Innovative Xenon Regulation for Electric Propulsion

IEPC-2017-202

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

Yoann Fendler[1], Simon Carpentier[2], Pascal Barbier[3], François Martin[4] and Eric Guilbaud[5]
Air Liquide Advanced Technologies, 2 rue Clémencière, Sassenage, 38360, France

and

Claude Boniface[6]
CNES – French Space Agency, 18 avenue Edouard Belin, Toulouse, F-31401, France

Abstract: **Air Liquide has developed, with the support of the French Space Agency CNES, a xenon flow regulator in rupture with standard systems. A very light valve, less than 10 grams, delivers a xenon mass-flow directly from the tank outlet pressure, covering the whole range of pressures from BOL to EOL : typically from 200 to 5bar (which are our current requirements, but this range can be adapted to higher pressures). Mass flow rate covers thrusters needs from 0mg/s to 20mg/s and is fully flight adjustable. Electric Propulsion architecture is greatly simplified with this disruptive architecture, bringing in one component two functions: pressure regulation and mass flow rate regulation. This new approach brings competitiveness for future product lines. This component is derived from a helium pressure regulator onboard Rosetta Philae and will be onboard ExoMars 2020 rover. This paper presents results of xenon regulation in closed-loop under vacuum and the results of endurance tests.**

Nomenclature

ALAT	=	Air Liquide Advanced Technologies
BOL	=	Beginning Of Life
BPRU	=	Bang-bang Pressure Regulation Unit
CNES	=	Centre National d'Etudes Spatiales (French Space Agency)
EOL	=	End Of Life
GC	=	Gas Chromatograph
MFV	=	Multi Function Valve
MOMA	=	Mars Organic Molecule Analyser
OP	=	Operating Point
PID	=	Proportional – Integral – Derivative
TRL	=	Technology Readiness Level
XFC	=	Xenon Flow Controller

[1] Project Engineer, Space Activities, yoann.fendler@airliquide.com.
[2] Project Engineer, Innovation Unit, simon.carpentier-sc@airliquide.com.
[3] Project Manager, Innovation Unit, pascal.barbier@airliquide.com.
[4] Design Authority, Space Activities, francois.martin@airliquide.com.
[5] Head of Onboard Gas Management Market, Space Activities, eric.guilbaud@airliquide.com.
[6] Dr., Electric Propulsion Engineer, Propulsion Pyrotechnics and Aerothermodynamics service, claude.boniface@cnes.fr

I. Introduction

The electric propulsion is a major breakthrough in platform architecture, enabling satellites size reduction and propellant mass savings compared to classical chemical propulsion. Moreover, to increase the competitiveness of the electric propulsion subsystem, Air Liquide Advanced Technologies proposes a micro regulation valve, normally closed and based on thermal expansion, with the aim to significantly reduce the regulation plate mass and complexity. This technology is already used on MOMA-GC of ExoMars 2020 rover. This new regulator has been designed to be able to deliver a xenon mass flow rate from 0mg/s to 20mg/s (corresponding to thrusters range up to 5kW) with upstream pressure from 5 bar to 200 bar.

This technology was initially developed to regulate an Helium mass flow, and it will be used inside the MOMA-GC (gas chromatograph) of the ExoMars Rover.

The main advantages of this regulation valve are :

- compatibility to high pressures
- very low leak rate (<10^{-7} mbar.L/s)
- very low mass (some few grams)
- size (some centimeters of length and some millimeters of diameter)
- Can regulate downstream pressure or massflow rate depending on the mounting and the control law

II. Multi Function Valve

The Air Liquide micro Multi Function Valve (MFV) is a regulation normally closed valve based on thermal expansion. This component has also already been used as ON/OFF valve on the MOMA-GC. The micro MFV is really compact (some few centimeters of length and some few millimeters of diameter), as shown on Figure 1, and can support a 200 bar inlet pressure. Fluidic interfaces are two capillary pipes whose size and material can be adapted depending on the required interface.

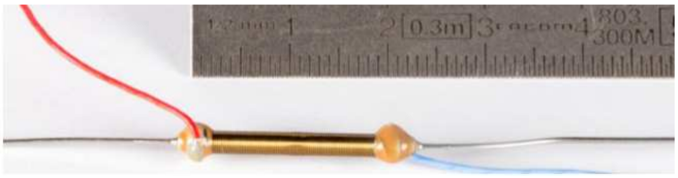

Figure 1. Air Liquide Multi Function Valve

Type of Valve	Normally Closed / Regulation electronically controlled micro valve (can also be used as an ON/OFF valve)
Size	Length < 25mm Diameter < 3,5mm
Weight	<10g
Tightness	<10^{-7} mbar.L/s
Media	Inert gas (He / N2 / Xe / Kr / Ar)
Mass flow rate range	0-20mg/s
Power Consumption	< 3W
Inlet Pressure	5-200bar
External environment	Atmosphere down to vacuum
Thermal environment	-40°C / 110°C

Table 1. Key features of Air Liquide micro Multi Function Valve

When the valve is electrically powered with a calibrated current, the surrounding winding ensures the heating of the component which induces a calibrated space between the valve seat and the valve piston. On the contrary when the valve power supply is switched off, the valve cools down (mainly by conduction and radiation) and closes. The power consumption of the micro MFV is lower than 3W (depending on the requested opening). The opening temperature of this valve is settled during manufacturing depending on the mission thermal environment. This parameter can easily be adapted to fit customer requirements. To minimize the power consumption it is recommended to settle the opening temperature, by keeping a reasonable margin, just above the maximal temperature expected during the mission. The leak rate measured with Helium is lower than 10^{-7} mbar.L/s. Main characteristics of the valve are summed up in Table 1.

III. Test bench

A test bench dedicated to micro MFV performances characterization has been developed by Air Liquide. This test bench is compatible with He, N2, Xe, Kr and Ar. It feeds the regulating valve with an upstream pressure between 1bar and 200bar. Thanks to a vacuum chamber, the micro MFV can be characterized under a secondary vacuum environment. The base plate on which the valve is fixed can be regulated in temperature from ambient up to 110°C. A vacuum pump can be used to have a primary vacuum downstream the micro MFV to be representative of conditions encountered in the feeding line of a thruster. This test bench can be coupled with a spectrometer to perform valve internal leak rate test or with a compressor to perform Xe high pressure tests.

The test bench is instrumented to perform the following acquisition during tests :

- Upstream pressure and temperature
- Valve temperature
- Valve power supply
- Vacuum in test chamber
- Temperature of base plate
- Downstream pressure and temperature
- Mass flow rate downstream the valve

For closed loop tests a Labview program has been developed and is used for regulation. A PID feedback loop is used to control the valve on the downstream pressure. The feedback loop can be easily settled on discharge current of the thruster.

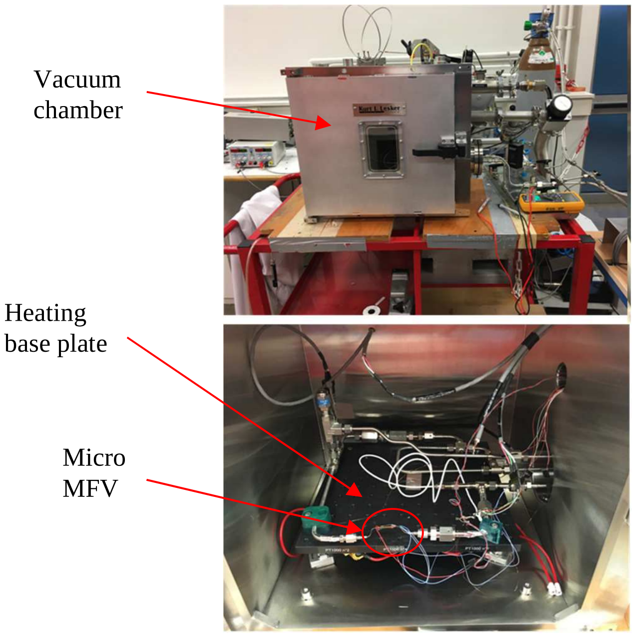

Figure 2. Micro MFV Test Bench

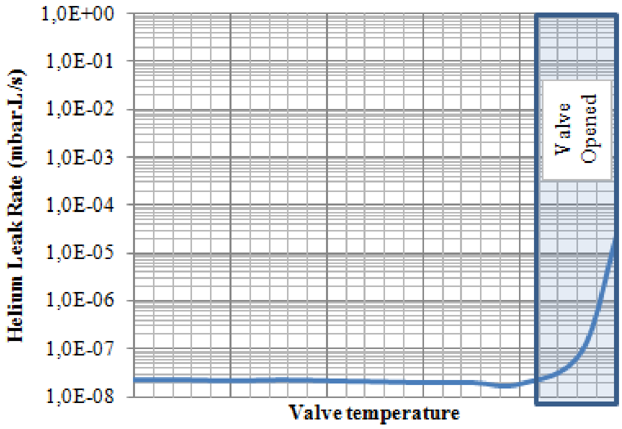

Figure 3. Micro MFV Leak Test Results

IV. Test results

A. Leak Test Results

The internal leakage of the component has been determined with Helium for different upstream pressure up to 180bar. The measured leak rate is always lower than 10^{-7}mbar.L/s until valve temperature is lower than valve opening temperature. An example of curves obtained (representing Helium leak rate as a function of valve temperature) is presented on Figure 3.

B. Open Loop Test Results

Even if this type of test is not representative of the final configuration of the micro MFV in a xenon regulation system, it is useful to enhance our understanding of valve behavior under various operational conditions. For instance this type of test allows evaluating the valve operating range, the valve power consumption or the valve opening and closing reactivity.

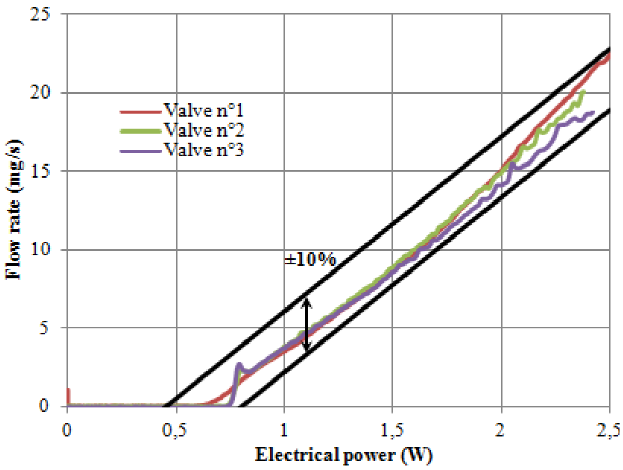

Figure 4. Micro MFV reproductibility (with Kr / 100bar upstream pressure)

For this type of test an upstream pressure is settled, and a defined current is imposed to the valve. When the valve temperature is stabilized, the mass flow rate is collected.

These stationary tests allow us to determine the operating range, i.e. the mass flow rate range which can be regulated for each upstream pressure, and consequently for the different phase of lifetime of the satellite. During this test campaign, we focused on the upper limit of this operating range. These preliminary tests were successful and demonstrated that the valve was able to deliver a mass flow rate up to 20mg/s required by a 5kW class thruster.

This test campaign also allows to determine, for a given upstream pressure, the power required by the valve to deliver a given mass flow rate. These curves represent the ID card of our valve and are used to compare the reproducibility of produced valves (figure 4). With this test, we have demonstrated that the valve manufacturing is well controlled and does not induced a dispersion in the behavior of different valves which could be a real danger, considering the size of the different parts and of the final component.

The valves tested can have a difference on the measured downstream mass flow rate of the order of 10% for a given power supply as we can see on figure 4. Such a weak gap can be easily counterbalanced by the closed loop regulation; indeed this component is not dedicated to an open loop use.

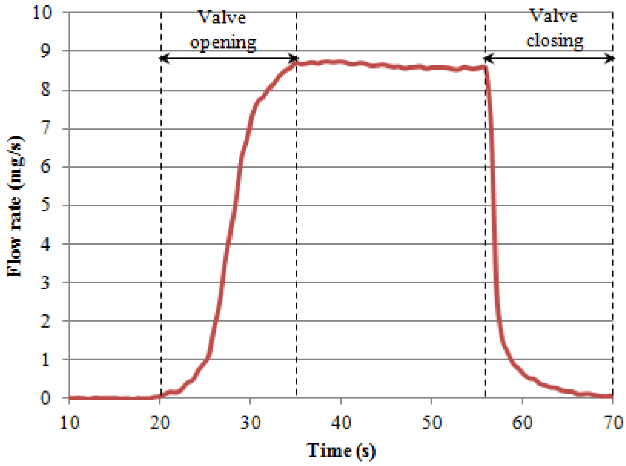

Figure 5. Closed loop test configuration with Kr

C. Closed Loop Test Results

A PID controller was developed under Labview with the aim to ensure the following performances: the targeted mass flow rate has to be reached in less than 30s and no overshoot greater than 105% of targeted mass flow is admitted.

The PID controller is used to regulate the pressure downstream the valve. The mass flow rate is ensured by a calibrated orifice located downstream the plenum and the micro MFV.

Some preliminary tests were performed with Krypton. For different upstream pressures (from 3bar to 150bar) the P, I and D parameters were optimized to obtain a targeted downstream plenum pressure as quickly as possible without significant overshoot. In all the cases the targeted mass flow rate were obtained in less than 20s.

The flow rates are regulated with an accuracy and a stability of ±2%.

At the end of these tests, the closing duration of the micro MFV after power supply extinction is measured. An example of results is given on Figure 5.

These tests demonstrated that the transient phases (opening and closing of the valve) can be reduced up to 10s to 20s, and that the flow rate can be regulated with a good accuracy and stability on the whole operating pressure range.

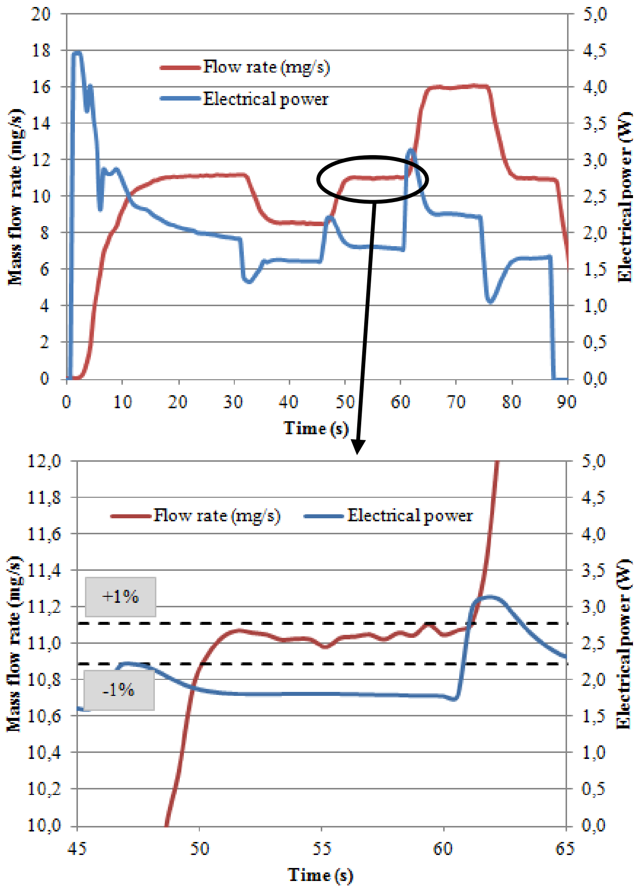

Figure 6. Sequence in closed loop configuration with Xe

A test sequence with several operating points in xenon was performed. Three operating points, representative of a 5kW range thruster, were targeted:

- OP1 : 8,5mg/s
- OP2 : 11mg/s
- OP3 : 16mg/s

The following sequence was performed : thruster ignition (micro MFV opening) ➔ OP2 ➔ OP1 ➔ OP2 ➔ OP3 ➔ OP2 ➔ disengaging thruster (micro MFV closing).

On the figure 6 the results obtained with xenon for an upstream pressure of 10bar are presented. For the opening of the micro MFV, the first targeted mass flow rate is reached in 20s. All the other transient phases (from an operating point to another one) are shorter than 10s.

All the targeted mass flow rate are reached and are regulated with a stability of ±1%.

The power consumption of the valve is below 3W (average), and can reach 4,5W (peak) at the opening.

This sequence was tested with different upstream pressure from 3bar up to 50bar (the upper limit that can be reached with xenon without compressor).

We can conclude that the micro MFV is able to regulate a flow rate from 0mg/s to 20mg/s with an excellent stability (±1% of targeted massflow rate) and accuracy for an inlet pressure from 200bar to 7bar (for high flow rates). Some additional works are performed by ALAT to decrease this low limit of pressure to 3bar.

D. Endurance Test Results

Some endurance tests were performed on this concept of regulated valve. 10,000 opening / closing cycles were performed. Some leak tests and a valve characterization in Helium and in open loop were performed at the beginning of the valve endurance test and all the 2,500 cycles. It was observed that the leak rate was not affected by the opening / closing cycles. A leak rate below 10^{-7} mbar.L/s is obtained all along the endurance test. The tightness of the valve is not affected by the successive opening and closing cycles.

A discrepancy is observed between the five different characterizations performed all along this endurance test (cf. figure 7). The behavior of the valve is slightly affected by these cycles, but this effect is easily balanced by a closed loop regulation.

Regarding these results it appears that the valve maintains its low leak rate and is able to regulate on the same range of flow rate all along its lifetime. We can conclude that there is no expected degradation of valve functioning during its life.

E. Impact of thermal environment

The micro MFV concept is based on thermal expansion of materials and on temperature regulation of the valve. It is important to demonstrate that this valve

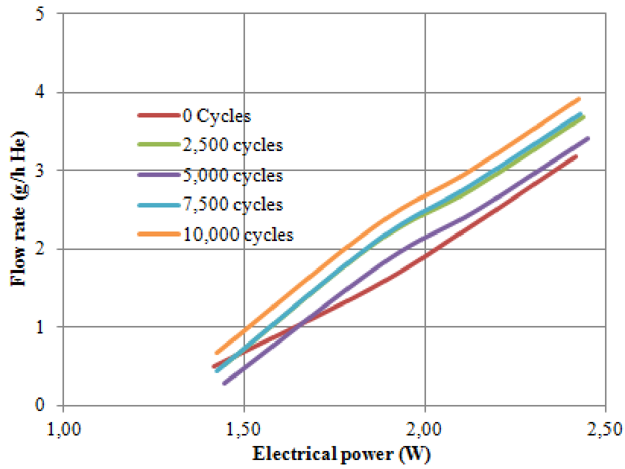

Figure 7. Evolution during endurance test

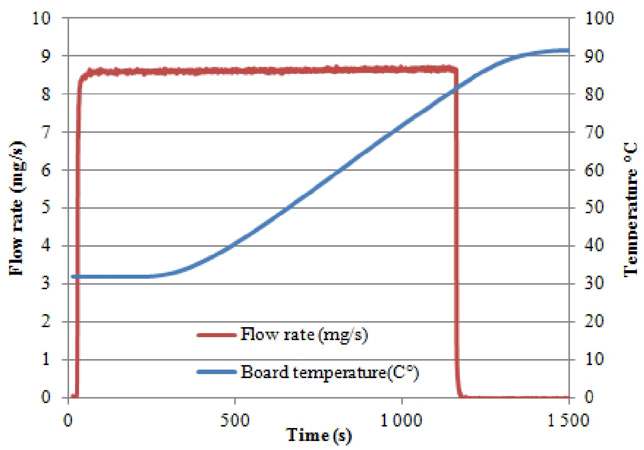

Figure 8. Mass flow rate evolution of the valve with a variation of the temperature environment

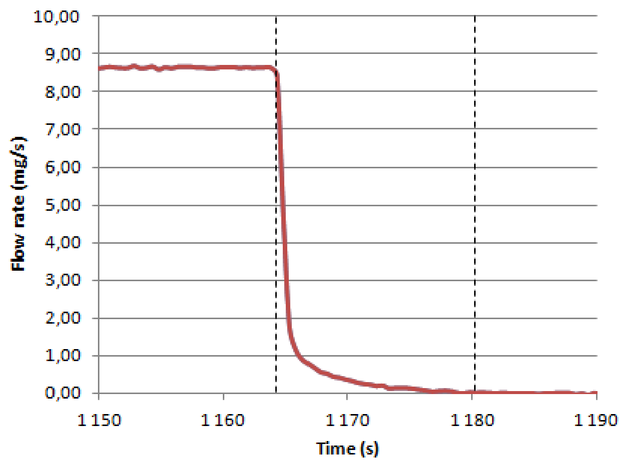

Figure 9. Valve closing in a "hot" environment (90°C)

can be used in thermal environments commonly specified for such a component. A test of regulation stability was performed with a temperature increase of the base plate. During this test the mass flow rate is regulated, thanks to the PID controller, at a value of 8,5mg/s in Kr with an upstream pressure of 70 bar. When the targeted mass flow rate is obtained, the temperature of the base plate is increased up to 90°C. The figure 8 shows that the mass flow rate is not affected by the temperature increase of the environment. The PID controller counterbalances this environment temperature increasing by decreasing the power supply of the valve.

Moreover the opening/closing temperature of the valve can be tuned during manufacturing process. This temperature is generally settled from 20°C to 40°C, depending on the required margin, above the upper limit of the operating and non operating temperature range requirement. We can observe that, even at 90°C the tested valve keeps its tightness. It ensures that the valve is tight on its whole temperature operating range. Moreover the closing time of the valve is not affected by a “hot” environment. As seen on figure 9, less than 20s are required for the valve closing at 90°C, which is typically the closing duration at ambient temperature.

The environment temperature seems to have no significant impact on valve behavior and on its closing duration.

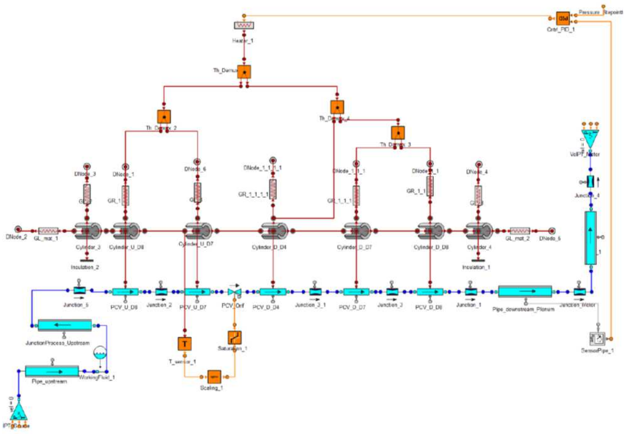

Figure 10. Functional scheme developed with Ecosim-Pro

V. Valve modelization

An EcosimPro model of the valve has been developed and calibrated on experimental data with the aim to be integrated in a model of a full xenon regulation system. The valve model can be used with Xe and Kr.

The result of the model helped us to find the good PID parameters for regulation without instabilities.

VI. Short terms on-going Developments

Some additional tests in xenon with high upstream pressure (from 60bar up to 200bar) are in progress. These tests require a specific test bench configuration with a compressor, instead of only a gas cylinder, upstream the micro MFV. These tests will allow characterizing the micro MFV comportment on its whole upstream pressure operating range from 200bar to 3bar, and more particularly to test it with supercritical xenon.

Moreover some coupled tests with a 1kW class Hall effect thruster are planned on November 2017. These tests will be realized in a closed loop configuration with a feedback control on downstream pressure, as a first step, and subsequently on the discharge current of the thruster. These tests will be realized under upstream pressure from 200bar to 3bar, in the aim to be representative of the whole life of satellite.

VII. Conclusions

A micro MFV is under development at Air Liquide. The tests which have already been performed are encouraging. The valve can deliver flow rates adapted to thrusters in the range 100W-5kW. The transient phases observed are lower than 30s (opening / closing / transition from one operating point to another one) and this component allows a regulation with a good accuracy and stability (<±2% of the targeted mass flow rate). Moreover, the cycling of the valve seems to have no significant impact on its performances.

The main strengths of this component are :

- Its compatibility to high pressures
- Its high tightness
- Its low mass
- Its small size

Some additional tests are under progress (xenon high pressure tests and coupled valve/thruster tests) with the aim to reach a TRL6 by the end of the year.

A high flow rate MFV, based on the same concept and dedicated to cold gas lines, ables to deliver a regulated mass flow rate of some few hundreds of milligrams in xenon is currently developed by Air Liquide.

References

Duchemin, O., Leroi, V., Öberg, M., Le Méhauté, D., Pérez Vara, R., Demairé, A., Björklund, M., Persson, S., De Tata, M. & Beekmans, S. (2013). Electric Propulsion Thruster Assembly for Small GEO: End-to-End Testing and Final Delivery, IEPC-2013-222

Lyszyk, M. & Lecardonnel, L. (2007). Thales Alenia Space Experience on Plasma Propulsion, IEPC-2007-301

Lyszyk, M., Baubias, P-P., Naulin, A., Pin, R. & Lecardonnel, L. (2011). XPS Plasma Propulsion System on AlphaBus, IEPC-2011-118

Stephan, J-M. (2000). Electric Propulsion Activities for Eurostar 3000. Spacecraft Propulsion, Third International Conference held 10-13 October, 2000 at Cannes, France. Edited by R.A. Harris. European Space Agency ESASP-465, 2001., p.81

Naclerio, S., Soto Salvador, J., Such, E., Avezuela, R. & Perez Vara, R. (2012). Small GEO xenon propellant supply assembly pressure regulator panel: test results and comparison with ecosimpro predictions, SP2012-2355255.

Duchemin, O., Leroi, V., Vial, V., Öberg, M., Bourgignon, E., Scalais, T., Demairé, A. & Lübberstedt, H. (2010). Electric Propulsion Thruster Assembly for Small GEO, AIAA-2010-6696

Biron, J., Cornu, N., Illand, H., Serrau, M., Rigollet, R., L Gray, H. (2005). The Thruster Module Assembly (Hall Effect Thruster) design, qualification and flight, IEPC-2005-213