

Concept of Electric Propulsion Realization for High Power Space Tug

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Abstract

Popular at the beginning of the Space Age ambitious projects aimed at Moon, Mars and other space objects exploration have returned with new technology and design level. High power space tug with electric propulsion system (EPS) is mainly considered as a transport vehicle for such missions. Modern high power space tugs projects as well as their spacecraft power and propulsion systems are reviewed in the paper. The main technologies and design solutions needed for high power EPS realization are considered.

1. Introduction

At present there is a growing interest in radically new space transport vehicle development. High power space tug with electric propulsion system (EPS) is mainly considered as a transport vehicle for implementation of ambitious deep space missions as well as for near-Earth application.

Due to high specific impulse values electric propulsion application for spacecraft (SC) stationkeeping, SC orbit insertion, interplanetary and deep space missions and so on provides significant fuel saving in comparison with conventional chemical propulsion. So number of SC with EPS is constantly increasing.

Electric propulsion as a space technology was born in 1960s. During past decades EPS technology was rapidly progressing. New kinds of electric thrusters were appeared, and a lot of flight and laboratory EPS models were developed, manufactured and tested.

Laboratory models of different types of high power thrusters were intensively researched in 1960s - 1970s for providing near-Earth and interplanetary perspective missions [1,2] but they did not find practical application and remained at laboratory level of development. Lack of on-board power needed for electric propulsion supplying was the main reason.

In the last decade of 20th century (1990 – 2000) main activity was focused on commercial and science electric propulsion application with single thruster of kilowatt power level and available on-board power level up to 10 kilowatt level [3,4]. Modern commercial SC on-board power level is about 20 kW [5] and single thruster power is up to 5 kW. SC onboard available power level and power of flight electric propulsion keep constantly increasing. Moreover, 260 kW SC power level is reachable now, it has been demonstrated at the International Space Station [4]. Thus, taking into account demonstrated on-board power level and renewal of high power thruster development activity [6, 7, 8, 9, 10, 11, 12, 13, 14], there is a good background of the high power space tugs development.

2. Projects and Missions

There are a number of modern projects aimed at solar [4,15] or nuclear [16,17,18] electric propulsion tugs development. Power level of considered tugs lies in the range from hundreds of kilowatts up to tens of megawatts.

Collaborative group of Russian enterprises, headed by the Russian Federal Space Agency (Roscosmos) and the State Atomic Energy Corporation «Rosatom», is currently working on an innovative project to create a transport power module (TPM) based on megawatt-class nuclear power propulsion system (NPPS) [18, 19].

National Aeronautics and Space Administration (NASA, USA) also shows interest in high power space tug development. NASA's initial plans provide for stepwise SC on-board power growth (30kW-90kW-250kW) up to multi-megawatt level in 2026 [20]. One can suppose that space agencies of other countries have such plans or may be even current activities too.

Such projects implementation will allow providing new challenging near-Earth and deep space missions which are hard to realize in other way.

These missions are given below [21]:

- Heavy payload transfer to geostationary orbit;
- Removal of out-of-operation satellites and space debris from near-Earth orbits;

- Earth protection from asteroid and cometary hazard;
- Moon exploration program;
- Mars manned mission;
- Deep space missions;
- ...and so on.

Projects mentioned therein under differ by missions and technical parameters but their analysis allows to identify common features, general tendencies in a space tug development and technical problem have to be studied and resolved.

2.1 Prometheus Project

The Prometheus Project was an element of the NASA Prometheus Nuclear Systems and Technology Theme. The Project was to develop a Deep Space Vehicle (DSV) for outer solar system robotic exploration missions that would combine a safe, reliable, Space Nuclear Reactor with electric propulsion [16]. The nuclear reactor, the power conversion system and the propulsion system were referred to as a nuclear electric propulsion (NEP) system.

Main NEP technologies are:

1. Primary power source - Nuclear Reactor with Radiation Shield;
2. Power Conversion System based on gas-turbine Brayton cycle;
3. Electric propulsion System based on Ion Thrusters (ITs) and Hall Effect Thrusters (HETs).

The Reactor Module, at the forward end of the DSV (see Figure 1), comprises a high temperature gas-cooled reactor directly coupled with redundant Brayton turbo alternators for power conversion, producing on the order of 200 kW of electrical power. Aft of the reactor is the Radiation Shield Segment, which provides a conical shadow of reactor radiation attenuation to the remainder of the DSV. Control and monitoring for the reactor is provided by the Reactor Instrumentation and Control Segment, with elements located both in the vicinity of the reactor and in protected areas of the spacecraft bus.

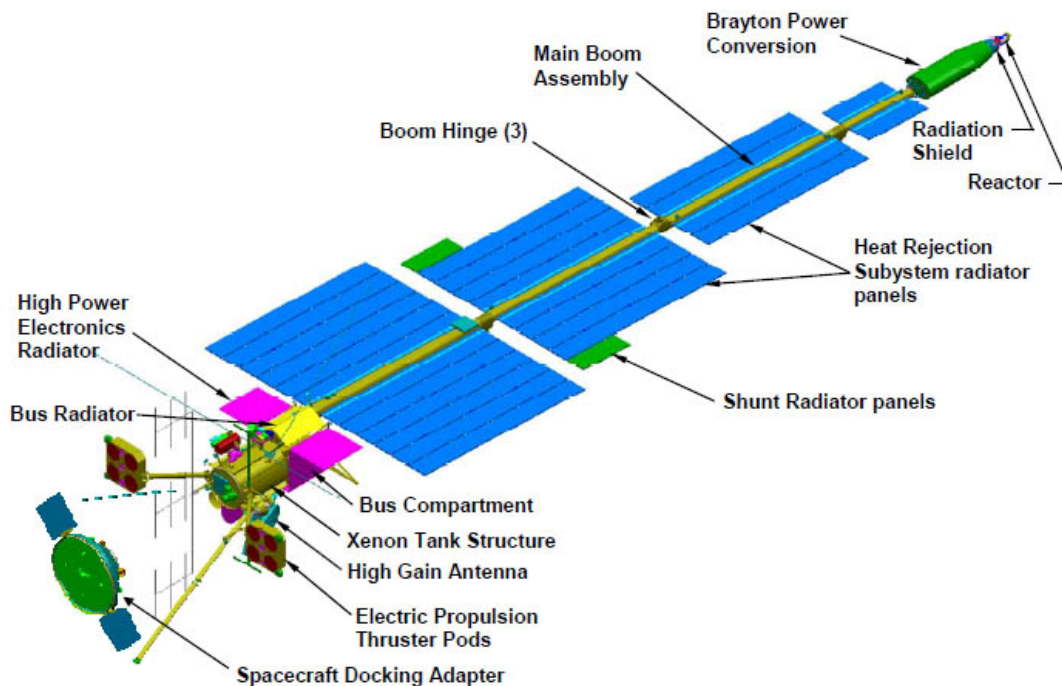


Figure 1: Prometheus Project Deep Space Vehicle

Main propulsion is provided by Ion and Hall thrusters mounted on two deployable thruster pods, making up the Electric Propulsion Segment of the Spacecraft Module. A spacecraft docking adapter (Docking Segment) is also included in the Spacecraft Module to support early on-orbit operations and docking with the interplanetary transfer stages. The docking adapter provides power, communications and attitude control functions for the DSV in the post-launch phases through deployment and commissioning.

The EPS includes Ion Thrusters (ITs) and Hall Effect Thrusters (HETs) mounted on two pods. Each pod contains four Ion Thrusters, three large Hall Effect Thrusters for thrust augmentation and six small Hall Effect Thrusters for attitude control. The power and Xenon fuel feeds are controlled internally in the EPS by eight Ion Thruster Power Processing Units (PPUs) and Xenon Feed Controls (XFCs) respectively, six large Hall Effect Thruster PPU and Xenon Feed Controls, and six small Hall Effect Thruster PPU and Xenon Feed Controls. Attitude Articulation and Control System (AACS) will control the electric propulsion valve drive electronics.

Unfortunately the Prometheus Project was directed to not proceed into next phase [16]. NASA re-evaluated its priorities in light of available funding. The Agency nuclear initiatives were postponed to a large extent, and work within the nuclear systems program was reprioritized. Nuclear electric propulsion (NEP) was given third priority behind nuclear surface power and nuclear thermal propulsion.

2.2 High Power Solar Electric Propulsion Freighter

The use of Solar Electric Propulsion (SEP) can provide significant benefits for the human exploration of near-Earth asteroids. These benefits include substantial cost savings – represented by a significant reduction in the mass required to be lifted to low Earth orbit – and increased mission flexibility. [4,22]. The key technology required for the SEP vehicle is the development of an autonomously deployable solar array with approximately 800 m² of solar cells. For such large, high-power solar arrays, mass reducing is provided by operating the array at high voltage. A peak-power voltage of 300 V was assumed in the vehicle mass estimates. High-power HETs, with an input power of approximately 40 kW, that provide a specific impulse of 2,000 s, and can process over 5,000 kg of xenon are also required. Direct-drive systems, in which the HETs are operated directly from a high-voltage solar array, are projected to provide significant mass savings, substantially simplify the thermal control subsystem, and facilitate the development of the direct-drive PPU (DDU). Conceptual design of a 300-kW solar electric propulsion (SEP) tug is given in the Figure 2.

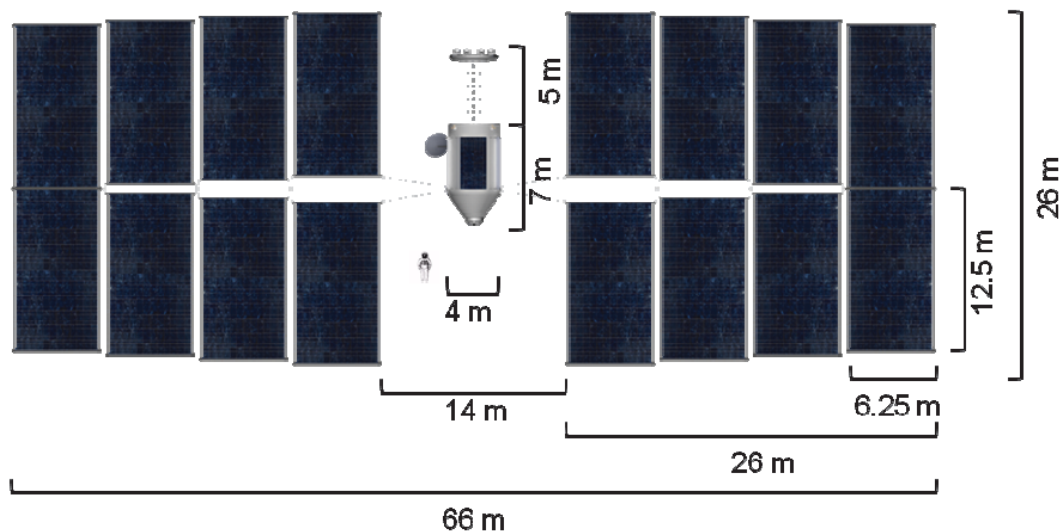


Figure 2: 300 kW Solar Electric Propulsion tug

SEP design power level is a little bit higher than International Space Station one (268 kW). At the same time SEP solar array design efficiency (33%) significantly exceeds ISS one (11%) [20], and it will provide considerable reducing of solar array overall dimensions and mass.

SEP electric propulsion subsystem consists of eight Hall thrusters in which seven are operated simultaneously with a PPU (or DDU) input power of 43 kW each. The seven Hall thrusters are assumed to be capable of processing the 37,000 kg of xenon.

The development of a PPU with the characteristics required for the 300-kW SEP Freighter – 43-kW input power, 250-V to 350-V input voltage, 95% efficiency, and a mass of ~80 kg – will certainly be challenging. A high voltage solar array, with a nominal peak-power output voltage of around 300 V, provides a substantial mass reduction for the SEP vehicle relative to a 100-V array. A high-power Hall thruster operating at a specific impulse of around 2,000 s requires an anode voltage of around 300 V, therefore, it is natural to utilize direct-drive approach in which the Hall thrusters are operated directly from the high-voltage solar array with a minimum of power processing electronics in between.

The SEP main technologies are:

1. Primary power source – 33% efficient solar cells array;
2. Electric propulsion System based on Hall Effect Thrusters (HETs);
3. Possibility of using Direct Drive Unit (DDU) instead of conventional Power Processing Unit (PPU).

Main SEP characteristics are:

- 300 kW power Solar Array;
- Single thruster power ~ 43 kW;
- Specific impulse ~ 2000 s;
- Deployable solar array with approximately 800 m² of solar cells;
- Storage system with 40,000 kg of xenon.

2.3 Mars-2033 project

The Mars-2033 NASA project architecture includes a cargo transfer vehicle (CTV) with NEP system providing 5 MW of electrical power and a crewed Mars transfer vehicle (MTV) with NEP system with two reactors providing a combined total of 10 MW of electrical power [23]. Both vehicles use a low-thrust, high-efficiency (5000 sec specific impulse) MPD system to conduct a spiral-out of the Earth gravity well, a low-thrust heliocentric trajectory, and a spiral-in at Mars with arrival in 2033.

The MTV uses two reactors, each providing 5 MWe, and a total of four Brayton power conversion units. There are two thruster arms with four 2.5 MWe magnetoplasmadynamic (MPD) thrusters (two operational, two spare) on each arm. Each thruster arm has a radiator to reject heat from the power processing units (PPU). The total planform area of the PPU radiators is 136.7 m² (273.4 m² effective radiating area). Six LH2 tanks that are 7.6 m in diameter and 19 m long occupy the middle truss section of the vehicle. The main radiator is comprised of two sections of double-sided flat panels attached to the center truss structure on either side of the propellant tanks due to center of gravity requirements. The total planform area of the main radiator is 2722 m² (5444 m² effective radiating area). The MTV is 182 m long and must be assembled in orbit. The configuration of the MTV is shown in Figure 3.

CTV and MTV electric propulsion systems are based on magnetoplasmadynamic (MPD) thrusters with hydrogen as a propellant. Per MPD thruster is operating at 2.5 MWe at a constant I_{sp} of 5,000 sec with a thruster lifetime of 7500 hr.

The MTV used four operating thrusters for a total power level of 10 MWe and had 4 non-operating spares for redundancy. Likewise, the CTV used two operating thrusters at a total power level of 5 MWe and had two non-operating spares for redundancy.

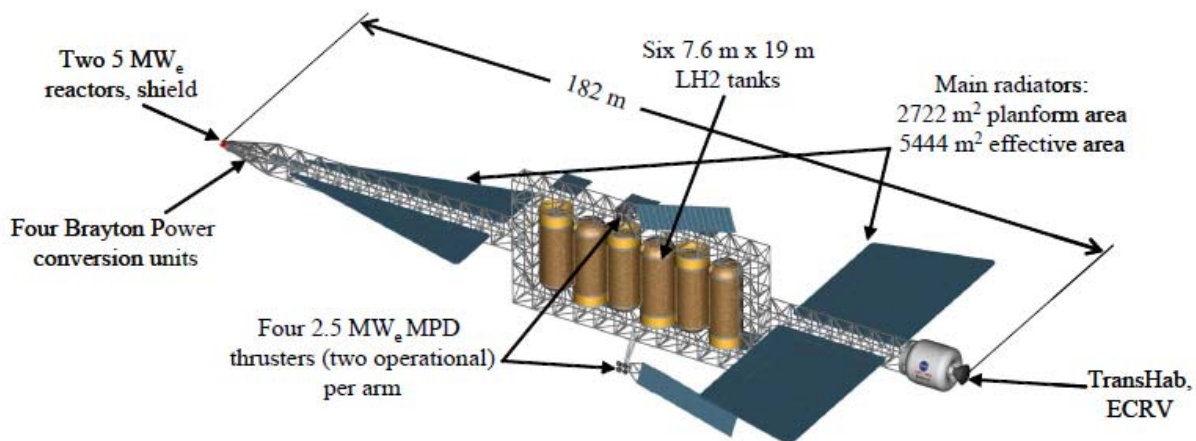


Figure 3: Mars Transfer Vehicle

MTV and CTV main technologies are:

1. One or two Nuclear Reactors;
2. Four closed gas-turbine Brayton cycle units;
3. Panel radiators;
4. MPD thrusters using hydrogen as propellant.

2.4 Transport Power Module Project

An innovative project to create a Transport Power Module (TPM) based on a Megawatt-Class Nuclear Power Propulsion System (NPPS) is currently being carried out within the framework of cooperation among a group of Russian enterprises headed by the Russian Federal Space Agency (Roscosmos) and the State Atomic Energy Corporation «Rosatom» [16,18].

The main phases of the project are:

- 2010 - beginning of the Project activity;
- 2012 - TPM and NPPS draft design development;
- 2013-2018 ground testing and TPM flight test preparation.

Main components of NPPS are (see Figure 4):

- Gas-cooled fast reactor with nuclear and radiation safety systems as a thermal power source;
- Power Conversion System based on gas-turbine Brayton cycle;
- EPS based on Ion thrusters with xenon as a propellant;
- Cooler-radiator (droplet or panel type);
- Power management and distribution system (PMAD).

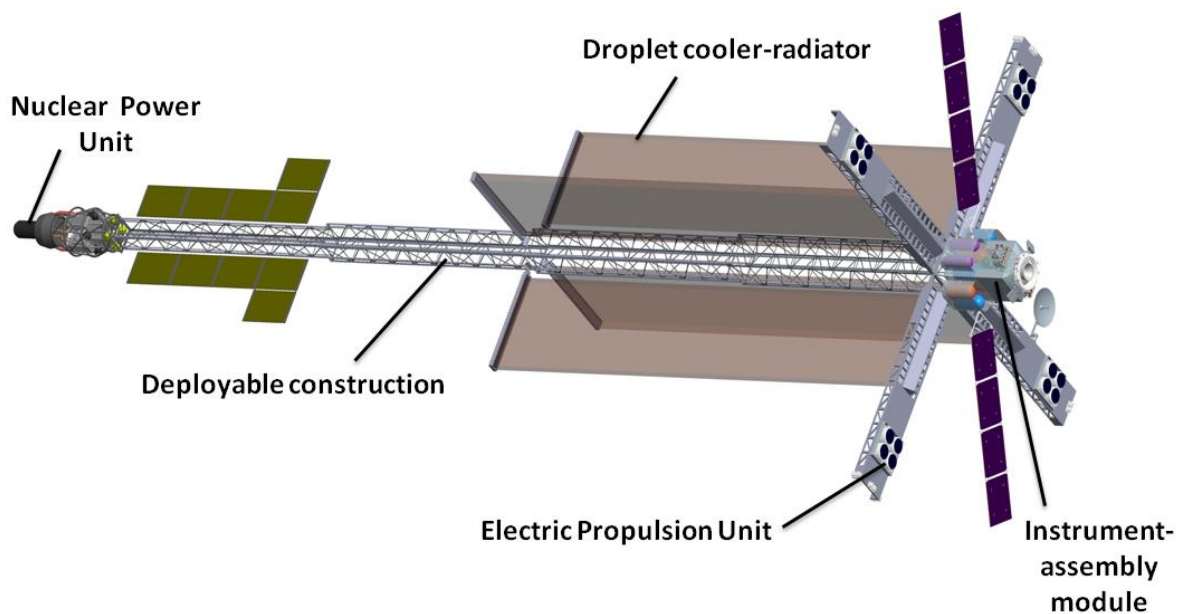


Figure 4: Transport Power Module based on a Megawatt-Class Nuclear Power Propulsion System

TPM main characteristics are:

- One nuclear reactor of 3,5 megawatt thermal power level;
- Four closed gas-turbine Brayton cycle units for thermal power conversion and generating of 1 MWe;
- Power management and distribution system (PMAD): managing available on-board power ~ 1 MWe;
- Primary electric propulsion: High power Ion thrusters of total power ~ 1 MWe with $I_{sp} \sim 7000$ seconds;
- Electric propulsion for TPM attitude control: Ion thrusters with $I_{sp} \sim 7000$ seconds.

3. Approach and issues of EPS realization for High Power Space Tug

Mentioned above space tugs are intended for distinct missions. So they have power propulsion systems based on different power source types and electric propulsion types (see Table 1).

Table 1: Characteristics of considered high power tugs

Project or Tug name	Mission objective	Power propulsion system technologies		Electric power, kW	Specific mass, kg/kW
		Power source and conversion types	Electric propulsion type		
Prometheus	Jupiter Icy Moons Orbiter	Nuclear reactor with closed gas-turbine Brayton cycle	Ion and Hall Effect thrusters using xenon as a propellant	200	~ 80
SEP Freighter	Near-Earth missions	Solar cell array	Hall Effect thrusters using xenon as a propellant	300	~ 36-40*
TPM	Near-Earth and deep space missions	Nuclear Reactor with closed gas-turbine Brayton cycle	Ion thrusters using xenon as a propellant	1000	~ 20
MTV (CTV)	Mars exploration	Nuclear Reactor with closed gas-turbine Brayton cycle	MPD thrusters using hydrogen as a propellant	10000 (5000)	~ 20

*Note: Lesser value corresponds to direct-drive PPU option

Power propulsion system (PPS) consists of four main components:

- Power Source;
- Power Conversion System (PCS);
- Power Management and Distribution System (PMAD);
- Electric Propulsion System (EPS).

Power source and conversion types selection issues were particularly considered in previously mentioned projects. And as it was shown that there are some specific features of their combined operation as well as features of interaction with main electric load – Electric Propulsion System [24]. These features should be taken into account while developing PPS operation algorithm. However EPS and PMAD integration and interference features have not yet been investigated in detail, so some EPS and PMAD design aspects that should be taken into consideration are presented in this paper.

In spite of significant distinctions of above mentioned projects there are a set of common technical solutions which relate to EPS and PMAD design:

1. EPS is based on combining of several simultaneously operating thrusters into one assembly referred as «cluster» [6].
2. All considered EP thrusters types (IT, HET and MPD) have cathodes – sources of electrons. These cathodes provide thruster operation and have important function – to neutralize ion fluxes, generating by thrusters.
3. Application of so called «direct drive» concept is proposed. It provides significant cables and transforming electronics mass savings, since needed for EP thrusters discharge nominal voltage is supplied directly and there is no need of any intermediate transformation.
4. Number of simultaneously operating thrusters can vary in accordance with space tug operation algorithm.

EPS and PMAD can have different architecture options which should be considered while analyzing integration issues of these systems. These architecture options and issues are given below.

3.1 High power EPS and PMAD architecture

Electric propulsion system includes thruster, power processing unit (PPU) and propellant feed system (PFS). Architecture of typical flight qualified EPS which are under utilization is the following: each thruster has its own PPU and PFS elements.

Multi-thruster EPS can be designed with help of two distinct approaches:

- Integration of several independent EPS;

– Creating of cluster assembly with several simultaneously operating thrusters, common PPU and PFS. In the second case it can be considered as a single multichannel thruster. Two ultimate cases of EPS architecture are given in figures below:

- 1) Independent EPS architecture (see Figure 5) includes a set of independent thruster modules. Each module consists of single thruster, cathode unit, PPU and PFS. Propellant storage tanks and onboard power system could be common.
- 2) Common EPS architecture (see Figure 6) is divided into functionally independent subsystems. Such subsystem includes several thrusters, cathode unit, PPU and PFS. Thus single PPU, single PFS and single cathode unit could provide operation of a number of thrusters.

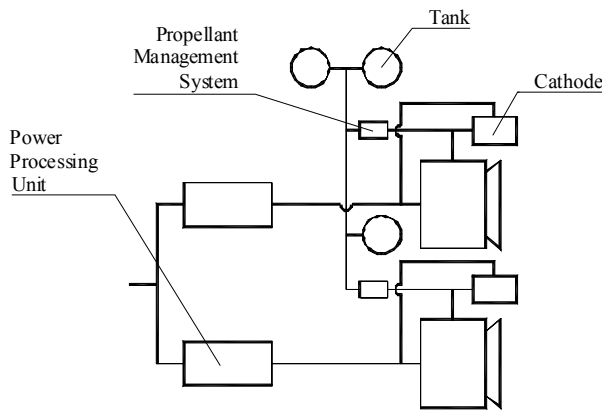


Figure 5: Independent EPS architecture

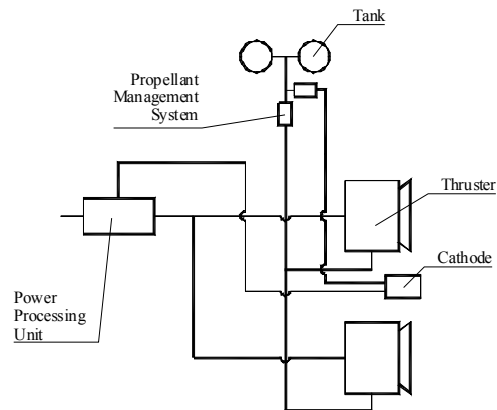


Figure 6: Common EPS architecture.

Common EPS architecture allows getting significant EPS mass profit, it also provides EPS parts nomenclature reducing and correspondingly total cost decreasing. In addition cluster can be optimized for providing of required reliability and lifetime with using of minimal thrusters number. So cluster is a quite universal technology, and it can be used for majority of EP thruster's types.

However, there are some issues that should be taken into account while developing the cluster design. As it was shown before [25, 26, 27, 28, 29] several thrusters can be operated with common cathode. There are no any factors limiting number of thrusters operating with one common cathode from the physical point of view. However, while considering EPS transient modes and operation algorithm such factors appear.

As it was above mentioned EPS should provide possibility operating of any intermediate number of thrusters from I to N , where N is maximal number of EPS simultaneously operating thrusters. Existing flight cathodes design allows emission current regulating in 5 – 10 times (see ref. [30]) without significant cathode efficiency and lifetime reducing. Cathode emission current value should be equal to thruster discharge current value or summary discharge currents value of several operating thrusters. Hence it appears that number of thrusters operating with common cathode is limited and determined by cathode emission current regulating range. So for cathode technology state-of-the-art number of operating thrusters will be 5-10, it will provide possibility to switch on any number of thrusters from I to N .

Another EPS cluster architecture feature relates to possibility of negative thrusters interference. EP thrusters use electric and magnet fields, while operating they are generating high power electromagnet and heat radiation. Therefore, there is a danger of negative thrusters interference. Though Hall and Ion based clusters testing results have showed [29, 31, 32, 33] that negative interference can be successfully minimized or even entirely eliminated.

Thrusters interference minimization approach consists in optimization of distance between thrusters and selecting optimal thrusters assembly configuration. On one hand thrusters can be situated at the far distance from each other, but it leads to increasing cluster overall dimensions. On the other hand in case of thrusters compact arrangement (for example, cluster based on BUSEK BHT-600 Hall thrusters see ref. [33]) single thruster magnet system switching off could lead to negative effects on magnet systems and operating modes of others.

As for PMAD there are following architecture options: centralized, channelized or hybrid [34]. Centralized architecture is characterized by presence of one (central) distribution node. Advantages of the centralized architecture are as follows: high efficiency and low mass of the PMAD components. There are several independent nodes in channelized architecture. Advantages of channelized architecture is good fault tolerance and reliability as well as low cabling mass. The most attractive architecture is the hybrid one, since it combines advantages of the others: modularity; reconfiguration possibility – supply any thrusters cluster from any PMAD module (cross ties); highest fault tolerance and reliability as well as good cabling mass and efficiency.

3.3 Issues of Direct-Drive concept realization

Even without the additional challenges of developing and qualifying new parts, PPU are expensive and time-consuming to develop. There is a possibility to simplify PPU design and to reduce its mass significantly. At the direct-drive concept realization the operating voltage of the thrusters is matched to the turbo-alternators or solar array output voltage, eliminating the need for high power DC to DC discharge converters.

EP thrusters, however, are subject to large amplitude discharge current oscillations, so a direct drive system would consist primarily of filtering, switches to isolate thrusters, and low power auxiliary supplies for cathodes and magnets. If direct drive can be successfully developed, it would result in a significantly higher efficiency system and significantly less waste heat. It could significantly reduce PPU mass with additional savings in structural, thermal management, and array mass. Direct drive systems are potentially much easier to develop than conventional PPU, reducing development cost, time, and risk. Direct drive has been studied at power levels up to one kW but successful startup and stable operation at high power with multiple thrusters must be demonstrated [22]. Issues of DDU realization are also discussed in the papers [35,36]. Advantages (green color) and drawbacks (red color) of DDU-based SEP in comparison with conventional PPU-based are given in the Table 2 [34].

Table 2: Solar Electric Propulsion: conventional PPU based versus DDU based (advantages and drawbacks)

Conventional PPU-based Voltage level 100 - 160 V	DDU-based Voltage level 300 V and higher
—//—	Significant EPS mass savings PMAD mass saving
Electronic parts for PPU and PMAD are commercially available	Electronic parts for DDU and PMAD mostly are not available 300-V solar array technical challenges include higher electron collection current 300-V class solar array designs consistent with de-rated performance of SOA electronic parts, insulators, gimbal and so on
—//—	Higher specific power (kg/kW) Superior power efficiency
Multi-mode is available. Discharge voltage and current (mass flow rate) can be varied and there is a possibility to provide modes with different combination of I_{sp} and thrust.	Only discharge current (mass flow rate) can be varied Mode regulation possibility is limited. I_{sp} could not be regulated.
—//—	Significantly less thermal load
Single thruster operation is isolated from the EPS Decoupling, galvanic isolation between the source (array) and thruster	Single thruster operation is not isolated from the EPS Bus voltage control is primarily tied to EP thruster
Simplifies ground testing of individual components (solar array, EPS, EP subsystem) May simplifies design of solar array electrical simulator Prevents interactions from multi-thrusters through the power bus	Additional research needed for thruster stable operation providing and EP start-up/shut-down and transition modes
—//—	Cathode current sharing for multi-thruster operation Effective grounding schemes

One of the issues that needs to be solved for DDU realization is the discharge current distribution between several simultaneously operating and galvanically connected cathodes. Cathodes discharge voltage values cannot be absolutely identical, and even a little difference of voltage values can cause significant emission current value changing. Therefore in case of cathodes parallel connection some cathodes would be overloaded and others, inversely, would be underloaded. Cathodes parallel operating can be provided by special means (see ref. [25]), however it will require EPS design complication and additional ground testing.

3.4 Typical requirements to high power EPS main components and EPS testing issues

There are special programs aimed for high power EPS components development [37] (high power thrusters with high current cathodes [38], gimbals, power processing units, propellant management systems, storage systems and so on). The most probable thruster candidates for high power EPS realization are the same as for above mentioned projects (see item 2): Hall Effect Thrusters [8,9,10,39,40,41,42], Ion Thrusters [11,12,43], and Magnetoplasmadynamic Thrusters [13,14,44]. Summarizing mentioned above reference data typical EPS components requirements can be obtained:

- 20-50 kW Thruster with thrust and specific impulse regulation (Multi-mode Thruster). Specific mass of thruster 1- 2 kg/kW;
- Cathodes with discharge currents up to hundreds amperes and with possibility to regulate current values in wide range;
- PPU specific mass < 1.8 kg/kW of components, efficiency >95% at the maximum flight allowable operating temperature of 60 °C. In case of DDU concept realization specific mass will be significantly lesser and efficiency higher;
- Propellant storage system with a low tankage fraction and reduced propellant residuals;
- The propellant management system with precise control of the propellant flow rate;
- Low mass thruster gimbal.

While considering high power EPS realization, one more important issue should be mentioned. There are practical limitations for high power EPS complete cycle of ground testing [45]. The main technical problem is to simulate the environment in which the EPS would operate in space. Possibilities of existing facilities allow providing needed level of vacuum for only single high power thruster testing. Modernization of existing facilities or building new one is very expensive, so it is proposed to use flight demo missions or to create special space platform to provide flight testing of newly developed high power EPS key components.

Conclusion

Actual high power space tug development projects have been analyzed from the applied technologies point of view. Perspective design solutions for space tug Electric Propulsion System (EPS) realization have been considered. It is shown that high power EPS design should be determined taking into account interference of correlate systems: Electric Propulsion System and Power Management and Distribution System (PMAD).

EPS cluster architecture with direct-drive joint application is the most perspective design direction. However for these concepts realization detail research aimed at operating thrusters interference as well as thrusters interaction within EPS+PMAD assembly should be carried out. During this investigation EPS and PMAD architectures should be determined, issue of discharge current distribution between several simultaneously operating and galvanically connected cathodes should be resolved and negative thrusters interference should be minimized.

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