Feasibility of High Power Multi-Mode EPS Development Based on the Thruster with Anode Layer

IEPC-2011-064

Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden • Germany
September 11 – 15, 2011

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Abstract: One of the spacecraft (SC) evaluation tendencies is lifetime and onboard power growing and it stimulates using electric propulsion system (EPS) for SC stationkeeping or primary propulsion. Spacecrafts with power level over 20 kW and with 10-15 years of life are currently being implemented. Interest in high power (hundreds of kilowatts or even megawatt) level electric propulsion for future challenging missions is renewed. Thrusters with anode layer (TAL) development tendencies and obtained results in regard to multi-mode high power electric propulsion systems design are discussed in the paper. TAL technology is on the research and development stage for now, however it has shown quite promising performance. Demonstrated main characteristics values are: specific impulse from 1000 up to 8000 seconds, thrust from several grams up to hundreds grams and power from hundreds watts up to hundred kilowatts in single thruster unit. TAL thrusters could use as a propellant various inert gases (Xe, Kr, Ar), their mixtures and condensable propellants (Bi, Cs, Cd) as well. Thus TAL characteristics allow their application for a majority of tasks such as: spacecraft (SC) aerodynamic drag compensation, SC orbit correction and orientation, SC orbit insertion, interplanetary and deep space missions. In addition there are TAL technology perspective features to be incorporated in the next generation EPS: multi-mode ability thrusters and several simultaneously operating thrusters assembly application.

Nomenclature

B = magnetic induction
Eff = efficiency
F = thrust
Ia = accelerating current
Isp = specific impulse
Ua = accelerating voltage
V = summary voltage

I. High power EPS potential application

There are a variety of challenging space missions to be realized, such as: payload transfer to geostationary orbit; removal of out-of-operation satellites and space debris from low-Earth orbits; Earth protection from asteroid and cometary hazards; Moon exploration program; Deep space missions to research solar system outer objects; Mars manned mission and so on.1 And it seems that creation of high power (hundreds of kW or Megawatt level) electric propulsion reusable tugs based on solar234 or nuclear56 power is the only option.

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The 32nd International Electric Propulsion Conference, Wiesbaden, Germany
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High power EPS development should be a result of comprehensive analysis and multi-parametric optimization. Mission analysis and development constraints determine technical requirements to main EPS characteristics: specific impulse, thrust and power; lifetime and reliability; electromagnetic noise and plume interaction with SC; mass and overall dimensions; development and qualification total cost and so on.

Available range of parameters of flight qualified thrusters is strictly limited and does not fit for high power electric propulsion systems. Majority of all commercially available EPS are based on:

- **Hall thrusters** with parameters: specific impulse ($I_{sp}$) 1200 – 2000 sec, power up to 4.5 kW and lifetime up to 9000 hours;
- **Ion thrusters** with parameters: specific impulse 2500 – 3500 sec, power up to 5 kW and lifetime up to 20000 hours.

Thus nomenclature of existing flight-qualified thrusters should be expanded. As a rule flight qualified EPS are designed to operate at only one optimal mode with particular set of parameters (thrust, specific impulse, power and so on). Different mission analysis proves that there is an optimal (from the SC mass saving point of view) constant specific impulse value for every mission, but it is also shown that variable $I_{sp}$ missions could provide notable payload gain in comparison with constant $I_{sp}$ missions.

The next generation EPS are planned to be used for distinct tasks during SC mission and multimode thrusters application is the most appropriate to optimize EPS parameters for each mission stage. Such multi-mode thruster with wide $I_{sp}$ operating range could easily find its application onboard commercial and science SC.

So two main options are under consideration:

- multimode thrusters for near-Earth application (orbit insertion and following orbit keeping): specific impulse operating range from 1000 to 4000 sec with power level 1-10 kW and lifetime 10000 – 20000 hours;
- for interplanetary and deep space missions: specific impulse operating range from 4000 to 7000 sec power level 10-100 kW, lifetime 20000 – 50000 hours.

Feasible operating ranges of different types of electric propulsion thrusters, ranges of flight qualified Ion and Hall thrusters and typical requirements to perspective electric thrusters are given in Fig. 1.

The combination of a high ratio of thrust-to-power operating modes and high specific impulse modes could be provided by high power Hall thruster technology. Hall thruster technology includes stationary plasma thruster (SPT) and thruster with anode layer (TAL). SPTs are well known and have a worldwide flight application, there are dozens SC with EPS based on SPT (SPT-70, SPT-100, T-160, PPS-1350 and so on). TAL technology is on the research and development stage for now. It has successful flight experience. Electric propulsion demonstration module (EPDM) based on TAL-WSF thruster (see Fig. 2) was flown in 1998 onboard spacecraft STEX.

In addition it also demonstrated quite promising characteristics during ground testing. Two-stage TAL is the only Hall thruster that can realize specific impulse values range from 1000 up to 8000 seconds for the present day. So TAL technology is capable of significant expanding of Hall thrusters operating envelope. Thus TALs are applicable for a majority of tasks such as: spacecraft (SC) aerodynamic drag compensation, SC orbit correction and orientation, SC orbit insertion, interplanetary and deep space missions. In addition...
there are TAL technology perspective features to be incorporated in the next generation high power EPS: multi-mode ability thrusters and several simultaneously operating thrusters assembly application.

II. High power EPS propellant choice discussion

One of the essential questions for discussion is the choice of the high power EPS propellant. Practically all commercially available Hall and Ion thrusters are operating on xenon. It is the only propellant under utilization in the current and near term missions. While magnitudes of propellant mass required for telecommunication satellites with 1 to 5 kW Hall thrusters are several hundreds of kilograms, electric propulsion system with hundreds of kilowatts of power level designed for interorbital or interplanetary missions would require tons of propellant. Therefore cost and availability of xenon are major concerns. Potential alternatives under discussion include krypton, argon or xenon-krypton and xenon-argon mixtures or condensable metal propellants.

Utilizing krypton or argon as a propellant may seem attractive based on their similarity to xenon. In practice, however, the higher ionization potential and lower atomic weight of krypton and argon not only lead to substantial decreases in Hall thruster performance but also require changing magnet induction distribution and value in thruster discharge channel. As it was experimentally shown the optimal magnet induction values for krypton and argon were significantly lower than for xenon. Such induction values reducing causes conditions for thruster discharge channel erosion increasing. However there is an acceptable solution: while operating on xenon-krypton or xenon-argon mixture there are special conditions when discharge structure is determined by just xenon part of mixture and optimal magnet induction value typical for operating on xenon is maintained. In that case an even significant krypton or argon parts increasing does not lead to discharge structure changing.

However there are limiting factors associated with development and testing of high power gas-fuelled thrusters. Condensable propellant allows overcoming basic limitations of gas-fueled thrusters – huge pumping systems and vacuum tanks required for testing a high power thruster in ground conditions. It can be noted, that achieved level of xenon flow rates in the Hall thrusters which are currently under development is already close to pumping speed upper limit of the biggest electric propulsion vacuum facility in the world – NASA GRC Tank 5.

Condensable propellants application makes possible high power thrusters ground testing but cause the necessity to exclude SC surface contamination. So there is an interest in utilizing substances which are able to vaporize from the SC surface at the temperature range from -100 °C to +100 °C. Iodine would perfectly fit, but due to of its chemical activity relating to some SC materials additional research has to be carried out.

Thus advantages (painted green color) and drawbacks (painted red color) should be taken into account while choosing propellant for particular EPS (see Tab. 1).

Table 1. Different propellants application feasibility.

<table>
<thead>
<tr>
<th>Condensable substances (bismuth, cadmium, iodine, cesium et al.)</th>
<th>Inert gases (xenon, krypton, argon and their mixtures)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC surface contamination potential hazard</td>
<td>Exclusion of SC surface contamination</td>
</tr>
<tr>
<td>Relatively small vacuum chambers and low pumping speed are required for high power EPS ground testing</td>
<td>Full cycle high power system ground testing impossibility</td>
</tr>
<tr>
<td>Substances abundance and low cost</td>
<td>High cost (xenon especially)</td>
</tr>
<tr>
<td>High density packing at storage tanks</td>
<td>High pressure tanks or cryogenic storage system using is needed</td>
</tr>
<tr>
<td>Propellant flow system units high temperature heating is needed</td>
<td>High temperature vaporizers and pipes are not required</td>
</tr>
</tbody>
</table>

III. TAL technology state-of-the-art

TAL history started in the early sixties of 20 century firstly with physical concept research and theoretical model of working process study and then to the laboratory hardware development and experimental activity. These efforts resulted in two TAL modifications development: one-stage modification (see Fig. 3) and two-stage modification (see Fig. 4) were created. Two-stage TAL has the first (discharge) and the second (acceleration) stages. Ionization mainly takes place at the first stage while ion acceleration happens at the second. Laboratory samples operating with different propellants: condensable substances (Bi, Cs, Cd) and inert gases (Xe, Kr, Ar) were created.
Thruster characteristics $I_{sp}$ up to 8000 seconds and efficiency up to 0.8 with power up to 140 kW were reached. One-stage TAL has only one stage and discharge where ionization and acceleration processes occur. It has more simple construction than two-stage one as well as power supply system. One-stage laboratory samples with different propellants operating were also created and tested. Following characteristics were obtained: $I_{sp}$ up to 3000 seconds and efficiency up to 0.7.

Both TAL modifications supplement each other. One-stage TAL can be operated at the specific impulse range 1000-3000 seconds. At the $I_{sp}$ value more than 3000 seconds one-stage TAL encounters difficulties connected with discharge instabilities and construction elements overheating. When higher $I_{sp}$ is needed two-stage TAL can be used. Moreover a possibility of the one and the same hardware (two-stage TAL modification) operating at both one-stage and two-stage connection schemes was successfully demonstrated. While operating in two-stage scheme ionization and consequent acceleration are realized in two separate discharges. While operating in one-stage scheme voltage is applied only to the second stage, thus ionization and acceleration happen in one discharge. The change from one scheme to another does not require the thrusters design modification and can be accomplished by power supply scheme switching.\textsuperscript{20,21,22} So two-stage TAL can provide $I_{sp}$ regulating at the very wide range. This feature is inherent for all two-stage TALs.

Along with advantages two-stage connection scheme has drawback – it needs more complex power supply system because of necessity to provide different discharge voltage values for ionization and acceleration stages of the thruster. However operation of the first and the second stages can be coordinated with help only one discharge power supply. As it was shown previously\textsuperscript{21,24} two-stage TAL can operate at so called "Floating Electrode" (FE) connection scheme (see Fig. 5). As one can see intermediate electrode – first stage cathode – is floating. Its potential is determined by discharge channel plasma. At this scheme with help of only one discharge power supply parameters analogous for two-stage scheme can be provided.\textsuperscript{25} FE scheme allows using advantages of the two stage connection scheme without complicating of the power supply system.

A. TAL operating modes and parameters

As it was mentioned above from a TAL technology potential application point of view there are two perspective development directions:

- Multi-mode thruster with variable specific impulse 1000...4000 sec (see Fig. 6).
- Thruster with very high specific impulse up to 7000 sec (see Fig. 7).

TAL experimental data analysis shows: there are several specific operating modes ("A", "B" and "C").\textsuperscript{18,22,24} All these modes could be realized in one and the same hardware. Particular mode application is determined by required set of thruster parameters. Characteristics in these modes are given in the Table 2.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{One-stage TAL scheme. 1 – Magnet system; 2 – Anode; 3 – Cathode-neutralizer; 4 – Guard rings.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Two-stage TAL scheme. 1 – Magnet system; 2a – The first stage anode; 2b – The first stage cathode; 3 – Cathode-neutralizer; 4 – Guard rings.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Floating Electrode connection scheme.}
\end{figure}
The fundamental difference between modes "A", "B" (I_{sp} range 1200 – 3000 s, voltage range 150 – 1000 V) on the one hand and mode "C" (I_{sp}>3000 s, V>1000 V) on the other hand is in the magnet field induction value required. There is an optimal relatively low magnet field induction value for stable and efficient TAL operating in the "A" or "B" modes at the particular set of parameters (mass flow rate and voltage). For "C" mode stable operating could be provided both at the relatively low magnet induction values (<0.06 T) and high magnet induction values (>0.1 T). Further magnet induction value increasing (up to 0.2 T) leads to guard ring erosion rate reducing and does not influence on other parameters (volt-ampere characteristic and efficiency). Thus, operating with maximal magnet induction value is preferable for reducing erosion rate and increasing the thruster lifetime (see Fig. 14).

**B. Multi-mode xenon TALs**

Multi-mode thrusters D-80 and D-60 photos are given in Fig. 8 and their characteristics are given in Tab. 2. Operating range obtained for engineering models D-80 and D-60 is given in Tab. 3. Multi-mode D-80 and D-60 detail design description and parameters are presented in papers Ref. 20,21,22,25,26,27,28,29,30,31,32,33.

The fundamental difference between modes "A", "B", "C" (I_{sp}>3000 s, V>1000 V) on the one hand and mode "C" (I_{sp}>3000 s, V>1000 V) on the other hand is in the magnet field induction value required. There is an optimal relatively low magnet field induction value for stable and efficient TAL operating in the "A" or "B" modes at the particular set of parameters (mass flow rate and voltage). For "C" mode stable operating could be provided both at the relatively low magnet induction values (<0.06 T) and high magnet induction values (>0.1 T). Further magnet induction value increasing (up to 0.2 T) leads to guard ring erosion rate reducing and does not influence on other parameters (volt-ampere characteristic and efficiency). Thus, operating with maximal magnet induction value is preferable for reducing erosion rate and increasing the thruster lifetime (see Fig. 14).

**Table 2. D-80 and D-60 characteristics.**

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass, kg</th>
<th>Power, kW</th>
<th>Thrust, mN</th>
<th>I_{sp}, s</th>
<th>Eff, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-80</td>
<td>7.5</td>
<td>600…8500</td>
<td>45…240</td>
<td>1200…4000</td>
<td>40…70</td>
</tr>
<tr>
<td>D-60</td>
<td>5.0</td>
<td>400…2200</td>
<td>35…140</td>
<td>1200…3000</td>
<td>40…60</td>
</tr>
</tbody>
</table>

**Table 3. TAL modes and characteristics.**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mode &quot;A&quot;</th>
<th>Mode &quot;B&quot;</th>
<th>Mode &quot;C&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connection Scheme</td>
<td>One-stage</td>
<td>Two-stage</td>
<td>Two-stage</td>
</tr>
<tr>
<td>Voltage, V</td>
<td>150 – 450</td>
<td>450 – 1000</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Specific impulse, s</td>
<td>1200 – 2000</td>
<td>2000 – 3000</td>
<td>&gt;3000</td>
</tr>
<tr>
<td>Magnetic induction, T</td>
<td>0.01 – 0.06</td>
<td>0.01 – 0.06</td>
<td>&gt;0.1</td>
</tr>
<tr>
<td>Efficiency</td>
<td>up to 0.6</td>
<td>up to 0.65</td>
<td>up to 0.75</td>
</tr>
<tr>
<td>Lifetime, h</td>
<td>&gt;10000</td>
<td>5000 – 10000</td>
<td>&gt;10000</td>
</tr>
</tbody>
</table>

D-80 and D-60 are able to operate at both modes "A" and "B". Areas of preferable modes using are shown in Fig. 9. High thrust level is provided in one-stage scheme and in low voltage modes (less than 450 V) – mode "A". High specific impulse is provided in two-stage scheme at high voltage modes (450 – 1000 V) – mode "B". D-80 and D-60 design features do not permit to realize high magnet induction values needed for operating at mode "C" (see Tab. 2). So the next obvious step is to develop hardware for operating at all mentioned above modes ("A", "B" and "C").
C. Very high specific impulse bismuth TALs

From the very beginning (during 60th...70th) Russian EPS research programs were oriented to future interplanetary missions, and this goal determined range of parameters of studied laboratory thrusters with very high specific impulse up 8000 sec and power range of a thruster from dozens to hundreds kilowatts. Laboratory TALs developed in early programs – namely D-160 (also called Drift-5)\textsuperscript{24,34} and D-200 demonstrated range of required performances. The volt-ampere characteristics of D-160 for several mass flow rates (5...25 mg/s) are shown in Fig.10.
There are two distinct ranges on these curves where accelerating stage current depends on accelerating stage voltage quite differently. Effective operating mode with focused ion beam named "accelerating" one relates to the region of nearly constant discharge current. When the accelerating voltage decreases to some value, the current begins to rise and the thruster transits to "anomalous" or "abnormal" operating mode characterized by enhanced oscillation level and low thrust efficiency. Due to substantial design margin and water cooling magnetic system D-160 thruster allows realizing high power operating regimes. Maximum achieved power level was about 140 kW.

After 80th such programs in the Russia were stopped. During several last years the resumption of interest to the similar tasks is observed again. Therefore new laboratory two stage thruster VHITAL-160 with average diameter of discharge chamber 160 mm was developed, fabricated and tested. The laboratory thruster D-160 was used as a prototype. Unlike D-160 the new thruster ensures radiant cooling during the long operation. The VHITAL-160 design was developed based on the known and approbated solutions (see Fig. 11). Two operating modes of the VHITAL-160 at the discharge power level 25 and 36 kW were demonstrated (see Tab. 4). The values of specific impulse about 5400 and 7700 s were achieved correspondingly. All above mentioned very high specific impulse TALs were operating in "C" mode.

D. TAL design features for lifetime providing
As it was above mentioned required EPS lifetime value depends on particular mission and can reach tens of thousands of hours. So the thruster lifetime providing is very essential and full cycle of lifetime testing is the most expensive part of the new thruster development. TAL construction elements ion sputtering is the main lifetime limiting factor. To protect the construction from erosion the thruster employs a special guard rings that are located adjacent to the magnetic pole pieces and are made from the sputter-resistant conductive material.

Table 4. VHITAL-160 modes and parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mode 1 (I_sp=5400)</th>
<th>Mode 2 (I_sp=7700)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power, W</td>
<td>25240</td>
<td>36755</td>
</tr>
<tr>
<td>Thrust, mN</td>
<td>527</td>
<td>618</td>
</tr>
<tr>
<td>Specific impulse, s</td>
<td>5375</td>
<td>7667</td>
</tr>
</tbody>
</table>

Figure 11. VHITAL-160 photos.

D. TAL design features for lifetime providing
As it was above mentioned required EPS lifetime value depends on particular mission and can reach tens of thousands of hours. So the thruster lifetime providing is very essential and full cycle of lifetime testing is the most expensive part of the new thruster development. TAL construction elements ion sputtering is the main lifetime limiting factor. To protect the construction from erosion the thruster employs a special guard rings that are located adjacent to the magnetic pole pieces and are made from the sputter-resistant conductive material.

Figure 10. Volt-Ampere Characteristics of D-160 Bismuth TAL.
Comparison of multi-mode TAL guard rings erosion profiles in one- and two-stage schemes low and high voltage modes had showed that erosion rate in high voltage modes (high I_sp modes) significantly exceeded one in low voltage in spite of the fact that the input power is the same (see Fig. 12). So the resume is that for TAL operating at "A" and "B" high voltage modes erosion rate is sufficiently higher due to voltage increasing.

There are several ways to provide the thruster lifetime required:
1. Very sputter-resistant materials utilization;
2. The guard rings thickness increasing;
3. External anode layer scheme application (see Fig. 13);
4. Magnetic induction increasing (only for "C" mode, see Fig. 14).

The first and the second ways are most obvious. However last two ways are most perspective. Magnet induction lines distribution for scheme with external anode layer is given in Fig. 13.

Magnet shunt application provides optimal positive gradient magnet field in the discharge zone and shifts this zone (anode layer) outside the thruster construction. Such shifting provides discharge channel length reducing and thruster construction elements erosion rate minimization. The thruster stable operating with discharge channel length value reduced down to 0.2 mm was demonstrated for TAL D-80. Magnetic induction increasing leads to erosion rate reducing.

E. Multi-mode TAL development discussion
Multi-mode TAL technology is a perspective option for high power EPS development. Once again let’s underline main TAL features:
- Two-stage design allows full realizing multi-mode ability. Different operation modes ("A", "B", and "C") are applied for regulating specific impulse, thrust and power values in extremely wide range. Preferable ranges for each mode are experimentally determined.
- TAL can use both inert gases and condensable substances as a fuel;

Figure 12. Guard rings erosion profiles in different operating modes.

Figure 13. Scheme with external anode layer.
1, 3 – magnet poles, 2 – magnet shunt, 4 – magnet coils.

Figure 14. Magnetic induction increasing leads to erosion rate reducing.
− Lifetime providing TAL design features, such as: erosion resistant materials application, guard rings thickness increasing, external anode layer scheme utilizing; high magnetic induction mode (mode "C") for specific impulse values higher than 3000 seconds;
− Floating electrode scheme application simplifies power supply system in comparison with two-stage connection scheme.

Reasonable power level of single thruster for future high power EPS is determined by possibilities of a thruster ground testing and thruster parts fabrication. As an example, simplified design envelope for new generation 15-20 kW xenon multi-mode TAL is presented here (see Fig. 15). Design average diameter of the thruster discharge channel would be 120-130 mm. Such power level is convenient for realizing of a possibility to operate at all three modes ("A", "B", "C") and to provide \( I_p \) value up to 7000 seconds. Operating envelope is bounded by curves that correspond to lowest and highest mass flow rate values permissible for the thruster. The thruster efficiency is not constant over most of the envelope, but varies with the mass flow rate and voltage values varying. Lowest efficiency (about 40\%) corresponds to the thruster lowest power level (mode 1, about 1 kW) and maximal efficiency (about 70 \%) corresponds to maximum of allowable power level (17.5 kW, modes 2 and 4). Analysis of multi-mode TAL operating envelope in details is given in papers. Such multi-mode thruster can be considered as a base for high power electric propulsion system.

IV. Development of a high power EPS based on TAL

There are two possible ways for creation of higher-powered EP systems:
− development and using of higher-powered thrusters;
− use of bunches of several, simultaneously working relatively low power thrusters, i.e. thrusters cluster.

Possibility of single Hall thruster power increasing theoretically is not limited. Power increasing could be simply provided by the thruster size growing, however there are set of technical questions to be solved, such as: availability of special design materials of appropriate size for the thruster parts manufacturing, testing facilities possibilities to run the high power thruster fire tests and so on. So these reasons determine the upper power limit by value about 100 kW for single Hall thruster. This power level was demonstrated by bismuth TAL D-160. As it was mentioned above D-160 had achieved record power level value of about 140 kW. Xenon TAL TM-50 was operated at 35 kW power level and further TM-50 power increasing was limited by testing facility possibilities. Nevertheless, there is an upper limit of single thruster power level. Therefore, the most rational way to create EPS of megawatt power level is to use several simultaneously operating thrusters integrated into cluster unit.

A number of activities have been dedicated to investigate capabilities of the two different ways as well as a rational combination of the both.

It follows from the available data that the cluster approach can be deemed as essentially important for advance propulsion systems. Using a narrow range of tried engines of a relatively small power, one can overcome difficulties with ground development tests and improvement of a high-power EP system, because it will be enough to develop the components, which it contains. So, a cluster (once developed and improved) enables designing of propulsion systems, which have diverse power. It is achievable via mere scaling, just by adding available propulsion modules (clusters), and allows saving time and money necessary for improvement of a system.

In spite of visual simplicity, implementation of EP on the basis of several electric thrusters, aggregated in a system and working at a time, needs investigation of some basic aspects:
− Summarization of the thrusts of engines in a cluster (additivity of thrust).
− Interaction of exhaust plumes of engines in a cluster (to ensure correct estimation of their effect on surfaces of a spacecraft).
− Interference (cross effect) of cluster engines.

Figure 15. Design envelope of multi mode TAL able to operate at "A", "B","C" modes.
The architecture (functional scheme) of modern EP systems on ion or Hall-effect thrusters is, as a rule, based on a linear principle - every engine has its individual cathode-neutralizer, propellant feed system (PFS), power processing unit (PPU).

A cluster - an integrated system, consisting of several, at-a-time operating engines, aimed at executing a common flight task – enables application of new schemes of EP systems in which, e.g., functions of feeding and control for every thruster can be integrated in one device for all, and one cathode-neutralizer can serve for operation of several thrusters etc.39,40

Thus, being a good solution for the main challenge – creation of a high-power EP system having any specified power, under conditions of a poor range of tried engines – the cluster technology provides new capabilities: it enables achieving of maximum flexibility and reliability of an EP system with reducing its weight as compared to the design when several, actually independent propulsion systems are just put together.

To make these capabilities real, a number of special engineering solutions inherent to the clusters, which were not investigated earlier, need an intensive research. In particular, the following problems should be investigated:

- Possibility for operation of several engines from a common power supply and a common, propellant feed system.
- Possibility for a cluster operation from a common cathode-neutralizer, probable limitations of the cluster size.
- Optimization of the number of thrusters in a cluster.
- Probable interaction of cluster thrusters, both through plasma and through internal electric circuits.
- Stability of a cluster operation under deviations of parameters of some thrusters in a cluster.

Following conditions should be met for studying of operating of any cluster system based on EP thrusters:

- The basic thruster should be fully characterized (volt-ampere characteristics, thrust, specific impulse, efficiency, discharge voltage and current oscillations, plasma plume characteristics and lifetime for every operating modes).
- Every thruster should be verified before and after its operation in the cluster assembly. Its integral characteristics during single operation in the one and the second cases should be coinciding.
- During joint thrusters operation in the different cluster configurations (electric scheme, geometrical placement, quantity of thrusters and cathode-neutralizers) its characteristics (according to the first item of the list) should be compared with ones obtained during its single operation.
- Characteristics of the cluster complex plume, generated by several simultaneously operating thrusters should be studied for every cluster configuration.
- Data obtained should be compared with single thrusters plume data for development of cluster systems calculation methods based on single thrusters characteristics.

Meeting all these conditions is a complex and hard enough task. The cluster integral characteristics obtaining is not enough for its operating features revealing. The cluster complex plume data are needed, that by-turn requires special equipment development and bulk data processing.

A. TAL Cluster operating with common and separated power supply unit for every thruster

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 Fig. 16) 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 Fig. 17) 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 provide operation of a number of thrusters.
Common EPS architecture allows getting significant EPS mass profit, it also provides EPS parts nomenclature reducing and correspondingly total cost decreasing. However, thrusters interaction should be taken into account while developing the assembly design.

In case of switching to common power supply architecture, determination of thrusts summation rule of clustered engines, stability limits of such system and their correlation to independent architecture should be analyzed. Given aspects require additional experimental research.

To study main features of cluster operation the assembly of three single-stage TALs has been selected. This number of thrusters in addition to early performed test of two-thruster assembly incorporates all main features of a cluster and provides necessary possibilities to study its operation specific. In Figure 18 a general view of the assembly with a common cathode mounted in the center is shown.

Cluster assemblies based on TALs D-55 thrusters was considered as a scale model for future powerful multi-thruster systems. The total power level of 3-TAL was about 3 kW. During low power modes cluster investigation it was supposed that all obtained parameters and features may be extended for higher power systems. The criteria of basic thruster selection for exploratory assemblies were assigned by level of thruster studying, absence of thruster scale factors associated with low power and by test facility features (vacuum system capability mainly). D-55 definitely has no scaling problems as compared with a bigger TALs with power level up to 50 kW, and working processes are one and the same for these thrusters at corresponding operation modes.

Goal of the initial series of tests was identification of a relationship between the thrust of a single engine and a total thrust of three simultaneously operating engines in the case of both independent and common architectures. Whatever the scheme of power supply was, there were no essential differences between the thrust values of a cluster in all investigated modes (discharge voltage: 200, 300 and 400V), and (within the accuracy of measurements) the resultant thrust is merely equal to the sum of thrusts of the three engines.
An illustration of the discharge current oscillations in the case of common power supply using in circuits of thrusters D1, D2, D3 for a mode of 200 V, 3 A as well as in the common circuit D1+D2+D3 is depicted in Fig. 19. One can see that although the frequencies of oscillations in all the three engines are close to each other, the phases of oscillations are different and vary arbitrarily in each thruster. The oscillations of two of the three tested engines are close to antiphase, and the amplitude measured in the common circuit is of the same order with the one in the circuit of one engine. This result is confirmed statistically by numerous repeated measurements, including after the shutdown and re-ignition of the cluster. The pattern of oscillations in discharge circuits for any thruster in a cluster was similar to the one observed at individual tests of the engine. Obtained result demonstrates that synchronization of the discharge current oscillations in the thrusters of a cluster is not a mandatory requirement to the simultaneous operation of several thrusters even in the layout with a common source of discharge voltage, which is the most “vulnerable” from this point of view.

Despite of that summary thrust magnitudes were identical for both common and independent architectures, limits of stable operation essentially depend on choice of circuit connection scheme.

B. Stability of cluster operation

One of a key criteria for cluster architecture selection is a reliability requirements, thus influence of thrusters in a cluster on each other and ability of the cluster to operate normally in case of one of thrusters failing is of critical importance for the whole system.

Mentioned above result was obtained when all the thrusters operating at identical modes and the amplitude and typical frequencies of the discharge current oscillations in all engines were close to each other. However, one can suppose that the oscillations in one of the thrusters (upon achieving some level) can have an impact on the oscillations in two other engines.

To study this aspect one of the thruster in the tested assembly has been especially turned into unstable mode, and even switched off to simulate thruster failure. In the case of common power supply cluster was tested when the engines D2 was purposely (by an intentional change of the magnetic field in its discharge) shifted into so-called “abnormal” mode when a drastic increase in the amplitude of the discharge current oscillations typically develops. The oscillations of discharge current in D2 influenced the currents in the other two engines and also the total signal from the cluster. However, measurements of the parameters of the other two operating thrusters in the tested cluster have shown that their regimes are quite stable despite of dramatic changes in the neighbor.38 So the whole system was stable. Observed impact can take place both via internal discharge circuits and through plasma.

Trying to resolve such dual-impact problem, a test was carried out when each engine in the cluster was powered from an independent, individual source. Such electric circuit can actually eliminate the interference of engines in a cluster via internal discharge circuits. Engine D1 was shifted into the anomalous mode. The remaining thrusters (D2, D3) did not change their patterns of oscillations, and there is actually no effect of engine D1. From this result one can make a conclusion that oscillations in such systems are mainly impacted via internal circuits, and are not impacted through plasma.

Obviously, obtained results are rather preliminary, and require further systematic studies of oscillation processes and electromagnetic noise in the cluster, however TAL cluster stable operation and the system independence from...
individual thrusters operating mode deviations have been successfully demonstrated. Nevertheless, it should be mentioned, that such stable operation is provided only if the cluster architecture is selected properly, in other case failure of one thruster will lead to whole assembly failure.

C. TAL Cluster assembly plume parameters measurement

It should be pointed that clusters complex plumes characterization is the one of the most critical tasks. Features of multi-thruster assemblies plume formation revealing is of critical importance for influence plasma flow upon spacecraft surface estimating. The diagnostic equipment and test procedures used for the TAL cluster plume study are described in Ref. 42.

Cluster ion current density space distributions measured at the distances 300, 500 and 1000 mm are given in Fig. 20.

As one can see, at the distances 300 (Fig. 20a) and 500 mm (Fig. 20b) three peaks corresponding to the plumes of three thrusters are well distinguished. With the distance increasing cluster plume transforms. At the distance equal to 1000 mm (Fig. 20c) plume areas corresponding to each thruster are almost disappeared. Thus, at long distances plume generated by three thrusters becomes similar to a plume generated by some single thruster located at the center of the cluster.

Comparison of measured cluster plume profile with calculated summa of the individual thruster plumes was made to verify additivity of the plumes. Corresponding data are shown in Fig. 21. Measured single thruster D1 (red curve) and cluster (blue curve) plume profiles are given in this figure. Black curve in Fig. 21 corresponds to the calculated cluster plume profile, obtained by mathematical adding of three single thruster ion current distributions. One can see, that mathematically obtained curve differs from the measured one in the high density area, which corresponds to the thruster D1 axis, but in remaining (periphery) areas both curves coincide. This difference exists in the central high density zone of the plume at all tested distances (300, 500 and 1000 mm) from the cluster, and radial dimension of this zone increases with the distance increase.

Obtained data allow to conclude, that the cluster plume distribution is not simple sum of distributions obtained for single thrusters operation.

As far as in all studied modes (as it was shown above) the cluster thrust is the sum of the thrust values of individual thrusters, one can assume, that the ion flux generated by each operated thruster in cluster corresponds to the ion flux generated by thruster operated individually. Therefore, the most probable reason causing the difference between measured and mathematically obtained cluster plume profile, is difference of the charge exchange conditions for the cluster plume as compared with plume of the thruster operated individually. Should be noted, that measured tank pressure in all

![Figure 20. Cluster ion current distribution.](image)

**Figure 20. Cluster ion current distribution.**

![Figure 21. Ion current density distribution of the cluster and single thruster.](image)

**Figure 21. Ion current density distribution of the cluster and single thruster.**
compared cases was one and the same, so average density of the neutrals was one and the same also, but local variations of the neutral atom density could be the reason of observed phenomenon.

V. Conclusion

TAL technology is a perspective option for the next generation high power EPS development. TAL can use both inert gases and condensable substances as a fuel. Xenon is the basic EPS propellant for a present day and near term future missions. It provides efficient EPS operation in the one hand and excludes SC surface contamination on the other hand. However xenon low availability and high cost limit its application for high power EPS (megawatt level or higher). Condensable propellants allow to simplify ground testing and to reduce expenses significantly. But condensable propellants utilizing will require additional working out of SC surface protection questions. So both options have advantages and drawbacks.

Two-stage TAL design allows to combine several operating modes with very distinct characteristics in the one hardware (multi-mode ability), thus one and the same EPS can be effectively operated in wide range of parameters (specific impulse, thrust and power). Experimental data obtained with multi-mode thrusters operating at modes "A", "B", and "C" form an excellent basis for development of higher power EPS with ability to vary specific impulse value in extremely wide range (1500 – 7000 seconds).

Cluster is a quite universal technology and it can be used for high power EPS development. TAL cluster integral characteristics: summary thrust, power, mass flow rate and stable operating range could be well defined with help of corresponding single thruster parameters. However, interaction between thrusters and, in particular, nonlinear interaction of the thruster plumes should be taken into account while developing the assembly design.

VI. Acknowledgments

Authors would like to thank staff of TSNIIMASH electric propulsion laboratory, working together was a real pleasure!

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