EPS-500 development status

IEPC-2013-063

Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013

F. Marchandise[1], V.Vial[2], M. Öberg[3]and N. Cornu[4]
Snecma Direction Moteurs Spatiaux, Vernon, 27200, France

D. Barbier[5]
Sagem Défense Sécurité, Valence, 26000, France

and

N. Arcis[6]
CNES, Toulouse, 31401, France

Abstract: EPS-500 is a propulsion subsystem concept with integrated functions gathering a thruster, a power processing unit, a fluid control device and its command electronics which, individually, are at TRL4. This activity is supported by SNECMA and CNES and the current maturity level obtained for EPS-500 is a TRL3 with the test of innovative individual functions. All the functions are optimized for the available power and for low cost recurrent hardware. The overall performances are compatible with 250kg class mass, low power satellite, LEO missions or GEO station keeping missions for small or big satellites according to the requested total impulse. The 500W version is designed to perform up to 0.5MN.s total impulse at around 30 mN thrust. Two other versions, dedicated to lower and higher input power around 300W and 700W, are under study with a minimum hardware modifications. This article describes the EPS-500 architecture function optimizations. It describes the different prototype activities for electronic supplies, thruster performance and fluid management. Articulations between power processing, flow rate implementation, thruster firing are declined towards lowering the number of electronic functions. Tests results show good thruster efficiency around 40%, good electric power supply efficiency above 90%, and fluid management data within expected global performance even at supercritical Xenon temperature and pressure conditions.

Nomenclature

Δt	=	time step
$F, F(t)$	=	thrust
m	=	satellite mass
ΔV	=	satellite speed increment

[1] Electric propulsion system/thruster design engineer, Plasma Propulsion Section, frederic.marchandise@snecma.fr
[2] Electric propulsion thruster design engineer, Plasma Propulsion Section, vanessa.vial@snecma.fr
[3] Electronics engineer, Plasma Propulsion Section, michael.oberg@snecma.fr
[4] Head of Electric propulsion section, Plasma Propulsion Section, nicolas.cornu@snecma.fr
[5] Electronic system design engineer, , daniel.barbier@sagem.com
[6] Head of the Propulsion, Pyrotechnics & Aerothermodynamics Office, nicolas.arcis@cnes.fr

I. Introduction

THE EPS500 is a fully integrated electric propulsion subsystem. Such concept of electric propulsion (EP) aims at approaching chemical type propulsion integration at system level. Integrated subsystems or similar approach already exist in the past and were tested in flight or ready for flying[1-4]. Our approach is to push the concept to its limits for performance to cost ratio optimization. We present the overall subsystem declination for adequate performances (ISP, Thrust) towards specific mission type. Descriptions of the different main functions with their TRL status are detailed with emphasis on specific way of subsystem use. PPS® Thruster was already studied[5], the power processing unit with auxiliary power supply philosophy is described with first results, and the pressure regulator unit is detailed with its specific tests including around the Xenon critical point.

II. EPS500 Subsystem innovative concepts and declinations

To achieve objectives, we come back to the initial specification for a propulsion subsystem and analyze the real spacecraft needs. It becomes clear that the need for thrust is closely linked to an impulse demand from the spacecraft and those specifications were often derived from classical chemical propulsion with its advantages and drawbacks.

Looking at the classical thrust equation $F = m\, \Delta V / \Delta t$, it appears that the demand from spacecraft is ΔV, mass m is a spacecraft constraint, thrust F and firing time Δt concern the propulsion subsystem. For a single station keeping thrust demand, spacecraft mass will not change in a way that it is mandatory to take into account the decrease of spacecraft mass during firing, the firing time should be limited to optimize the trajectory performance and the fuel consumption. Due to the high thrust, this is done naturally for chemical propulsion, but for EP, this is a more stringent constraint that may lead to small performances decrease. Of course, for very high impulse needs, the criticality of thrust and firing time decreases as far as the propulsion subsystem knowledge is good enough. Anyway, in that case, there is often secure strategy of firing with for example a long pulse followed by orbit evaluation and shorter correction pulses to achieve the goal.

As an example, the needs for minimum impulse bit for chemical thruster were converted to a level of precision for the thrust itself because the duration of firing was always short and was already critical. For electric propulsion, this level of thrust knowledge is still important but the thrust firing time is also a parameter of the same importance with lower criticality because of the low thrust level. As far as the impulse per firing is the real need, the real critical parameter is the firing time per thrust level integral:

$$\int_{t0}^{t1} F(t)\,dt$$

Any good knowledge of the thrust during time is enough to fulfill requirements of firing impulse, this allows relaxing the flow rate constant level if the transfer function between thrust and flow rate is well known.

From these above considerations, we perform studies to concentrate the fluid feeding functions, the electrical power supply functions and the thrust functions. We also optimize the subsystem with architecture simplification about redundancies and with functional sequence simplifications to avoid too costly components in electronics. Thermal constraints were also addressed to minimize thermal control device at spacecraft interface.

A. EPS500 subsystem studies

The EPS500 propulsion subsystem requirement was initially based on a 500W available input power. The total impulse targeted for the subsystem is 500kN.s for the same input power. Performances of the PPS®X00 first prototype shows that the thruster could achieve extended range of this input power between 300W up to 700W.

After that first performance evaluation, it became clear that the range of mission could be extended from specific LEO missions to small satellite with lower power (orbit control, drag compensation and end of life disposal) and to small GEO satellite commercial missions (station keeping) or even bigger satellites (East West Station Keeping in case of orientation mechanism failure for North South Station Keeping). This drive the subsystem extension

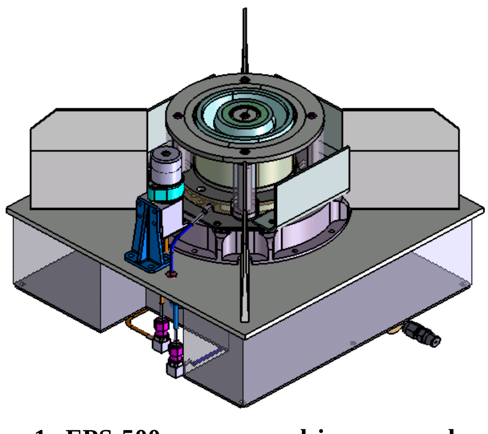

Figure 1. EPS-500 propulsion subsystem architecture. *EPS-500 architecture with thruster (PPS), power processing unit (PPU) and pressure regulation unit (PRU) mounted on the same structure. Interface with satellite is between thruster and PPU.*

studies with the same objective of cost reduction.

Optimizations have been done from initial design to decrease electronic complexity and to minimize the thermal load on the spacecraft. This led to a more flat electronic box with additional external radiators dedicated to electronics cooling, see figure 1. Interface sizes have grown to the allowed 250mm x 250mm while the height above spacecraft skin has been kept to less than 100mm.

The input of the subsystem is the propulsion fluid at high pressure (typically Xenon at up to 150bar), the electric power from power bus (typically at 28V for low earth orbit platforms or 50V to 100V for some other platforms) and the communication bus with the different simple commands, control and health monitoring of the subsystem.

To achieve the three main missions, the operational functional points are evaluated for thrust from 15mN to 30mN and 40mN, and for subsystem specific impulse from 1300s to 1500s with respectively 300W, 500W and 700W at subsystem level.

B. EPS500 subsystem declinations for typical missions

Usually, the operating point for the mission is known well in advance during the mission definition, so we considered that at the time of propulsion subsystem supply order, these data would be available without real change in the thruster and subsystem performance. This allows doing some adjustment during manufacturing that lead to less complex electronics and subsystem architecture.

Based on this principle, the EPS500 is declined for each main component (Power Processing Unit [PPU], Thruster [PPS®], and Pressure Regulation Unit [PRU]) with some minor modifications.

PPU modifications are concentrated on the electronic power supply card that allows optimizing the efficiency for each power (300W, 500W, 700W) and adapting to the input power bus (28V for 300W and 500W, 50V-100V for 500W and 700W). Auxiliary power supply, logic and sequence of operations cards are identical.

PPS® modifications are concentrated on the channel size to optimize the gas density towards available magnetic field and eventually front plate for magnetic field shape adjustments. Interfaces, structure, cathode, anode and Magnetic field generator are identical hardware.

PRU modifications are concentrated on the internal pressure level (together with a few electronic hardware components modifications), high pressure and low pressure flow restrictors levels to adapt the total flow rate to anode and cathode needs for each power.

All other functions are performed with identical hardware such as structural and thermal architecture, power supplies for heaters, pressure transducer and valves, or general hardware comprising pressure transducer, valves, etc…This leads to a family of EPS500 subsystem called EPS500-300, EPS500-500, and EPS500-700 for the currently foreseen input power range.

III. PPS®X00 prototype and evolutions

HET low power capability has been widely demonstrated through numerous thrusters all over the world mainly on test bench. A few of them went across the qualification process to get their flying certification and successful mission.

The PPS®X00 first prototype has been tested[5] and has shown good anode efficiency for this category of thruster and help to select the functional points for each input power available. The selected thrust and system specific impulse target are described in Table 2. The two lines about specific impulse translate the loss that occurs for short firing because of gas losses during thruster starting and stops in the highly simplified version.

Because of the flow rate optimization towards plasma density, for the different powers, the channel width will be adapted together with the front plate. All other components are identical for each input power.

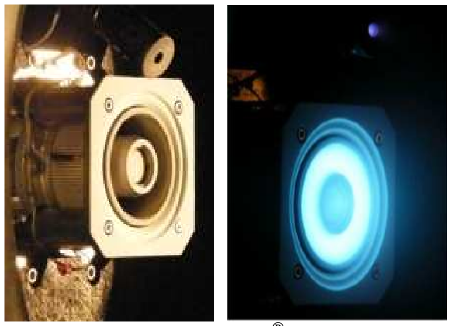

Figure 2. Thruster PPS®X00 prototype n°1. *Thruster firing during initial validation test Designed for 300W, it shows anode efficiencies up to 40%*[5]

IV. Power Processing Unit concept and critical power supply prototype

One of the many goals of the EPS-500 subsystem is to design as far as possible a highly compact and efficient plasma thruster system, integrating novel technologies and design approaches in many applicable fields. Due to the power processing unit being highly integrated in the subsystem, and the inevitable heat load from the thruster nearby the electronics, this imposes a careful design approach when integrating this part into the overall system.

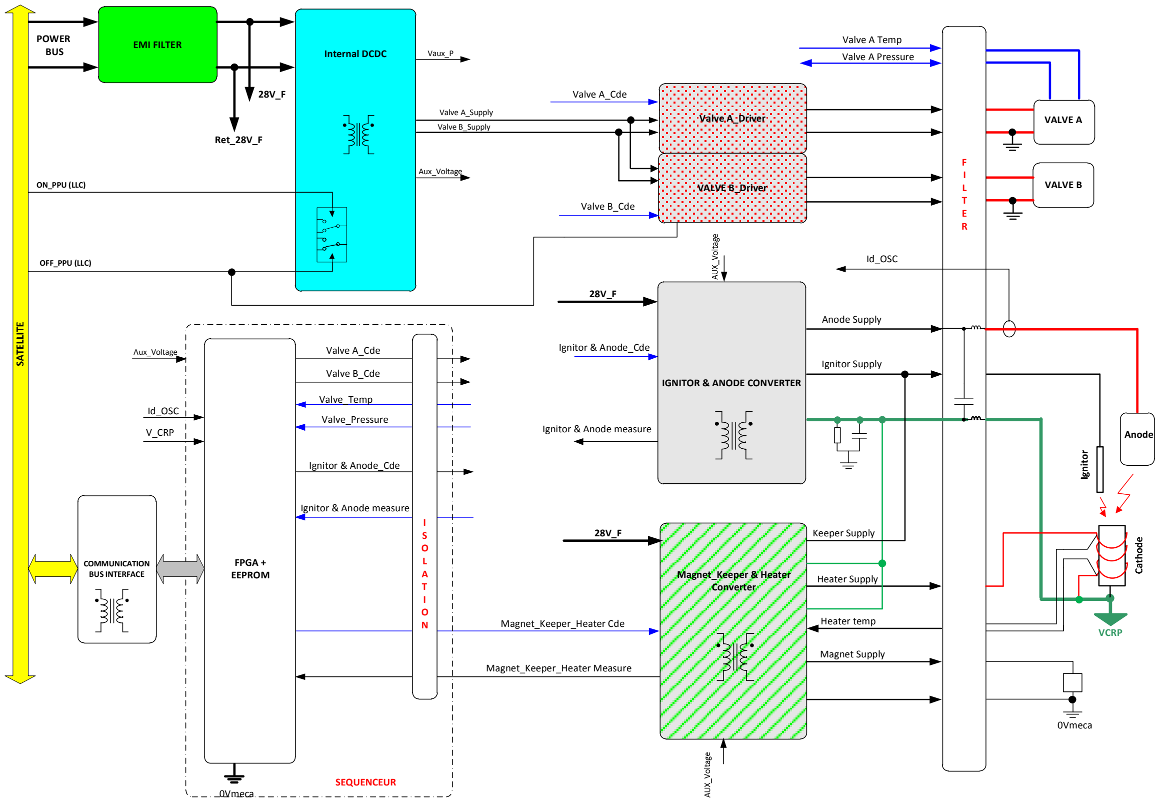

Figure 3. EPS500 PPU architecture

The power processing unit for the EPS-500 has to fulfill the following tasks:

- Input filtering and EMC protection on the primary power bus
- Valve commands (Xe mass flow regulation)
- Anode power generation and keeper functions
- Magnet and Heater current generation
- Thruster filtering protection (Filter Unit)
- S/C communication bus I/F
- Sequencer functions

During the first phase of the project, the main design and pre-development effort was aimed at the anode power supply architecture. This part is considered the most critical from a thruster point of view and is also the highest heat generator which in conjunction with the additional thruster heat load could be a critical design issue for the thermal aspects of the EPS-500 system.

The figure 3 shows the different elements making up the entire EPS-500 Power Processing Unit.

A major difficulty in designing the anode converter was the fact that the primary power bus was a non-regulated 28V bus, presenting a voltage span of 24 – 34V. This, together with the relatively high input current on the primary power bus, approximately 20A, the thermal constraint aspects, imposed a highly optimized anode converter design. The requirement on the EPS-500 system's power consumption was limited to 500W for the version developed for this phase of the project. This means that the available power to the thruster is roughly 400W (max), at different anode voltages (150V - 400V). It was decided that the anode converter be optimized for a desired anode voltage of 250V, knowing that the efficiency would be lower at 150V and 400V.

C. Anode power module architecture (F4)

The chosen architecture for the anode power supply is a full-bridge phase shift converter with active secondary diodes snubber to limit the power drawn from the primary power bus, required to be less than 500W continuously. The anode power supply has to be isolated from the primary due to the requirement imposed by the thruster of having the anode power supply floating electrically against ground. The active power management acts on the output voltage and total power level applied on the anode power output, knowing that the additional power supplies are less critical from a transient power surge point of view.

Due to the relatively low input power bus voltage and power level, the primary circuit MOSFETs could be chosen from a lower voltage (#100V) class of transistors presenting a low R_{DSON}. However, the fact that the transistors work under low voltage / high current imposed the choice of having two (2) transistors in parallel to limit the losses due to the global R_{DSON} and overall requirements on converter efficiency.

To be able to regulate precisely the output voltage and power, the PWM control circuit is placed on the secondary side and referenced to the cathode reference potential (CRP). The regulation of the primary MOSFETs is performed through a transformer isolated circuit to guarantee the galvanic isolation between primary and secondary side.

The fact to be able to supply at constant power output (400W) within a large voltage span (150 V – 400V) penalizes heavily the electrical performances of the anode converter module. This is due to the accumulation of high secondary output voltage (400V) and high output current (400W/150V=2.7A). Nethertheless the efficiency obtained (computation and measurement) are fully acceptable.

D. Breadboard anode equipment (Figure 4)

During the pre-development, an anode breadboard equipment was developed aiming at validating the anode module architecture chosen for the EPS-500.

A certain number of elements had to be specifically developed to be able to meet the stringent requirements imposed on this module. This was in particular true for the transformer, which was identified early in the project as a potential "bottleneck" component, with regard to the strong requirements on efficiency and thermal dissipation aspects.

The converter works at a switching frequency of 200kHz.

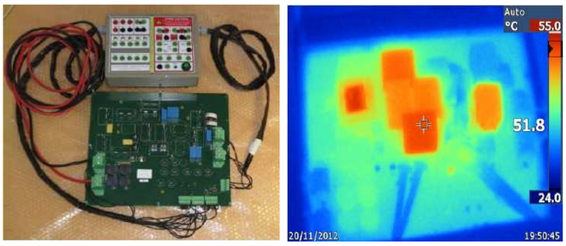

Figure 4. Electronic power supply breadboard. *Electronic anode discharge power breadboard tested at 500W (infrared image showing that hot spots are fully acceptable at component level).*

Results concerning the efficiency and performance of the chosen architecture have confirmed the very good behavior of the topology in general. Below is a table synthesizing the overall performances at two different anode output voltage levels at different primary power bus input voltage levels.

Measurements P_{out} (W)	Vout (V)	Vin (V)	Efficiency η (%)
≈ 400W	279.6	22	94,3
		24	94,8
		28	94,4
		30	93,9
	399.3	22	93.0
		24	94.0
		28	93,8
		30	93.2
≈ 200W (mid-power)	279.7	28	95.0
	399.4	28	91.8

Table 1. Breadboard measurement efficiency

V. Pressure Regulation Unit concept and prototype tests results

E. PRU concept description

The pressure regulation unit cumulates the functions of the usual pressure regulator and of flow rate regulation. From remarks on spacecraft needs and observing the large Hall Effect Thruster range of possible working points, we propose to perform a non-constant thrust during one firing to obtain the demanded impulse. This allows a huge simplification of the fluid subsystem as sketched in figure 5 where the minimum valve number is obtained in the fluid line. This is interesting when the number of thruster is limited, which is usually the case on spacecraft.

The valve [5] is always open during firing and is there for emergency shut down and double barrier for tightness. The valve [6] cycle to feed through the restrictor [7] the volume [2]. Its pressure is controlled through pressure transducer and secured with temperature measurement.

The size of volume [2] allows integration close to the thruster. A PRUX00 prototype has been manufactured to check the concept feasibility.

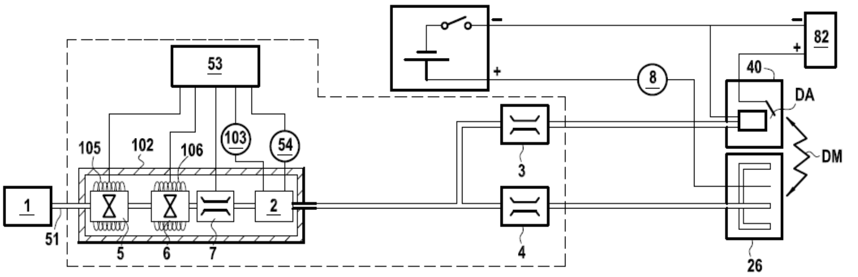

Figure 5. Sketch of Pressure Regulation Unit with thruster and power supply *Storage subsystem [1] feed valves [5] and [6] at high pressure and restrictor [7] allows regulating pressure in volume [2]. Fluid is dispatched through restrictor [3] and [4] to feed thruster cathode [40] and thruster anode area [26].*

The life limitation is linked to the valve number of cycle and to the different volumes in the line. Accurate design allows minimizing the size of the whole regulation subsystem to be mounted on the bottom of the PPU (see Figure 1). The only interface to the spacecraft is the high pressure tubing. For this type of thruster, a 3500h lifetime fulfills most of the missions. So, we dimension this PRU for 5250h lifetime to get the qualification margin.

In this concept, the loss of the volume [2] gas after each firing occurs but due to the low volume size, this is acceptable at system level. Anyway, the blow down firing process minimizes this loss of gas. A possible other option is to implement the valve [5] after the volume [2] with a lower level of robustness for degraded operation which appears for some operators as a drawback.

F. PRUX00 prototype tests

A prototype was manufactured for concept verifications purpose. It is modular and allows the change of restrictor level and the change of volume [2] level to check different behavior and was built with one solenoid cycling valve [6]. A thermal area was implemented around the valve and high pressure restrictor. Flowmeters were positioned in the inlet line and in the two outlet lines. Tests have been performed between 3bar and up to 145bar inlet pressure. The high inlet pressure was obtained at ambient temperature and needed specific supply. In fact, the Xenon storage for spacecraft is done at a specific density level, typically 1600 kg/m^3. It gives ambient pressure storage around 75bar. The high pressure is obtained because of thermal excursion and result in same density level. The test performed at ambient temperature and high pressure is a kind of extreme simulation test at higher density (around 2000kg/m^3) than what will be done at spacecraft level. Around the Xenon critical point; tests were done at 20°C and 10°C to check the subsystem regulation behavior.

Tests consisted in a series of regulation commands of the pressure using high pressure level, temperature measurement and pressure measurement of the volume [2] conditions. The typical pressure measurement shows the test sequence in figure 6. This test was foreseen at 5bar, 20bar, 55bar, 58bar, 60bar, 100bar, 150bar. Difficulties occurred during testing and we obtained 145bar max for the very high pressure. Anyway, tests results with nitrogen shows that the regulation could perform a very accurate pressure regulation with a very rapid activation of valves. This would lead to millions of cycles. That number is higher than current space qualified valves. As foreseen, we decrease the activation number with regulation parameters tuning toward a typical 18s cycle at 1bar of Xenon, compatible with qualified number of cycles. The range of pressure obtained in the volume [2] was at its maximum at +/-23% and +/-26% from 1bar regulation targeted for 20°C and 10°C. This was observed for very high inlet pressure without surprise for ambient temperature and at 58bar for the 10°C test. This decreases to less than 16% and +/-18% from 1.5bar regulation. Anyway, it remains compatible with thruster working range capability. Several tests at higher pressure regulation were done; this shows a better and better ratio between higher pressure and lower pressure. The test at 10°C was done with a temperature of the valve and the restrictor below 9°C and we get surely supercritical Xenon at the inlet of the valve. This test was performed at the end because of potential risk of two fluidic phases overpressure. In fact, it shows a

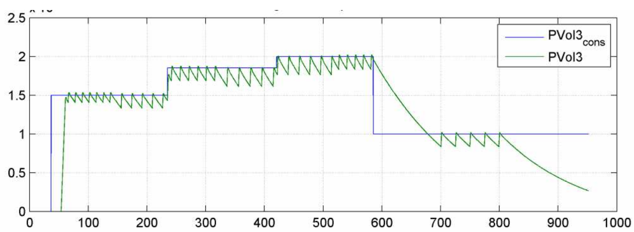

Figure 6. Pressure Regulation Unit typical test: *Measured pressure in volume [2] versus pilot pressure with 55bar inlet pressure during time.*

good behavior of the valve and of the regulation with a good tightness level before and after the test. This allows performing regulation even with supercritical Xenon without heating it, but this has to be confirmed at lower temperature that may be encountered in the spacecraft, such as -20°C to -45°C.

Without surprise, the time between pulses versus inlet pressure follow a curve close to the Xenon density curve. With short time for low pressure inlet up to 40bar up to twice the initial value for high pressure. As far as we did not introduce Xenon real gas model in the regulation, the calculated valve opening time is equivalent to the perfect gas and the effect is to observe a longer delay between valve openings. This is coherent with Xenon density increase. A similar behavior occurs with the test in cold conditions (see figure 7). The 58bar, 10°C test show a behavior in the same range of the 142bar, 21°C test about delay between valve actuation. The general behavior was expected due to the large difference in density for the two tests conditions, but this is still a small surprise because we expected a behavior longer for the 142bar, 21°C test than for the cold test (respective expected density at 2000kg/m^3 and 1800kg/m^3). We can find explanations through even colder conditions because of cold depressurization for the 58bar that could generate apparent colder conditions or also in the small time difference for the valve closing and opening because of temperature difference or through the regulation law that takes into account the inlet pressure information.

In any case, the behavior of the regulation keeps the pressure well in the regulation range demand and it was slightly affected by the temperature conditions or the inlet pressure condition. This results in a reproducible flow rate (even if the flow rate type of measurement was too slow to give the maximum peak due to the pressure difference in volume [2]).

Thanks to all these tests and results, the PRUX00 concept has reached the TRL4. Improvement of tests conditions and colder tests in all pressure conditions will allow exploring the range of capability of the concept whose limits are unknown. We even explored higher pressure regulation range up to 5bar and reached a flow rate setting point close to the Smart-1 operating point of the PPS®1350-G. The next step will be to gather thruster, pressure regulation and regulation law to improve the EPS500 TRL from 3 to 4.

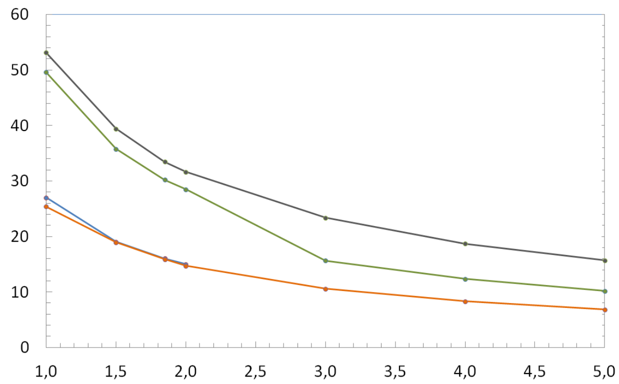

Figure 7. valve opening delay versus pressure: *Regulated pressure in volume [2] (x axis), time (y axis), 58bar,21°C before (blue) and after (orange) cold test, 58bar,10°C cold test (black), 142bar,21°C (green).*

VI. EPS Performance predictions

The EPS performance prediction includes all the losses of the subsystem. The Table 2 resumes the different EPS500 performances with input power at nominal high and low level. The thrust level has been extrapolated from tests results and we optimize the thrust level to the available input power from the PPU efficiency. The expected Isp includes the cathode mass flow rate. The "No losses PRU Isp" column indicates Isp of thruster with cathode consumption which represents an important fraction of the nominal flow rate. The column Isp 500s firing and 3600s firing represents the Subsystem Isp reduction after the use of blow down and stop of the thruster at the minimum level for the cathode flow rate. The gas residual pressure of the volume [2] is then lost across the thruster and its impact on the performance decreases down to around 2% Isp losses with 1h firing time. The 500s firing time is considered as a minimum firing time to keep still good performances.

EPS-500 input power	PPU efficiency	Peak Thrust	No losses PRU Isp	Isp 500s firing		Isp 3600s firing	
300W	94%	16.7 mN	1208s	1042s	13,7%	1182s	2,2%
500W	94%	28.9 mN	1264s	1072s	15,2%	1234s	2,4%
700W	94%	40.0 mN	1314s	1158s	11,9%	1290s	1,8%

Table 2. EPS® performance targets. *Estimation from thruster tests results[5], subsystem PRU properties observed during tests and 94% efficiency for PPU as tested. Cathode consumption hypothesis is around 0.25mg/s (and half this value for blow down limit).*

VII. Conclusion

EPS500 critical components were submitted to individual tests at TRL4 level, demonstrating the capabilities of new principles and confirming the foreseen performances that can be obtained by such a subsystem. The full subsystem principles and performances are also defined and the concept reaches TRL3. After the demonstration of the compatibility to supercritical Xenon, the gathering of the simplified Pressure Regulation Unit on a PPS®1350 thruster type with improved regulation is next promising steps to a low cost integrated subsystem.

Acknowledgments

Authors thank the recurring support of CNES, SNECMA and SAGEM to this work through Research and Technology programs and self-funding program for their advice and availability, and Moog,inc company for their on-time recovery effort to deliver the PRUX00 prototype valve.

References

Periodicals

[1]Plasma physics reports, Vol.29, n°3, 2003, pp.251-266 translated from “Fizika Plazmy”, Vol. 29 n°3 2003, pp 277-292. Original russian text copyright © 2003 by Kozubskii K.N., Murashko V.M., Fakel EDB Kaliningrad, Russia, Rylov Yu.P., Trifonov Yu.V., Khodnenko V.P., All Russia Scientific and Research Institute of Electromechanics (VNIIEM), Moscow, Kim V., Popov G.A., Obukov V.A. RIAME of the MAI, Moscow “The 30th anniversary of SPT Operation in space – Stationary Plasma Thruster Operate in Space” final form September 25th 2002.

Conference papers

[2]Caveny L.H., Ballistic Missile Defense Organization. Washington DC, Sankovic J.M., On-Board Propulsion Branch, NASA Lewis Research Center. Cleveland. OH, Allen D.M., Herbert G., W.J. Schafer Associate. Inc., N.Olmsted. OH, Garner C.E. Jet Propulsion Laboratory. Pasadena. CA. “The BMDO electric propulsion flight readiness program”, *24th IEPC-1995-132* – September 1995 Moscow, Russia

[3]Alexander V. Gorbunov, Vladimir P. Khodnenko, Alexander V. Khromov, FGU Research and Production Enterprise – All Russian Research Institute of Electromechanics (VNIIEM), Moscow, Vyacheslav M. Murashko., Alexander I. Koryakin, Valery S. Zhosan, Gennady S. Grikhin FSUE OKB “Fakel”, Kaliningrad, Vladimir N. Galayko, Nikolay M. Katasonov, JSC Scientific & Industrial Centre “Polus” Tomsk “Vernier Propulsion System for Small Earth Remote Sensing Satellite Canopus-V”, *32rd IEPC-2011-001* - September 2011 Wiesbaden, Germany

[4] Semenkin A.V., TSNIIMASH, Moscow, Testoedov N.A., Yakimov E.N., Ermoshkin Yu.M., Volkov D.V., Yukseev S.V., NPO PM, Krasnoyarsk, Sevast’yanov N.N., Verkhoturov V.I., Romanov S.Yu., Samitov R.M., Borisenko A.A., Ostrovsky V.G., RSC “Energia”, Moscow, Makridenko L.A., Volkova S.N., Khodnenko B.P., VNIIEM, Moscow, Poletaev B.I., Lyannoy E.G., Romanov A.V., Pavlov A.Yu., DB “Arsenal”, Saint-Petersburg, Partola I.S., Kuznetsov S.V., State Space Scientific and Production Center named after M.V. Khrunichev, Moscow, Resh G.F., Arakin M.V., Savosin G.V., Prokhorchuk Yu.A., Maksimov I.I., Lizunov A.A., Kabanov B.A., NPO MASH, Moscow, Murashko V.M., EDB “Fakel”, Kaliningrad, Popov G.A., Kim V.P., Obukhov V.A., Antropov N.N., RIAME, Moscow, Morozov A.I. (Kurchatov Institute), Bugrova A.I., Sigov A.S., Lipatov A.S., Kharchevnicov V.K., MIREA, Moscow, Lukyachenko V.I., Semenkin A.V., Garkusha V.I., Tverdokhlebova E.M., TSNIIMASH, Moscow ”Overview of electric propulsion activity in Russia”, *30th IEPC-2007-275* - September 2007 Florence, Italy

[5]Marchandise F., Cornu N., Snecma, Arcis N., and Arrat D., CNES, “Compact Hall Effect Assembly Propulsion subsystem PPS®X00, first test results in the range 300W-500W,” *32nd IEPC, Wiesbaden, September 11 – 15, 2011*, IEPC-2011-111