POSSIBLE STRUCTURAL-DESIGN SCHEMES OF SPACECRAFT
WITH NUCLEAR-ELECTRIC PROPULSION SYSTEMS


Abstract

This report includes description of the conception of structural-design scheme of SC with nuclear-electric propulsion system for power-intensive flights in near-Earth space and flights to the planets and minor bodies of Solar system. The advantage and possibility of Transport-Power Modules with of using promising design solutions are shown. The design version of spacecraft is presented.

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The space research effectiveness depends much on structure and technical perfection of SC onboard systems and is connected with various consumption of energy including delta-V for SC injection into the given areas of space, maneuvering and providing onboard equipment operation.

The increase of SC special equipment complex composition and its reliability by means of the most critical elements redundancy, the increase of onboard systems power consumption, expanding the SC maneuverability will result in SC mass increase. This circumstance, in its turn, will require increase of energy consumption for SC injection and attainment of necessary velocity increment.

In this connection, the necessary increase of economic and target-oriented effectiveness of the planned space projects can be provided by development of the new technical solutions in particular the power-propulsion blocks based on powerful EJPs (Electric Jet Propulsions) and power plants and creation on their base the autonomous or included in SC composition electric-jet Transport-Power Modules (TPM).

The possible flight schemes (for example, missions to distant planets with use of big-thrust chemical propulsion) can be divided into two groups:

- trajectories of direct flights,
- trajectories with gravity assist maneuvers.

Use of the trajectories with gravitational maneuvers allows to reduce required delta-V with some increase of flight time. However, among missions to distant planets only trajectories like “Grand Tour” can provide essential decrease of delta-V with acceptable flight time. The main disadvantage of these trajectories is low frequency of their recurrence.

The rest methods of “pumping up” the orbital energy by fly-by smaller planets than Jupiter or Saturn (such as Earth, Venus or Mars), even multiply, will lead to significant increase of mission duration.

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Taking the aforesaid into account, we considered only the direct trajectories to distant planets (including accelerated-type trajectories) for missions, based on use of chemical propulsion.

The flight duration to distant planets for energy optimal trajectories is: 3500-7000 days to Uranus, about 14000-15000 days to Neptune and 14000-17000 days to Pluto. It is not acceptable.

The maximal characteristic velocity (about 16-17 km/s) can be achieved by "Proton" or "Atlas-Centaur" type launcher using multistage upper stages for payload mass about 150-200 kg. For accelerated-type direct trajectories (launch e.g. in 2000) SC can reach Uranus for 3-4 years, Neptune for 5-6 years and Pluto for ≈8 years.

The new step forward can be done by using of low thrust propulsion. Their main features are:

⇒ high exhaust velocity of Working Medium (WM). The specific impulse of EJP can reach $10^3...10^4$ s; it provides essential decreasing of mass consumption during thrusting;

⇒ large duration of active arcs of trajectory, when propulsion system is operating; it allows significantly increase maneuver velocity increments with acceptable spending of WM mass. It allows to plan the unique scientific missions, for examples: comets accompanying, fly-by several asteroids, sample return missions, flights to giant planets and their moons and etc.

The available payload mass depends of choice both the launcher and the cruise thruster characteristics. In particular, very important parameter is power (in a jet stream) of electric-jet propulsion (EJP).

The sufficient for many asteroid and comet missions level of EJP power is relatively low - about 10...20 kW (electric power 15...30 kW). Nevertheless for missions to the distant planets and for injection SC into geostationary orbit it is expedient to increase power of the power plant up to 60...100 kW for relatively short time (up to a year) on condition that mass of power plant will not increase so much.

The most important for SC face characteristics for near-Earth transport operations and missions to the distant planets, comets and asteroids in orbital mechanics point of view are as follows:

- flight time with turned-on low thrust (active trajectory arcs),
- energy consumption,
- initial velocity increment provided by chemical upper stage,
- initial mass of SC,
- payload mass near the target body,
- propellant (or WM) mass, mass of the fuel tanks and auxiliary systems,
- electric power of the power plant.

One of the main systems which affect radically appearance of Transport and Power Module (TPM) and spacecraft as a whole is a power supply system (PSS). It is known that Nuclear Power Systems (NPS) have a number of advantages in comparison with conventional spacecraft-borne power systems. For example, NPS lifetime and mass depend weakly upon fuel loading and power level; they are prone less to effects of space adverse factors, have better mass and dimension characteristics at power level of several tens kilowatt and more, they can operate in the forced modes at electrical power which is 2...2.5 times more than nominal power by weak NPS mass dependence upon forcing level, have low level of mechanical disturbances connected with NPS operation and so on.
The powerful energy source on the TPM board expands its operational capacities. The energy source is remaining in SC structure after finishing of transport operation and can provide the special and service equipment of SC (including power-intensive equipment e.g. during technological tasks solution) with electric energy and provide attitude control and stabilization of SC, orbital corrections and maneuvering. In this case the high effectiveness of TPM/SC cooperative operation can be achieved by development of common structural-design scheme with part of common service and supply systems such as power supply system, thermal-control system, motion control system, etc.

During determination of expedients of TPM using it is necessary to take into account in addition to high energy possibilities also a number of specific features connecting with using of EJP and powerful energy plants.

Among this features is low level thrust that results in longer duration of propulsion plant operation in comparison with big-thrust chemical propulsion. It is necessary to take into consideration that required time of cruise propulsion plant operation (therefore total flight time) will be determined also by characteristic velocity (delta-V) for compensation of gravitational and aerodynamic losses which are greater if launching orbit is lower. It is possible to decrease these losses and duration of aggressive environment influence to SC by means of the both thrust increase (by EJP power increase, including forcing of Nuclear Power System (NPS) output power) and increase of launching orbit altitude.

It is expedient to combine low thrust with traditional big thrust propulsion which allows to accelerate SC from near Earth orbit to hyperbolic escape trajectory. Optimal choice of hyperbolic velocity gives advantage in payload mass near the target of flight. For instance, in this case for existing launchers (and for prospective projects of launchers for nearest future) and low-thrust cruise propulsion system the payload mass delivered to t to minor bodies of Solar system can be from 700 to 2000 kg (except TPM mass) with flight duration from 2 to 6 years.

So it is expedient to use Top Stage (TS) with liquid-propellant engine in structure of launcher head for effective modification of initial orbit parameters for TPM with SC and optimal payload mass. The vehicle for inter orbit and interplanetary transportation will be a combined transportation system: top stage (upper stage) with liquid-propellant high-thrust engine and TPM with low-thrust engine.

An effective direction in space technology development is the updating of the spacecraft, constructed on the modular principle. The spacecraft of such type are composed of standard and unified units and systems, admitting various structural modifications and a possibility of step-by-step modernization and the introduction of new technologies in the development of separate modules of the spacecraft.

Taking into account high energy consumption of the assumed missions, the prospective spacecraft should have a minimum mass because of use of promising materials and fiber-optical information cable circuits. In addition, long terms of active functioning of such vehicles demand the use of a radiation-resistant element base with long service life.

The SC should have a high degree of autonomy in the circumstances of long term operation in the extreme environment. It should have the capabilities of:

- providing reliable operation of the onboard equipment in outer space during the entire mission,
- conducting investigations of the celestial bodies from fly-by trajectories,
providing delivery of a payload to the target of mission,
transmission of scientific data from the payload modules.

The SC structure consists of TPM and trajectory unit (TU).

All SC structural elements are arranged in sequential order (nuclear power plant, propulsion unit, trajectory unit). This is done because the main on-board systems and SC equipment should be positioned at the maximum possible distance away from the nuclear reactor which produces ionizing radiation. Besides, such arrangement is gravity-stable in motion around the planet, thus providing spacecraft orientation in flight without spending too much of the propulsive mass for vehicle control around the center of gravity.

The class of the problems which can be solved by combination of NPS and EJP under considered, dictates the necessity of formation an autonomous space unit - TPM. In this case the TU realizing the scientific flight task is a payload of TPM.

The space TPM is intended to solve the main tasks as follows:
providing required level of thrust during the given time for payload delivery to the target of mission,
power supply for payload from beginning of TPM operation during entire flight time,
providing attitude control of TPM-TU assembly during the flight with using of TPM EJPs as actuators.

As TPM is included into TPM-TU assembly, so for minimization of total mass the such integrated assembly it is expedient to distribute operational functions between TPM and TU so that the main functions of TPM control, transmission telemetric data to Earth and functioning of TPM subsystems are provided by TU.

TPM consists of the main components as follows:
- NPS including shadow Radiation Shield (RS) and Radiator-Cooler (RC) for surplus heat rejection,
- EJP (cruise and control EJPs with system of automatics and safety),
- deployable truss,
- rechargeable battery,
- system of storage and feeding of working medium with automatics system,
- Thermal-Control System (TCS) of Equipment Compartment (EC),
- support structure of EC,
- electrical equipment units and cable wiring.

The radiators of TCS are placed on the side surfaces of EC. At the same time it provides meteoroid protection of equipment.

The bunches of EJP are placed on the brackets, which attached to EC. Each propulsion bunch can be placed on the gimbaled unit. Turns of the propulsion provides control moments of pitching, yawing or rolling in order to supply given attitude of TPM-SC assembly and realize its program turns.

Considered configuration provides maximum decrease of NPS radiation affecting to TU, shields TU by TPM EC and also allows to minimize heat flow affect to TU from EJP and NPS ACS (Automatic Control System) operation.

EJP and TPM EJP operation begins after TPM-TU assembly separation from TS last stage by command of TU control system. After that the truss is deployed and NPS begins to operate. Until this moment and during NPS reaching the data-sheet mode the power supply of TPM is provided by own accumulator. After NPS reaches
the data-sheet mode the TPM-TL assembly is oriented with the given direction and EJP begins to operate. During the flight the required thrust law of TPM is provided by switch-on and switch-off of EJP.

Among the possible NPS types the NPS with thermionic energy conversion are the most expedient in the power range from ten kilowatt to megawatt level.

To present, relying on the results achieved under making NPS of first generation in the framework of TOPAZ program and on a large body of experimental research and design developments, the concept of thermionic NPS of second generation has been elaborated; these NPS are based on in-core thermionic reactors (ITR) on thermal and fast neutrons in wide range of electrical power - from several tens to several hundreds kilowatt by lifetime up to 7 and more years. These ITR use unified thermionic fuel elements ensuring voltage no less 125 V at ITR terminals. In parallel with prolonged operation mode which are characterized by specific conversion density 2...3 W/cm², the forced mode is possible for NPS of second generation during about 20% of total lifetime, under which specific conversion density is 2...2,5 times more than at nominal mode. These NPS are characterized by high level of nuclear and radiation safety at all operation stages.

NPS consists of nuclear power generating module (NPGM), automatic control system (ACS) and cable network connecting NPGM and ACS.

NPGM as separate assembly includes ITR with servicing systems, shadow RS and heat removal system with RC as the most large-sized NPGM unit.

ACS including system of automatic regulation, system for telemetry and diagnostics of NPS and electric power supply system which provides required electric parameters at NPS output terminals is instrument, low-temperature and radiation sensitive NPS part; it is placed in instrument spacecraft module which is removed away from NPS and equipped with thermal management system. Arrangement of ACS apparatus in unpressurized compartment at thermostabilized panels is possible also.

Attenuation of ITR ionizing radiation at radiation sensitive NPS and spacecraft apparatus is ensured by RS and also by NPGM moving away from module with this apparatus in operation state with the help of separation system as a member of spacecraft. Owing to RC in the form of folding construction consisting of the sections assembled of movable panels upper fixed NPGM part and movable frames are placed underneath RC panels at launch position; it allows to ensure minimal axial dimension defined by the dimensions of ITR, RS and NPGM equipment compartment arranged behind RS. NPGM transition into working position is performed by separation system after action of the locks releasing NPGM from mating with spacecraft module.

Amongst described NPS the NPS based on thermal neutron reactor ПИ-25 with emission area about 1, 6 m² - ЯЭУ-25 - is characterized by the most high level of elaboration; this NPS may be considered as a base design.

Single-mode ЯЭУ-25 with electrical power level about 30 kW by mass about 2350 kg can be arranged at launch position in the zone with length less 4 m and maximal diameter no more 3 m.

Introduction of forced mode requires: increasing effectiveness of heat removal system at the expense of increasing temperature and RC radiating surface; increasing RS thickness in accordance with the growth of ITR total power output; increasing cross-section of power electrical cables.
Increase of NPS power connected with enumerated measures does not exceed 500 kg at useful electrical power of forced mode 65 kW. In this case NPS launch dimension may be kept up, and the effect of RC area increase to NGPM length at working (orbital) position isn’t essential inasmuch as overall distance from ITR core center to the plane of mating with spacecraft components is defined from the condition of selection of optimal moving away distance between NGPM and spacecraft instrument module.

NPS Υ3Υ-50 based on ITR with total emission area about 2.3 m² can provide more high levels of electrical power. Dual-mode NPS Υ3Υ-50 can ensure electrical power above 100 kW in forced mode by mass about 4000 kg. It should be note that all scheme, design and technological solutions of base NPS Υ3Υ-50 are kept up in such NPS.

Technical characteristics of cruise EJP are chose according with requirements providing the performance of defined task. The main of these requirements are as follows:

- characteristic velocity,
- EJP power consumption,
- EJP specific thrust impulse.

Only three types of EJP among all existing EJPs as to specific power-mass parameters can be used for considered tasks: stationary plasma propulsion, propulsion with anode layer and plasma ion propulsion.

In common case cruise EJP consists of three main systems connected by cable circuit and working medium (WM) pipeline:

- thrust module(s) (TM),
- working medium storage and supply system (WM SSS),
- power transformation and control system (PTCS).

WM SSS consists of tank for WM storage and blocks of working medium supply into thrust module with given pressure. For some reasons the variant when SSS consists of several WM SSB can be more preferable than system with one tank in spite of possible weight increase. These reasons can be exploitation requirements for fueling and launch preparing, maintainability, technologic limitations on tank manufacturing with volume more than 1 m³ for gas working medium storage with operational pressure about 120 bar and storage pressure 320 K. Storage parameters follow from providing the highest coefficient of working medium store taking into account xenon exploitation characteristics. It is expedient to place SSB near or evenly around SC mass center in order to provide minimal force moments because of SC mass center offset during exhausting of fuel.

PTCS serves for following goals:

⇒ transformations of the onboard power supply system voltage to operational voltage for feeding of the EJP units;
⇒ control of subsystems and EJP units by external commands generated by the SC onboard Managing/Information Complex;
⇒ regulations by modes of the EJP operation in an automatic mode according to programmed onboard algorithms and with taking into account data measured by sensors;
⇒ provision of emergency protection and EJP diagnostics.
Use of radiation-steady elements (capable to survive under an integrated flows up to $10^6$ rad and $10^{13}$ neutron/cm$^2$) is very important point in creation of the PTCS. At insufficient characteristics of elements it is necessary apply special design solutions with local additional protection.

Proceeding from stated, weight EJP may be about 500 kg.

A variant of the SC layout with forced NPS is shown on the figure 1.

Structural scheme of SC includes the additional second system for moving aside, providing in aggregate with the first stage a safe distance between NPS and TU. A tank with WM and the bunches of engines are situated close to center of gravity of the SC. As the engines can be gimbaled, it is possible to change the attitude of a thrust vector without change of the SC attitude. Besides influence of jet stream on the elements of the SC structure, including the NPS with the RC, is in this case may be reduced to a minimum.

As it is shown on figure 2, the SC in a transport position can be placed inside of head fairing of the "PROTON" LV.

The TU of the SC, being payload for the TPM, can have as various functional assignment as structural designs. It provides the control of the SC motion, orientation and stabilization at all stages of flight beginning from the moment of separation from launcher, communication with the Earth for reception of control commands, trajectory measurements, scientific and service data transmission, carrying out of research experiments, communication with separated probes, feeding of the TU subsystems from a moment of start up to beginning of nominal operation of the NPS.

For fulfillment of the specified functions the TU is equipped by the following systems:

- a complex of the scientific equipment, depending of a mission goal,
- onboard managing complex,
- onboard radio complex with antenna/feeder system,
- autonomous radio complex with antenna/feeder system for communication with separated probes (if necessary),
- system of thermal control,
- system of the power supply,
- reserve chemical propulsion system,
- system of electric equipment with pyrotechnic devices and cable wiring,
- carrying structure.

Trajectory Unit can be equipped with hyrostabilized platform with the scientific equipment, astroorientation sensors and TV cameras.

CONCLUSIONS

Is shown, that in comparison with SC, equipped with traditional chemical propulsion systems, the much wider spectrum of problems may be resolved in the missions to planet Earth and to distant planets by use of the SC with the NEPS.

Thus as a base components of a space complex were considered "PROTON" LV, EJP based, for example, on the stationary plasma engines and thermoionic NPS of the second generation of the "TOPAZ" type power plant.

The possible scheme SC design for realization of the missions with very high required delta-V to near-Earth space and to planets and small bodies of Solar system is described and offered to further study.
Fig. 1 Structural scheme of spacecraft

1. NPS with electric radiation shield and radiator-cooler
2. Propulsion unit
3. Deployment shroud
4. Trajectory unit

Fig. 2 Spacecraft arrangement under head fairing