The Perfect Electric Thruster: a Spacecraft System Approach to Its Definition

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Abstract: Although many electric propulsion (EP) technologies has been conceived and developed so far, only few of them made it up to space or are about to achieve that. Each EP technology has its own pros and cons that are usually thoroughly analysed in dedicated papers. Beside that there are also more general aspects, at spacecraft system level, that can be critical for the success of a given EP technology and for its implementation as a specific thruster or system. These aspects are taken into account when selecting candidate EP technologies for application to future missions, early in their development phase (Phase 0, Phase A). The present paper considers such aspects and namely: impacts on the design phase (impacts on the whole spacecraft design, impacts on other spacecraft subsystems), impacts on the assembly, integration and verification phase, impacts on LEOP phase and impacts on operational phase and ground segment operations.

Analysing all existing EP technologies against such aspects is certainly a useful exercise but cannot be contained in the scope of a congress paper. Therefore, the current paper starts from a completely different approach:

- **It defines an ideal, perfect electric thruster from a spacecraft system perspective**
- **It explains its features according to the above mentioned general spacecraft system level aspects,**
- **It indicates how any deviation from the proposed ideal solution could make success harder to achieve or even jeopardise the success of the thruster itself and, also, of the EP technology on which it is based.**

Nomenclature

AIT	=	*Assembly, Integration and Tests*
AOCS	=	*Attitude and Orbit Control Subsystem*
CPS	=	*Chemical Propulsion System*
EO	=	*Earth Observation*
EP	=	*Electric Propulsion*
EPS	=	*Electric Propulsion Subsystem*
EPT	=	*Electric Propulsion Technology*
ETh	=	*Electric Thruster*
GEO	=	*Geostationary Earth Orbit*
LEO	=	*Low Earth Orbit*

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LEOP	=	*Launch and Early Operations Phase*
OBC	=	*On Board Computer*
PA	=	*Product Assurance*
PCDU	=	*Power Conditioning and Distribution Unit*
PCU	=	*Power and Control Unit (of an EPS)*
S/C	=	*Spacecraft*
SW	=	*Software*
TM	=	*Telemetry*
TMTC	=	*Telemetry and Telecommand (Subsystem)*

I. Introduction

Although many electric propulsion technologies (EPTs) have been conceived and developed so far, only few of them have been implemented into electric propulsion subsystems (EPSs) that made it up to space or are about to achieve that.

Each EPT has its own performance range, with pros and cons that are usually thoroughly analysed in dedicated papers.

Beside that, there are also more general aspects, at spacecraft system level, that can be critical for the success of a given EP technology and for its implementation as a specific thruster or subsystem.

These aspects are taken into account when selecting candidate EP technologies for application to future missions, early in their development phase (Phase 0, Phase A).

A. A Matter of Confidence

A first broad selection, or "shortlisting", is carried out purely on the base of expected propulsion performances. Yet, the final selection for implementation is usually carried out having as main parameter the confidence that a given EPT and its deriving EPS could actually meet all requirements and allow the mission to be successful (in all Phase 0 and Phase A studies EPT/EPS technology maturity and associated risks are considered from the start in any programme).

This means:

- confidence that problems that might be encountered during design and AIT with the rest of the S/C will be solved
- confidence that no hidden criticalities could result in swelling of costs and schedule (don't push the limits, use space materials and processes, proper EP characterisation beyond working envelope, concept of modularity and ease of testing)
- confidence that the final customer will deem the EPS suitable for the mission and consent to fly it (test and qualification processes and PA control that follows space standards)
- confidence that the system will work once in space (life test, all involved physics very well understood and under control)

Obviously, EPSs that have already been flown offer very high levels of confidence on all these fields. But this creates a closed loop that tends to prevent flying new promising EPTs as well as new EPSs..

In order for a new EPT to make it through to fly, it shall show clear benefits in terms of performances above other most proven propulsion technologies and, at the same time, provide a level of confidence that shall be as high as possible in all above mentioned fields.

B. About This Paper

All these fields are briefly analysed in following sections (also suggesting a practical approach to such analysis) and, at the end, an ideal "perfect" electric thruster is described from this perspective. Each of the features of this perfect electric thruster can be also taken as a sort of guideline toward success for being selected for implementation and flight.

After all, this paper is dedicated to all those developing a new EPT or a new electric thruster (even if based on existing technology) with the best wishes of making it all the way, up into space.

C. A Definition of EPT, Electric Thruster and EPS

To the purpose of the present paper, an EPT can be defined as the physical implementation of a concept for accelerating propellant. And, in the same way:

- an electric thruster can be defined as the practical result of an engineered EPT, with the final aim to produce thrust for space applications

- an EPS can be defined as the electric thruster and all the dedicated components it needs to work

The other components apart the thruster(s) of a typical EPS are: power management, propellant management, management software, thermal control, diagnostic systems and other possible ancillary elements (harness, pointing mechanisms, structural elements, etc.).

II. EPS Design with the Rest of the S/C: a Harmonised Design Approach

The best way to ensure a high level confidence about a successful design of EPS within the frame of the whole S/C would ideally be a harmonised design approach scenario. In such scenario the EPS and the rest of the S/C would be designed concurrently (e.g. by real time concurrent engineering), with the EPS design team being aware of the design of the rest of the S/C and the rest of the S/C being aware of the design (and characteristics) of the EPS.

In reality, this is feasible when the EPS is based on proven technologies and its most critical components (thruster, power management and neutralisers - if any) have a solid and consistent flight heritage.

For new EPT, or even for new EPS with little or no flight heritage, the reality usually gets away from the ideal case, with the EPS and the S/C being developed separately and with the consequent need of several iterations in order to harmonise the overall design. The number of such interactions and the possible criticalities arising from each of them are what lowers the confidence of S/C system engineers in a given EPS (and, thus, in the EPT on which it is based).

Criticalities are of two types:

- arising from the S/C (i.e. at system level) and having impact on EPS design
- arising from the EPS and having impact on S/C design

Usually, criticalities deriving from S/C design are very well definable, since S/C design draws on years of experience and flight heritage (at least at component levels, if not at subsystem level) and are flown down to EPS as new requirements. Some new payloads (especially scientific ones) could result in unexpected criticalities, but these too are flown down as new requirements. In any case, criticalities deriving from S/C are flown down to EPS as new requirements and their impact must be accommodated by EPS design.

Criticalities arising from EPS are usually resulting from limits imposed by physics, by materials and by available technologies for generating the required fields (electric, magnetic). Such criticalities have unavoidable impacts on the rest of the S/C. These impacts shall be accommodated by the S/C either by relaxing requirements on EPS or by modifying part of the design of the rest of the S/C.

Running into this type of criticalities, either as result of EPS development or as result of new requirements from the rest of the S/C, is the main fear (or "perceived risk") of S/C system engineers and it is the largest deterrent against the use of new EPTs or new EPSs (even if based on existing EPTs).

In this case, the main ways to lower the perceived risk (and also the actual one) and higher the level of confidence about a successful design of EPS within the frame of the whole S/C are:

- to limit as much impact of the EPS on the rest of the S/C design and AIT
- to define, quantify and contain such impact, to avoid a chain of knock-down secondary effects.

D. Finding Out the Impact of EPS on the Rest of the S/C

As mentioned, an EP technology turns a physics concept into implementation, the EP thruster is its engineering implementation and the EPS is all the rest that is needed in order to work on a spacecraft.

A practical method to assess the impact of a whole EPS on a S/C is to subdivide both of them in their constituents (EPS components and S/C subsystem) and evaluate the possible impact of each EPS component on each of the S/C subsystem.

This can be done in the form of a matrix, with S/C elements as headings of each column (i.e. in the first row) and EPS elements as headings of each row (i.e. in the first column). In the following table, there is a general example of it (with cells to be filled).

	Power	OBC	OB S/W	AOCS	CPS	Thermal Control	Structure	TMTC	Payload
Electric Thruster(s)									
Neutralizer(s)									
Power Management,									
Propellant Management,									
Management Software,									
Thermal Control,									
Diagnostic System									
Harness									
Pointing Mechanism(s)									
Structural Elements									

Table 1. EPS-S/C Impact Assessment Matrix. *A tool to be used both as a checklist and as a summary of all impacts of EPS on S/C.*

E. Practical Use of the Impact Matrix for the Design

This matrix, the "impact matrix", can be used both as a possible impact checklist and as a tool to visualise and map the EPS impact scenario on the S/C.

It works as a checklist at the moment of finding out possible impacts: all EPS components are put in front of all S/C subsystem, so that it is unlikely to oversee a possibly critical interaction.

Each cell of the impact matrix should be filled with a list of bullet indicating the possible impacts of the EPS component of the same row on the S/C subsystem of the same column. This exercise can be performed either against a defined individual S/C (either existing or in the design phase) or against a whole class of S/C and missions (small GEO telecom satellites, large GEO EO satellites, large LEO EO satellites, etc.).

Once filled in, the impact matrix works like an impact map in case new requirements or changes are imposed on the EPS. For example, a new requirement on the EPS Power Management unit can have impacts on all S/C subsystems that have a non-empty cell on the "Power management" row.

There are three ways to use the impact matrix to practically reduce the risk and increase the confidence that problems (encountered during design with the rest of the S/C) will be solved:

- to identify the EPS components that need to be simplified (or, if possible, eliminated), in order to reduce the number of the bullet items contained in the impact matrix cells (or possibly to reduce the total number of non-empty)
- to show to the S/C system engineering team that all possible aspects have been considered
- to use it as a tool for communicating impacts of modifications or new requirements during working meetings with the rest of the S/C design team

Although the use of the impact matrix cannot replace concurrent engineering and flight heritage, it helps a lot in keeping track of all possible impacts and deriving criticalities, so that it helps to increase the overall confidence about design and possible arising issues. This is true also in the case the impact matrix is filled in against a class of S/C and, to a certain extent, also against classes of missions (e.g. Earth Observation LEO, Telecom in GEO).

F. EPS Complexity Against Risk

In order to ensure a proper implementation (i.e. to work flawlessly as required within required margins during the whole lifecycle) of the EPT, the resulting EPS tend to become large and complex.

Increased complexity is often a result of trying to squeeze out the last 20% of maximum achievable performances.

But the more complex it gets, the more it is perceived as a risk, the more it costs and the more risk mitigation is going to be costly (cost of time and money). A complex EPS needs more development and more testing to prove its reliability.

Also, more critically, a large EPS is going to have extensive impacts on the rest of the spacecraft system and on the mission lifecycle, i.e. many entries on the impact matrix of any mission lifecycle phase. Therefore, not only a complex EPS is going to cost more time and money, but it is going to make also the rest of the S/C more expensive and more time requiring.

Thus, a very simple EPS is more likely to have less impact on the rest of the S/C and should be a design guideline.

III. EPS and its Testing

The following fields of confidence have to do with tests:

- confidence that problems that might be encountered during AIT with the rest of the S/C will be solved
- confidence that the final customer will deem the EPS suitable for the mission and consent to fly it
- confidence that the system will work once in space

The test history of an EPS can be summarised as follows:

- Tests at EPS components level are needed to verify that they work as required, each one on its own
- EPS level tests are needed in order to verify that all EPS components are working together and that, therefore the EPS is working as required
- EPS tests together with the rest of the S/C (usually very limited in scope, as normally the thrusters cannot be operated in air)

Proceeding with higher level, tests are necessarily becoming more complex and the test facility size becomes bigger. Beside that, tests of EPS can be quite expensive, since in most cases dedicated EP test facilities are needed to provide the required general conditions (level of vacuum, room and temperature) for long periods of time.

G. Making the Most of Test since the first Test Campaign

To increase test related confidence there is no shortcut to tests. But it is possible to increase the confidence in positive result of such tests by using the typical space industry PA (methodologies, materials, processes, parts and documentation) since the very beginning of the development of the EPT.

Following typical space industry PA will decrease the risk of encountering problems during AIT because the whole EPS would result already designed for a typical S/C AIT campaign.

Design or material changes of a given component of an EPS in order to make it acceptable for space related standards will cause a decrease of confidence and very likely more tests, so it shall be avoided.

H. Avoid Overselling the EPT

It is better to avoid marketing an EPT on expected extreme performances of a deriving EPS based on the assumption that a currently testes thruster lab-model has got potentialities (often, once explored these potentialities are leading to other criticalities): 20% of efforts usually brings to 80% of result: it applies also for EP, when the efforts are about development and results are about performances. This also means that to squeeze that remaining 20% out of the EPS it is needed an amount of work and time which is in the range of four times the one carried out so far.

And it could also be worse than that: overselling can also mean that a mission which seems feasible on paper becomes impossible in reality, as there is often some performance loss once going a properly space engineered set of hardware

I. An Impact Matrix also for Tests

Another way to increase confidence about tests to be performed and a positive outcome of them, is to consider the interaction of the EPS components with the rest of the S/C subsystems: what test of the EPS will have impact on the test of the rest of the S/C and on the whole of it.

A new impact matrix, this time filled in bearing in mind EPS test campaign and its impact on the S/C, can again help both as a checklist for planning test campaigns, both as a map of impact if test campaign needs to be modified.

IV. EPS During Launch Campaign and LEOP

An important part of the confidence that the final customer will consent the EPS to fly and that the system will work once in space is to actually demonstrate that the EPS can endure all the way to space.

Launch campaign, launch itself and early operation phase are usually the most challenging mission phases for flight equipment in terms of mechanical loads of any type and extreme uncontrolled temperatures.

Ground storage temperatures during launch campaign can easily range from -40C up to +60C, while static acceleration during launch can also easily go up to 10g, not to mention all possible launch induced vibrations and shocks.

Early operation phase threats are coming from the mechanical shocks that could be generated by the detachment of last stage or by the deployment of other structures (solar arrays, antennas) as well as by extreme thermal loads due to the fact that the thermal control system might not yet be activated.

In order to increase the confidence about the EPS capability to actually survive to such phase, either the use of brittle materials for large components shall be minimised or there shall be evidences that they have been designed to survive to such environments.

V. EPS in Space

There is nothing like a proper life test to give confidence that the EPS will work once in space (indeed, now industry standard require full life test of EPS and it is a mandatory requirement for most commercial missions).

The life test duration shall have some (required) margin over the expected life cycle duration and shall be performed on flight representative hardware. Any slight deviation from flight configuration could lead to different long term results because of the effect of these cumulative phenomena like e.g. deposition, erosion, embrittlement.

Any previous life test on similar hardware conduced in accordance with space industry PA could increase a lot the level of confidence, but a life test on flight representative (i.e. the same) hardware is a must and should be carried out.

Beyond the confidence given by a life test, the other main contributor to confidence of EPS working in space is to an idea on how to operate it once in space (i.e. how to make it work).

Apart from a clear set of modes (and mode transitions) and a basic set of telecommand and telemetries, is it necessary to assess the operational constraints of the EPS itself. (beside the fact that available TM channels and rate are limited onboard the S/C)

Some of them are intrinsic to the EPS (e.g. the thruster cannot be fired unless the neutraliser has been warmed up and is operative) some others are deriving from interaction with the S/C (e.g. the thruster cannot be fired in a given S/C mode because there is no enough power available for that). Also, the EPS could impose constraint on the rest of the S/C (e.g. disturbing certain radiofrequency bandwidth when operating at full power)

The best way to find operational constraint is to use once again the impact matrix, filling it in with possible impact of the S/C on the EPS and, if needed, vice versa.

VI. Summarising About Increasing the Level of Confidence on a Given EPT and/or EPS

Although is not always possible to have the ideal "harmonised design approach" while developing an EPT into a specific EPS, it is possible to get close to it by starting to think well in advance to its final use in space.

This means:

- develop the EPS using typical space industry PA as much as possible (methodologies, materials, processes, parts and documentation)
- start envisaging what are the possible impacts on the rest of the S/C (and its subsystem) during all mission lifecycle phases (design, AIT, Launch Campaign, LEOP, operations) and efficient way to reduce them
- Keep the EPS design as simple as possible
- perform all necessary tests using as much as possible typical space industry PA, in order to make the most out of them during the rest of the development.

VII. The "Perfect Electric Thruster" Concept

Assuming that performances are in line with what expected for a given application, it is possible to define an ideal EPS that would be eventually selected for flight.

J. Defining the Ideal EPS

As mentioned, simplicity is definitely a guideline: it minimises the design, the hardware to build, the tests and the impact on the rest of the S/C. On the other hand, inherent system simplicity increases the confidence that the system can work, can be easily troubleshoot if needed, will be easy to test, won't have hidden criticalities.

Therefore, the ideal EPS has got the minimal amount of ancillary components and they are anyway reduced to the very essential. In this way, the EPS is reduced to little more than the electric thrusters it has. Of course, the way the thrusters have been conceived shall support such minimal EPS approach. That's why the title refers to a “perfect

electric thruster", rather than a "perfect EPS".
The minimal EPS could therefore be defined as having the following components:

- The thruster itself (more about it in a next sub-section)
- No neutraliser (the thruster ideally should not need it)
- No power management (just the power in leads, directly from the PCDU of the S/C)
- No management software (simplified working modes are run directly by the OBC)
- Minimal telemetry (temperature, voltage and current, directly collected by the OBC)
- Minimal propellant management (possibly without moving parts and without piping)

The OBC could have a single board dedicated to interface with the electric thrusters on board, but this is not regarded as an EPS PCU.

K. Defining the Ideal Electric Thruster

The ideal electric thruster can thus be defined by applying:

- all possible actions and processes to higher the level of confidence, as summarised in Section IV
- the thruster concept deriving from the ideal EPS
- a general drive to keep overall associated costs down

This is actually the perspective of a S/C system engineer, whose technical role is a key one in deciding what EPS to fly (or if flying an EPS at all).

The definition of the "perfect" (ideal) electric thruster is better done by parts and features, as in the following subsections.

L. Thrust Beam

It shall be of (quasi) neutral plasma, because the thruster shall not require neutralisation. "Quasi neutral" refers to a plasma with an equal count of ion and electrons: this is also necessary in order to avoid thrust beam charge excess to get neutralised in average among onboard thrusters, by means of currents streaming across the S/C.

Also a heated non-electrically-charged gas (electro-thermal propulsion) would suit this requirement.

The beam divergence angle is close to zero for few S/C lengths, to minimise interaction with S/C appendages and other components. Also, beam real direction and pointing stability should be easily predictable across all throttle ranges and the whole lifetime (to shorten test and simplify in orbit operations).

Its RF signal shall be limited in a very narrow bandwidth and its variation (frequency and intensity profile) shall be easily to predict, in order to have the least possible disturb impact with onboard radio-link with the ground segment. Also, ideally, there should be no conducted emissions back onto the S/C power bus.

M. Thrust Chamber & Nozzle

The thrust chamber and nozzle is the assembly where the propellant is turned into plasma and then accelerated.

Ideally, the ionisation and acceleration process should be achievable also at room pressure and in presence of air (allowing for due scaling of thrust parameters), to keep clear from all vacuum testing criticalities (facilities, costs, bookings, impact on the tests of the rest of the S/C).

The ionisation should require the minimum amount of power, whereas most of the power shall be used by acceleration.

N. Propellant

The propellant shall require a very simple propellant management system, so it shall ideally be either in solid state, fed into the thruster by a loaded spring, or (less ideally) in a phase equilibrium (liquid/vapour or solid/vapour) so that the gaseous fraction keeps a constant pressure once the propellant is kept at a given temperature.

The propellant should also be non-toxic and inert at room conditions, to simplify handling, storage and testing.

A solid propellant would be the most cost effective option for handling, storage and testing, whereas the phase equilibrium solution would allow the simplest propellant management system while still delivering gaseous propellant to the thruster.

The exhausted propellant shall be gaseous at the typical temperature of S/C coldest external surfaces, to avoid build-up of back-deposited propellant on external S/C surfaces.

O. Power and Control Interface

As mentioned, this thruster should not require a PCU, in order to result in a simple EPS, and it shouldn't be moved to the upper level, e.g. into the OBC or into the PCDU. Also, the PCU should not be moved to the lower level, on the thruster, in the form of some electronics attached to one of the thruster sides (nevertheless, a minimal number of discrete components might be present). Therefore, what remains on the thruster should be something like a power and control interface.

Ideally, the power interface should be given in the form of two leads running at the same voltage of the general PCDU power bus. This allows on one hand to have a very simple interface and on the other hand to keep the feeding voltage low. High feeding voltage should be avoided, because they bring complications at test level and because available options for connectors (both flight and test ones) become less with higher voltage.

The on-off mode shall be commanded by giving power to the interface, the thrust level shall be commanded by varying one parameter only (either voltage or current). If it is possible to vary both thrust and Isp, then these parameters shall be univocally commanded by a couple of voltage and current parameters. This would reduce both the complexity of mathematical models and the complexity and length of testing. Also, the conversion of such voltage and current parameters should be ideally linear, in order to avoid conversion errors in S/C SW.

The needed telemetry shall be given by the feeding (voltage and current) and by a few thermistors only. This would keep telemetry inherently simple, decreasing the test time and complexity.

The working mode and the phase transition diagram shall be kept as simple as possible, so that this translates into a much simpler SW (if any, running on the OBC) to manage the thruster.

P. Integration and Test

Ideally, the thruster should not (as much as feasible) require dedicated facilities and should (as much as feasible) be firing also at room conditions. It should be easy to test, both in its elements and as a whole or together the rest of the spacecraft

The thruster shall be conceived in such a way to be as modular as possible, both physically and functionally (and physical modularity should coincide as much as possible with function modularity), so that it is possible to test its individual components before assembling it. Also, modularity would allow an easier integration with the rest of the S/C (easier interweave of integration steps and functional tests in the AIT procedure)

It should be possible to test-fire the thruster as part of its acceptance (i.e. unlike pyros or solid rocket motors)

A thruster model with a configuration similar (relevant) to the flight one shall have successfully passed a life test, giving confidence on all cumulative processes and phenomena are well understood and factored in.

Q. Product Assurance

The use on the thrusters of materials and processes that are not used in the space industry shall be minimised. This keeps both qualification costs down and confidence on no hidden criticalities high.

According to the same philosophy, the use on the thrusters of EEE parts that are not commonly used by the space industry shall be minimised.

Possibly, the use of materials, parts and processes that are usually employed by the space industry shall start since the very beginning development of the EPT. This avoids a later conversion into typical materials, parts and processes that is a source of extra expenditure and is a potential source of hard-to-solve troubles later on in the thruster qualification phase.

VIII.Conclusion

Starting from the “secondary issues” that might determine the selection of a given EPT and its deriving EPS, it has been shown the S/C system engineer approach, taking into account the confidence that the EPS could actually accomplish the mission to be flown.

Following that, an ideal EPS and its main constituent, the ideal thruster (the “perfect thruster” of the title) have been defined in some of their features, remarking why such feature would help building the necessary confidence to select the thruster for flight.

Such a thruster of course does not exist, but its concepts represent a benchmark: the farthest away a thruster gets from it, the less are the probabilities that it will be selected among others with similar performances.

Of course, the effect of getting far away from the "ideal thruster" can be offset (but up to a given extent only) by better performances and lower cost.

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