impulse of electric propulsion leads to an increasing of optimal charging of a chemical propulsion installation. The minimal insertion time is being determined by maximum of a admissible charging of a chemical propulsion installation. At increase of specific impulse of electric propulsion this minimal time is being increased. For the examined project the minimal insertion time is equal 55 day at the minimal specific impulse of electric propulsion.

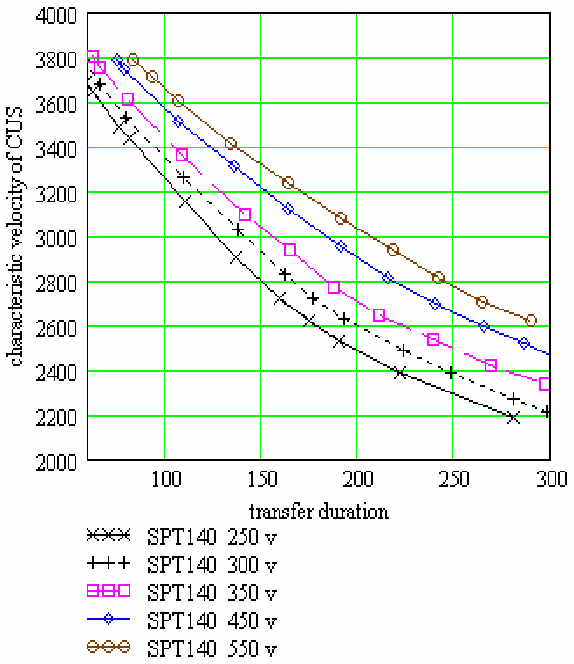


Figure 11. The characteristic velocity [m/s] of chemical engine as a function of transfer duration [days] for SPT with different specific impulses

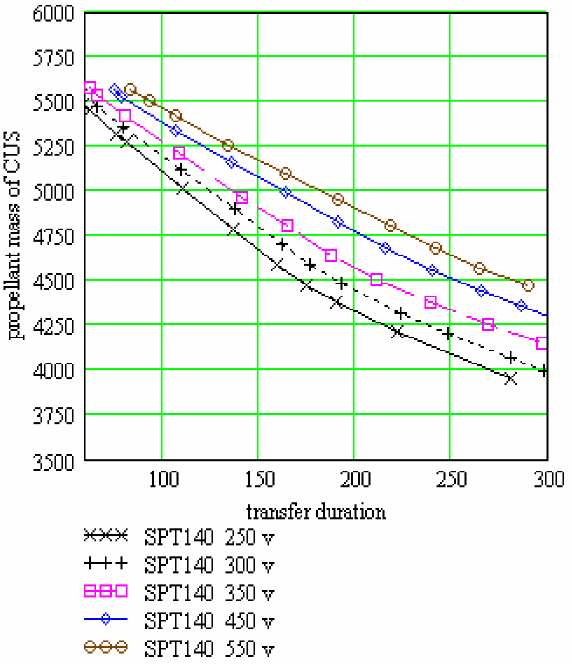


Figure 12. Optimal propellant mass of chemical engine [kg] as a function of transfer duration [days] for SPT with different specific impulses

VII. The analysis of influence of specific impulse on characteristics of the examined project of SC insertion into GEO

A. Optimal specific impulse of SPT-140 at SC insertion into GEO

Payload mass as a function of specific impulse of SPT is shown in Fig. 13. The upper line corresponds to transfer duration 270 days. The lines corresponding to smaller insertion times are disposed below: 240, 210, 180, 150, 120, and 90 days. The functions corresponding to insertion time equal and smaller 210 day, have a maximum in the left border of a range of specific impulses. And only when insertion time is 240 and 270 day the maximum is disposed in an internal point of a range of an independent variable (of specific impulse).

It is visible, that for a considered case a maximum of payload mass corresponds to small values of specific impulse (16-17.5 km/s). Great values of specific impulse are not optimum even for very greater durations of the insertion.

Payload mass as a function of anode voltage of SPT is shown in Fig. 14. It is visible, that for a considered case a maximum of payload mass corresponds to small values of anode voltage (250-300 V).

Such conclusion was for us much unexpected. The analysis shows, that the optimal specific impulse is minimal of examined impulses (16033 m/s, anode voltage 250 volt) at large range of insertion time (from minimal insertion duration – 55 days up to 213.3 day). That at large insertion time (150 day and more) optimal value of specific impulse is equal to the minimal specific impulse (the using of the minimal anode voltage is expedient) was unexpected fact. This fact was not agreed to results of the researches conducted by us earlier).

At increase of an insertion time the optimal specific impulse is increasing. It is the natural and clear fact. But unexpected fact is the use of the thruster with second-largest value of specific impulse (17228 m\s, anode voltage

300 volt) is more expedient than use of the minimal specific impulse of 16033 m/s only if insertion time is more 213 day (very large insertion time for commercial projects).

We have found an explanation of these unexpected conclusions for examined characteristics of SPT-140.

B. The analysis of the thrust cost and the thrust efficiency of SPT-140

This unexpected fact is explained so: the thrust cost essentially increases at increasing of specific impulse of the examined thruster. At the minimal specific impulse (anode voltage 250 volt) the thrust cost (the relation of input electric power to the thrust magnitude) is equal to 13.4 kW/N. The thruster efficiency is rather high 0.535. At anode voltage of 550 volt the thrust cost is equal to 21.5 kW/N (efficiency of the thruster is 0.453 only). The specific impulse increasing which leads to such reduction of efficiency and to increase of the thrust cost is inexpedient. We shall note, that if developers of the thruster will manage to increase the specific impulse without such essential falling of efficiency (thus that the cost of thrust considerably would not increase) optimal values of specific impulse will be increased at examined duration of a spacecraft insertion into a working orbit.

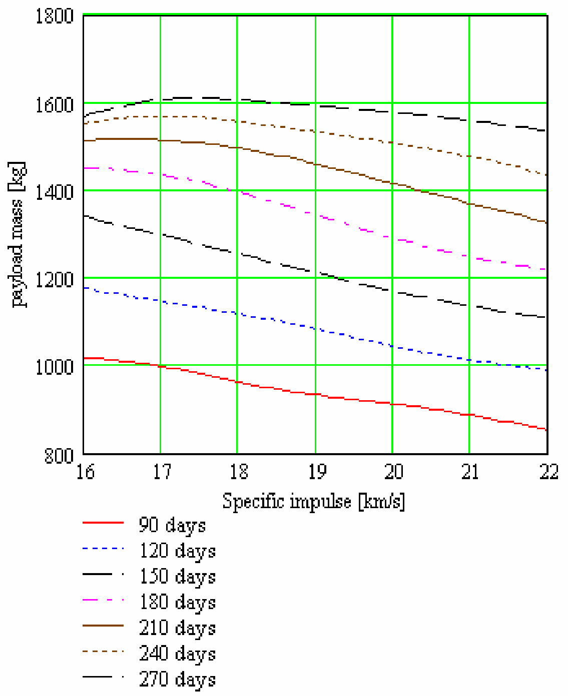


Figure 13. The payload mass [kg] as a function of specific impulse [km/s] for SPT with different transfer duration

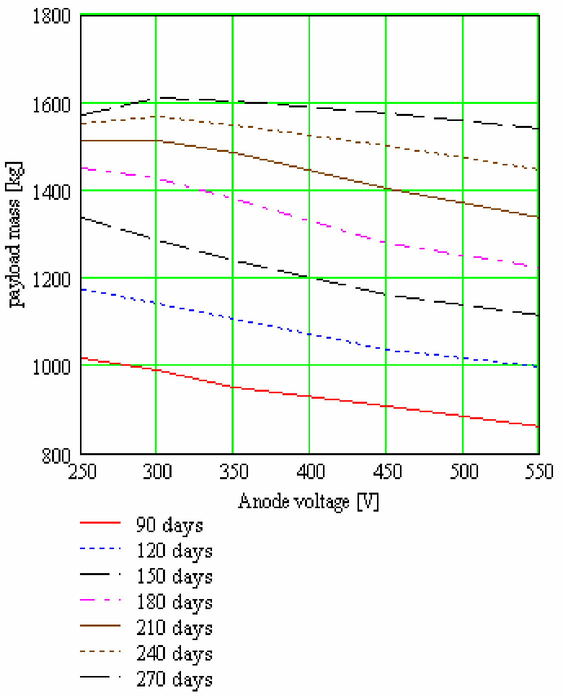


Figure 14. The payload mass [kg] as a function of anode voltage [V] for SPT with different transfer duration

An efficiency of the examined thruster as a function of anode voltage and a function of specific impulse are shown in Fig. 15 and Fig. 16. It is visible, that in a range of anode voltage from 250 volt up to 600 volt the efficiency of the thruster is essentially being decreased (from 56.4 percents down to 47.7 percents).

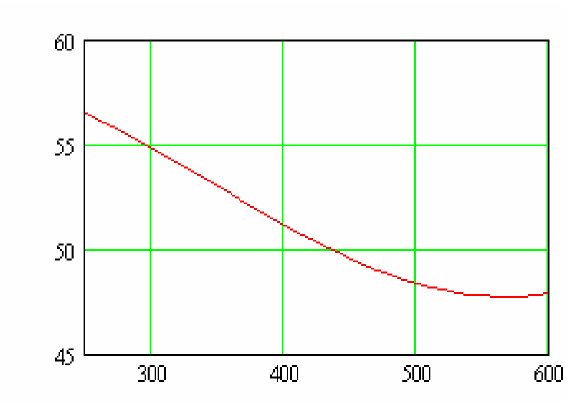


Figure 15. Efficiency of the thruster [percents] as a function of anode voltage [V]

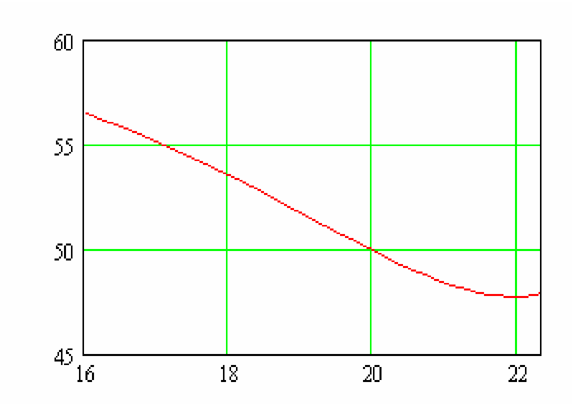


Figure 16. Efficiency of the thruster [percents] as a function of specific impulse [km/s]

This circumstance leads to essential increasing of the thrust cost of this thruster. It is illustrated by Figs. 17 and 18. The cost of thrust is a function of anode voltage and is a function of specific impulse are presented in these figures. It is visible, that the cost of thrust increases from magnitude 14.2 kW/N (for the minimal anode voltage 250 volt) up to 23.3 kW/N (for the maximal anode voltage 600 volt).

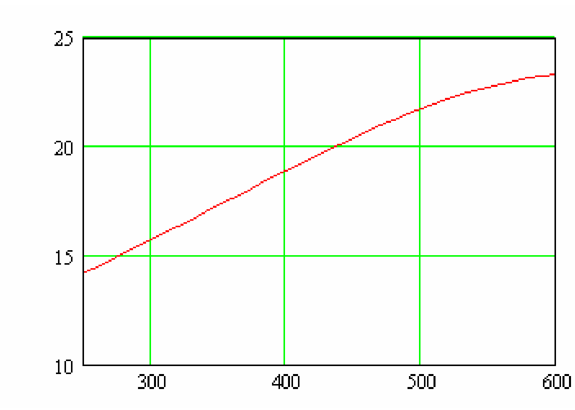


Figure 17. Thrust cost of the thruster [kW/N] as a function of anode voltage [V]

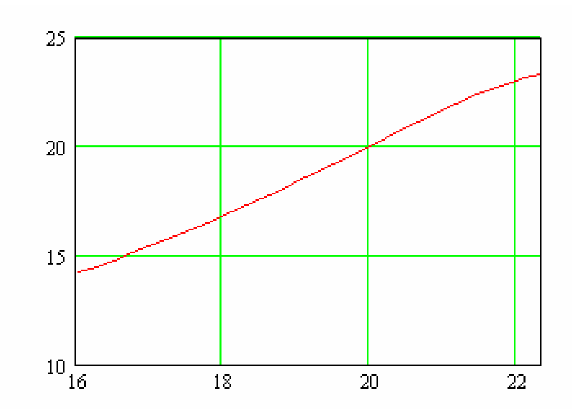


Figure 18. Thrust cost of the thruster [kW/N] as a function of specific impulse [km/s]

In Fig. 19 and Fig 20 we have presented the efficiency (Fig. 19) and the thrust cost (Fig. 20) as the functions of specific impulse for the thruster SPT-140, considering in this paper as well as and for the thruster which was earlier researched in the paper [1].

A principal difference of the examined functions is evident. With increase of specific impulse the efficiency grows in one case. It is natural enough and a good opportunity. In other case, which we analyzed, the efficiency is dropping practically in all examined range of anode voltage. It is the main reason that the minimal anode voltage appears optimum practically for all range of insertion time interesting for a practice. Such change of efficiency leads to that speed of increase of the thrust cost with increase of specific impulse more than twice exceeded this speed in typical version. For example, in the project researched in paper [1] a range of this speed is 0.48-0.59 (this speed is dimensionless). In our case the growth velocity of the thrust cost reaches magnitude 1.695.

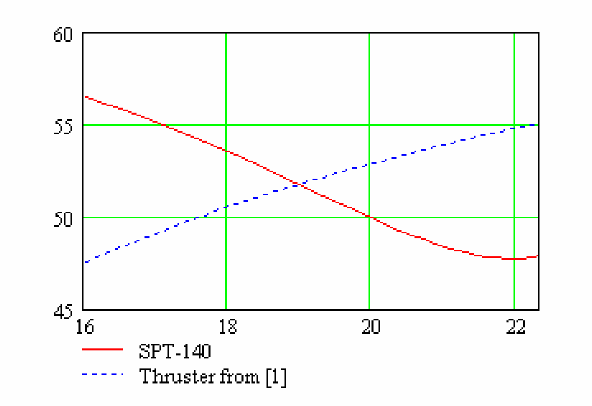


Figure 19. Efficiency of the thruster [percents] as a function of specific impulse [km/s]

The solid line corresponds the thruster SPT-140, considering in this paper. The dashed line corresponds to the thruster which was earlier researched in paper [1].

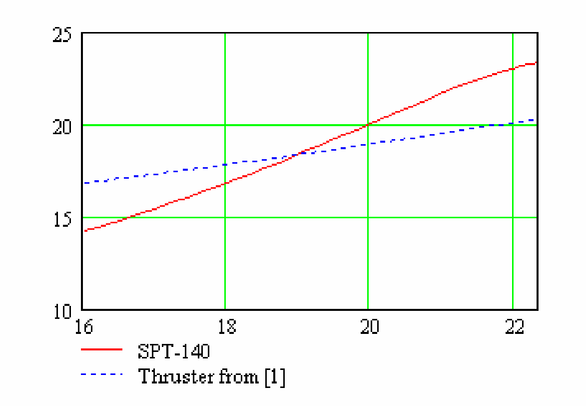


Figure 20. Thrust cost of the thruster [kW/N] as a function of specific impulse [km/s]

The solid line corresponds the thruster SPT-140, considering in this paper. The dashed line corresponds to the thruster which was earlier researched in [1].

The comparative analysis of growth velocity of the thrust cost of two thrusters (the examining thruster SPT-140 and the thruster examined in paper [1]) can be executed by means of a Fig. 21.

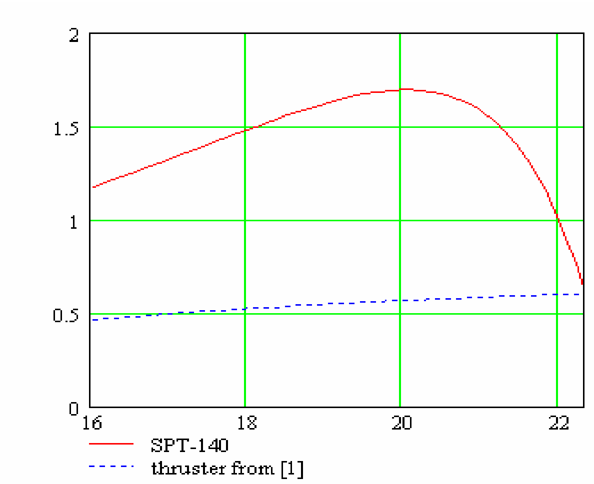


Figure 21. Velocity of change of thrust cost as a function of specific impulse [km/s]

The solid line corresponds to the thruster SPT-140, considering in this paper. The dashed line corresponds to the thruster which was earlier researched in the paper [1].

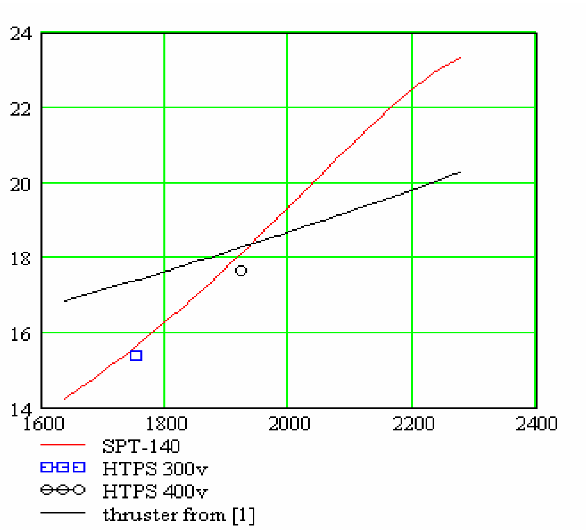


Figure 22. Thrust cost of the thruster [kW/N] as a function of specific impulse [km/s]

The solid line corresponds to the thruster SPT-140, considering in this paper. The dashed line corresponds to the thruster which was earlier researched in the paper. Two points corresponds to HTPS with anode voltages 300 V and 400 V.

The lower line of figure corresponds to the thruster examined in [1]. The upper line corresponds to the thruster examined in the present paper. It is visible that only for the maximum of specific impulses the examined speeds are close. In this area the efficiency of the examined SPT-140 ceases to decrease.

C. The using of Hall Thruster Propulsion System and XIPS-25 for SC insertion into GEO

We have analyzed two more types of the thruster for examined transport operation:

- a possibility of using Hall Thruster Propulsion System (HTPS), which are certificated by company Aerojet-Redmond Operation, [13, 14]
- a possibility of using of the ionic engines of type XIPS-25, which are developed Hughes Electron Dynamics, today known as Boeing Electron Dynamic Devices. This thruster is used for space platform 702. [15-18]

The values of the thrust cost of Hall Thruster Propulsion System (HTPS) for two anode voltages (300 and 400 volt) are shown in a Fig. 22. In the same figure the functions of the cost of thrust for earlier examined thrusters are shown. It is visible, that the thrust cost of HTPS is close enough to the thrust cost of SPT-140, but this cost is a little less than the thrust cost of SPT-140. At anode voltage 300 V the thrust cost of SPT-140 is 15.7 kW/N, the thrust cost of HTPS is 15.4 kW/N. At anode voltage 400 V the thrust cost of SPT-140 is 18.9 kW/N, the thrust cost of HTPS is 17.6 kW/N. For analyzed points these costs below the thrust cost of the thruster, researched in [1].

Research of possibility of using of HTPS with anode voltages 300 and 400 volt has shown practically absolute identity of results with results of use of SPT-140 of development Design Bureau "Fakel". In Fig.23 the payload mass as a function of an insertion time for SPT140 with anode voltage of 300 volt and for HTPS with anode voltages 300 and 400 volt are shown. Practically full coincidence of functions is visible. At a small duration of SC insertion into a GEO the optimal value of specific impulse is enough small. It is visible, that for HTPS the using of anode voltage 300 V is more preferable, than voltage 400 V if insertion time less 225 day.

In a Fig. 24 except for the information, which we has shown in a Fig. 5 (payload mass for different specific impulses of SPT-140), we in addition show the payload mass if the ionic thruster of type XIPS-25 is used. Characteristics of this thruster we supposed such: a nominal input electric power is 3.9 kW; the specific impulse - 32 km/s; the thrust - 0.195 N. We do not know precisely enough the mass characteristics of EP with the ionic thruster of type XIPS-25. Therefore the shown function can be not absolutely correct. To not make an error in mass model of a vehicle at use of the ionic thruster, we decided to show the estimation of mass of a space vehicle at the moment of the SC ascent into a geostationary orbit (Fig. 25).

From Fig. 25 it is visible, that if an insertion time is more 225 day the application of this thruster can be more preferably, than the application of stationary plasma thruster, which was been examined before. It is connected with low cost of thrust of this engine (20 kW/N) as well as with high efficiency of this thruster (0.8). We shall note that for anode voltage 476 volt the cost of thrust of the examined SPT-140 is equal to 20 kW/N. But its specific impulse is equal to 20.7 km/s only.

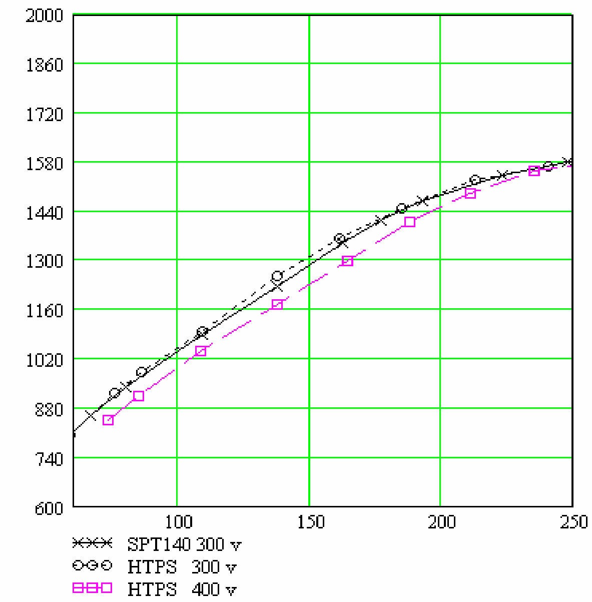


Figure 23. Payload mass [kg] as a function of transfer duration [days] for SPT-140 with anode voltage 300 V, and for HTPS with anode voltages 300 and 400 V

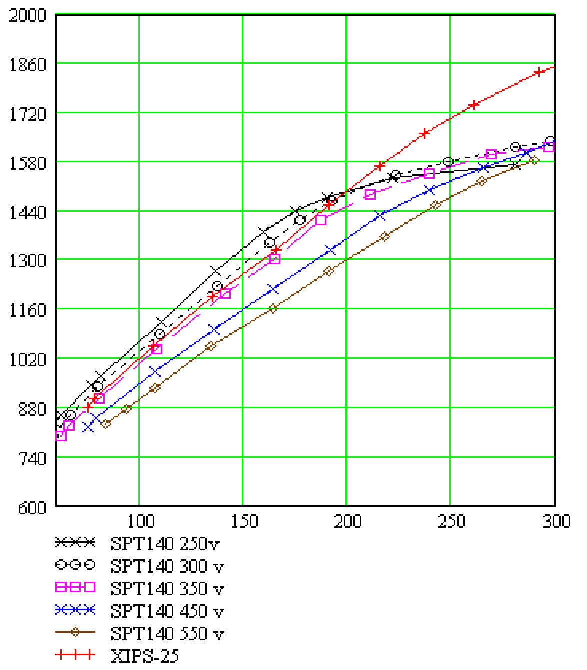


Figure 24. Payload mass [kg] as a function of transfer duration [days] for SPT-140 with different specific impulses and for XIPS-25

D. The analysis of rational change of thrust efficiency at increasing of specific impulse

We researched a question on it is necessary to increase efficiency of examined SPT-140 that the increase of specific impulse was expedient by what value. The question has been considered as follows.

The optimum anode voltage is equal to the minimal voltage of 250 volt for available characteristics SPT-140 if an insertion time into GEO is equal to 105 day. Thus the maximal mass of a payload is equal to 1093.9 kg. Use of anode voltage of 300 volt at a same insertion time 105 day reduces a payload mass of a spacecraft injected into a GEO (down to 1066.4 kg). The problem is formulated so: how it is necessary to increase efficiency of the thruster at anode voltage of 300 volt that the payload mass was not being decreased but was equal to the same 1093.9 kg. The result of the analysis was the following. The payload mass will not decrease at use of anode voltage of 300 volt, if the thruster efficiency (for anode voltage 300 volt) will be increased on almost five percent. It means that value of thrust efficiency 54.81 % is necessary to increase up to value of 57.40 % (about 2.5 %).

The payload mass for several insertion time (90, 105 and 120 days) and at specific impulse of the thruster of 17.228 km/s (corresponds to anode voltage 300 V) as a function of the thruster efficiency is shown in Fig. 26. It is visible, that these functions are monotonously increasing functions. At increase of an efficiency of SPT-140 on one percent the payload mass is increased on 9-12 kg. It is a little less one percent of a payload mass.

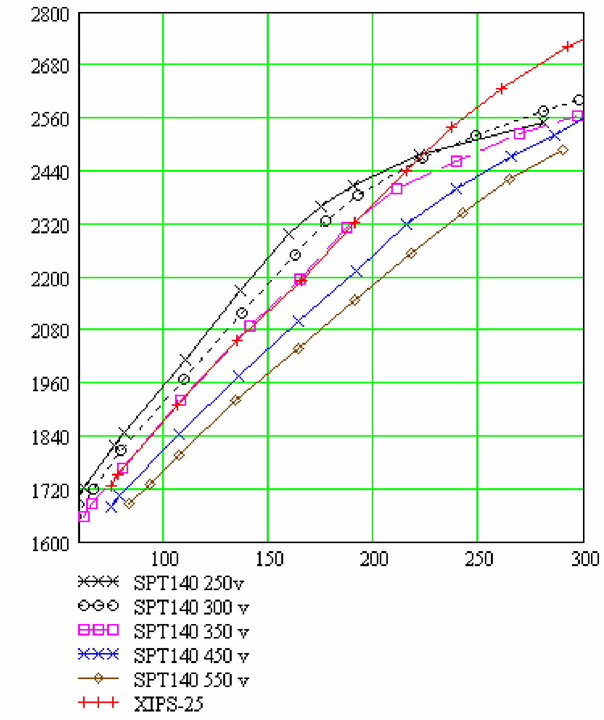


Figure 25. SC mass into GEO [kg] as a function of transfer duration [days] for SPT-140 with different specific impulses and for XIPS-25

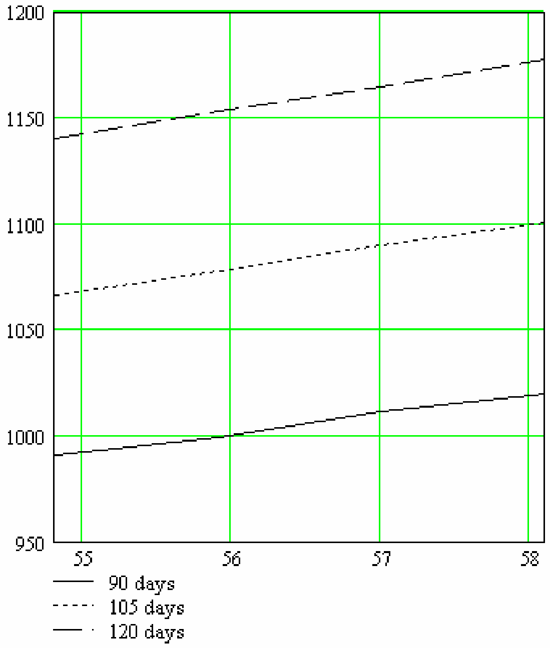


Figure 26. Payload mass [kg] as a function of efficiency [%] for SPT-140 with specific impulses 17.228 km/s for different transfer duration

The lower line corresponds to duration 90 days. The upper line - 120 days

If transfer duration is equal to 105 day at efficiency 57.40 % the payload mass is equal to 1093.9 kg (the payload mass injected into a GEO at anode voltage 250 V of SPT-140).

If transfer duration is equal to 90 day at efficiency 57.67 % the payload mass is equal to 1017.0 kg (the payload mass injected into a GEO at anode voltage 250 V of SPT-140). The anode voltage 300 V will be optimum at an insertion time of 90 day, if it will be possible to increase efficiency of the SPT-140 on 2.86 % (from 54.81 % up to 57.67 %).

That transition to higher specific impulse was expedient it is necessary to satisfy the some condition of character of change (of growth) of thruster efficiency. It is possible to confirm, that if an insertion time into GEO is equal to 90 day (105 day) the increase of specific impulse on 1 km/s should lead to increasing of efficiency on 0.8 % (0.79 %). While for analyzed SPT-140 the increase of specific impulse at 1 km/s leads to decreasing of efficiency on 1.36 %. Due to this reason a minimal specific impulse is optimum.

VIII. Conclusion

1. For a problem of the SC insertion into a geostationary orbit the using of the SPT-140 with low specific impulse, which corresponds to small anode voltage (250-300 V), is expedient.

2. The using SPT-140, which are being developed by Design Bureau “Fakel”, with the high specific impulse (corresponding to anode voltage 350-550 V), is expedient only if insertion time of SC into GEO is very great (≈300 day).
3. The use of SPT-140 with high specific impulses at the SC insertion into a geostationary orbit will become expedient if the increase of specific impulse will be accompanied by small enough increase of the thrust cost. It is necessary to satisfy the some condition of character of change of thruster efficiency that transition to higher specific impulse was expedient. For example, if an insertion time into GEO is equal to 90 day (105 day) the increase of specific impulse on 1 km/s should lead to increasing of efficiency on 0.8 % (0.79 %).
4. For the examined transport problem (the SC insertion into a geostationary orbit) results of the analysis of SPT-140 and HTPS practically coincide. It means, that these thrusters are expedient to use with small values of specific impulse.
5. At great insertion time into a geostationary orbit the use of ionic thruster XIPS-25 is expedient. It is explained by the following reasons:
    - at high specific impulse (32 km/s) this thruster has very high efficiency (80 %). While SPT-140 efficiency is less than 50 % at specific impulse greater than 20 km/s;
    - the thrust cost of XIPS-25 of 20 kW/N. It is less the than thrust cost of SPT-140 for high specific impulses.

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