AIAA-2004-3977

Robust Pressure Regulation System for the SMART-1 Electric Propulsion Sub-System

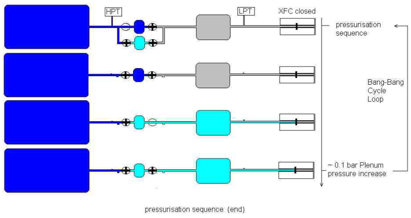
Christophe R. Koppel [*] and Frederic Marchandise[†]
Snecma Moteurs, Site de Villaroche Nord, Direction Propulsion et Equipements Satellites, Aérodrome de Melun Villaroche, France.

Denis Estublier[‡].
ESA/ESTEC, Keplerlaan, 1, Noordwijk, The Netherlands.

Onboard the ESA SMART-1 spacecraft, (Small Mission for Advanced Research in Technology), the Xenon feeding system operates since the September 30th 2003.

EPS Contractor, ESTEC, and EPS manufacturer, SNECMA MOTEURS, present in detail the major performances of the Pressure Regulation System, with a comparison to the ground tests results.

The PPS ® -1350 Hall Effect plasma Thruster needs a regulated xenon pressure as input of the flow controller. Such pressure is delivered and controlled by two pieces of hardware, the "Bang-Bang Pressure Regulation Unit" and the "Pressure Regulation Electronic Card". The concept is described as well as its main features: the robustness by design that cannot allow a direct communication between the high-pressure parts (the xenon tank) and the low-pressure parts (the thruster input).



The paper highlights the possibility for various parameters to be tuned by telecommands in order to reach different performance levels of the pressure regulation. The real flexibility of the concept allows smoothing the pressure regulation.

This paper describes the performances results of the pressure regulation in space environment compared to the ground tests results. It discusses also the advantage of the regulation tuning capability during the first flight phase. This new features of primary electric propulsion subsystem demonstrates its robustness and flexibility toward thruster initial requested tuning to keep the thruster loop fine pressure regulation in an adequate range.

I. Introduction

The EPS (Electric Propulsion Sub-System) of SMART-1 has been presented in numerous papers [1, 5, 6]. The main characteristics of the EPS are roughly described hereafter and then the focus will be pointed to the regulation of the xenon pressure and its behaviour in flight

The Smart-1 power is generated by two GaINP/GaAs/Ge solar arrays panels (1850 W beginning of life) enabling thruster operation at a discharge power of maximum 1190 W at beginning of life.

In some failure-cases, the available power can be reduced to 700 W or less. This is therefore an essential requirement for thruster and PPU to work within a range of pre-set power levels and to be able to follow a dedicated start-up sequence that does not generated power overshoots. This capability is also required for deep-space missions involving variable sun distances.

The whole EPS, fig.1, is designed for the three following main functions:

- Xenon supply system
- Electrical power supply and thruster
- Digital interface and communication system

[*] Tel. 33 (0)1 6471 4693, Fax. 33 (0)1 6471 4617 E-mail: Christophe.Koppel@snecma.fr.
[†]. Tel. 33 (0)1 6471 4683, Fax. 33 (0)1 6471 4617 E-mail: Frederic.Marchandise@Snecma.fr
[‡] Tel. 31 71 565 4106, Fax. 31 71 565 5421 E-mail Denis.Estublier@esa.int

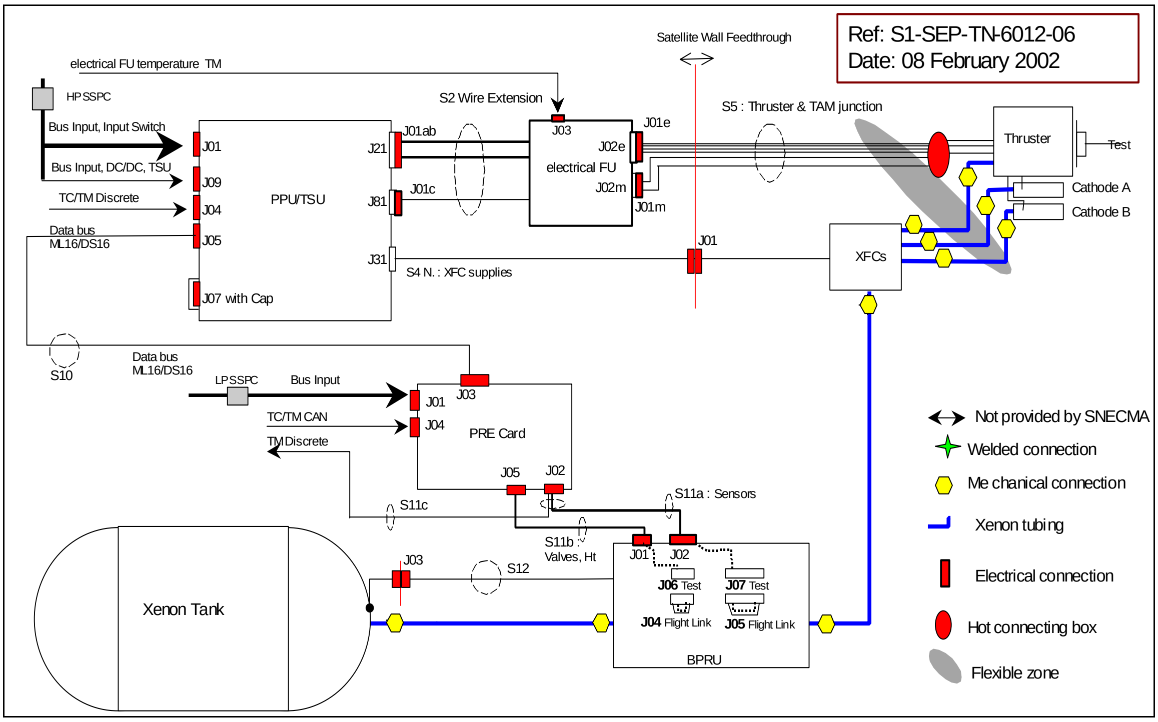


Figure 1. EPS functional diagram: the xenon system feeds the thruster cathodes and anode

A. The xenon system

The xenon is stored in the main Xenon Tank, 82.5kg at launch, under high pressure (up to 150bar). A pressure regulator called the Bang-bang Pressure Regulation Unit (BPRU), designed by Snecma Moteurs and Iberespacio (Spain), regulates the xenon down to a constant low pressure (around 2bar). The low-pressure xenon is then fed into the adjustable flow regulator, called the Xenon Flow Controller (XFC). A simple and robust control loop algorithm, located in the Pressure Regulation Electronic Card (PRE Card), controls the constant pressure delivered by the BPRU. The XFC then provides fine control of xenon mass flow rate to the thruster anode and cathode. The flight hardware is shown in figure 2. This system is described more precisely later.

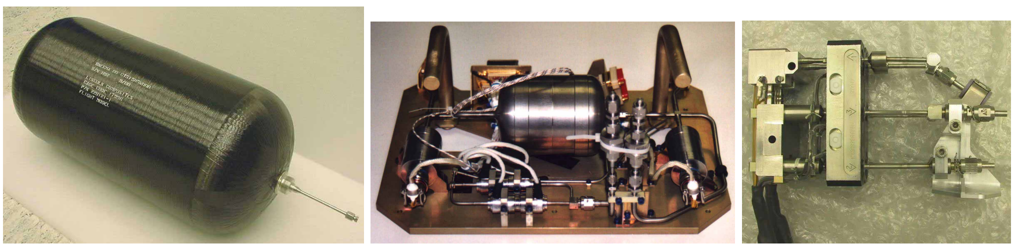


Figure 2. Flight model hardware: tank, BPRU and XFC

B. Electrical power supply and thruster

The electrical power supply and thrusters, fig. 3, is composed of a main power transformer called Power Processing Unit / Thruster Switch Unit designed by ETCA (Belgium) which transform the electrical voltage delivered by the satellite, 50 Volts DC, into the voltage required by the thruster (from 220 up to 350 Volt DC). Between the thruster anode / cathode, and the PPU/TSU, an electric filter called Filter Unit (FU) produced by EREMS (France) is designed to reduce the electrical thruster oscillations and to protect the electronics of the PPU/TSU..

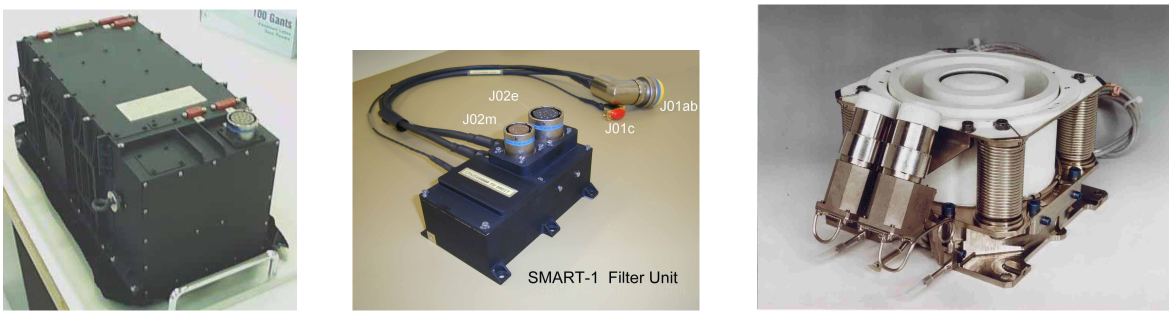


Figure 3. Flight model hardware: PPU, FU and thruster PPS®1350-G

In order to deliver a constant thrust while the thrusters is firing, fig. 4, a simple and robust algorithm loop is integrated into the PPU/TSU and generates the analogical control signal to the XFC. The telemetries available from that system are the main parameters: Discharge current (mean value and ripple value – ie the RMS value of the AC waves called FUoscillation-), discharge voltage, voltage between the Cathode emissive crystal and the ground satellite – so called Cathode Reference Potential (CRP) - and other housekeeping parameters.

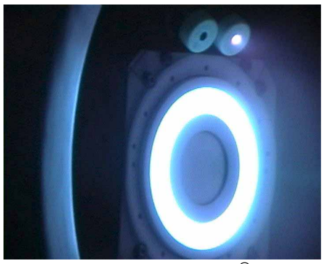


Figure 4. Thruster PPS®1350-G FM during acceptance tests Firing sequence.

C. Digital interface and communication system

The digital interface and communication system is composed of one main interface located into the PRE Card designed by Atermes (France), fig. 5. All Telemetry (TM) and Telecommands (TC) are interfaced to the EPS through the PRE Card. Commands reaching the PRE Card are either executed by the PRE Card (if relating to the BPRU control) or passed to the PPU.

Both the PRE Card and PPU contain software with “automatic mode” subroutines. These routines reduce the number of commands that need to be routinely sent to the EPS.

In routine operation the EPS has two automatic loops running. One software loop, contained in the PRE Card, regulates the Xenon pressure, in the low-pressure tank feeding the XFC. The PPU hardware applies a power limited voltage source to the anode, selected by the ‘nominal power set’ command, which also sets the discharge and magnet current levels. The PPU then performs fine control of the thruster discharge current via a signal to the XFC, which varies the mass flow rate accordingly.

The telemetries available from that system are the status parameters of the logic with other housekeeping parameters.

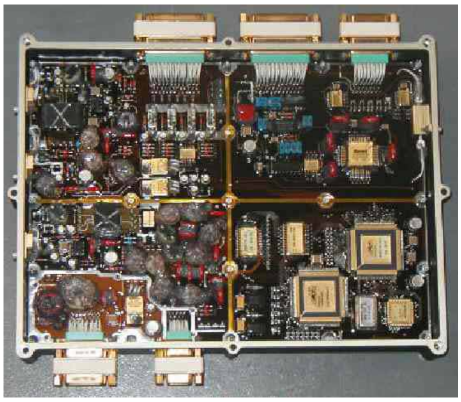


Figure 5. Atermes PRECard Flight-Model

D. Variable Power Feature

As a main feature of the Smart-1 program, the thruster is able to be started and continuously used with a variable input electrical power. The reasons of such feature are related to the satellite solar arrays cells performance evolution as well as to cover a failures case.

The user can send, at any time, a “Nominal power set” parameter tele-command to the EPS in order that the thruster use more or less electrical power and to produce more or less thrust.

The consequence of such requirement on the pressure regulation system is that the mass flow of xenon depends on the level of power commanded to the system.

II. The Bang-Bang Pressure Regulation (BPRU)

As explicitly mentioned in the name of the subsystem, the BPRU rely on the use of valves in bang-bang mode. Moreover, instead of using the valves with the classical concept of Pulse Width Modulation (PWM), the chosen concept for the system is to use an intermediate small volume for the transfer of a small quantity of gas from the High pressure tank, and then after a time step, release that quantity of gas toward a plenum volume. This intrinsic concept of Bang-Bang regulator introduce a very regular fluctuation of the "constant regulated pressure": each time the plenum measured pressure becomes lower than the target pressure, the bang-bang valves are activated and a small positive step in the pressure of the plenum volume occurs. This characteristic, as the heart of the system, is visible on about all the tele-measured functional parameters of the EPS. The telemetries available from that system are the main parameters: Pressure and temperature of the tank (called HPT and Ttank), Pressure and temperature of the plenum volume (called LPT and Tplenum) and other housekeeping parameters.

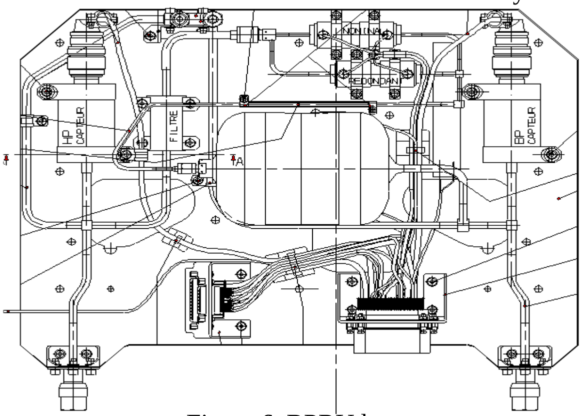


Figure 6. BPRU layout

A. Technical description

The technical description of the BPRU, fig. 6, follows on the next sketch, fig.7. The xenon is delivered to the BPRU thorough a mechanical connection. A filter provided by Sofrance, Snecma Group, assure the cleanliness of the xenon gas before entering into the Bang-Bang valves provided by Moog, USA. After the Bang-Bang valves, the gas is allowed to fill a plenum tank of one liter.

The number and the location of the pressure transducers has been optimized. The redundancy of the pressure transducer in managed at EPS level and at satellite level, using the properties of the Electric propulsion electrical parameters that can give a rather good estimation of the xenon pressure feeding the thruster, so that only one Low-pressure transducer is needed in the design, a virtual redundant pressure transducer being integrated into the system (see here below the Second level check paragraph). The same approach was followed for the High-pressure transducer, because the tank high pressure can also be estimated roughly via bookkeeping techniques, so that only one High pressure transducer is needed in the design. This makes the cost of the BPRU very attractive because the number of pressure transducers may represent an important part of the hardware cost.

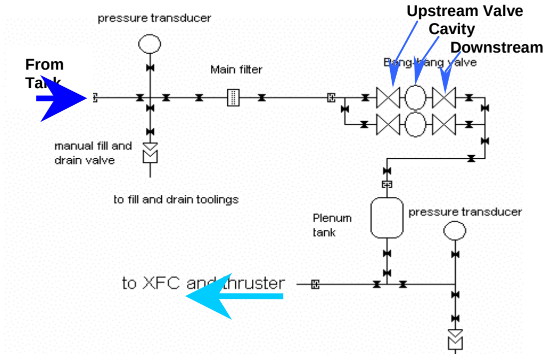


Figure 7. BPRU system functional flow diagram

The location of the Low-pressure transducer has been optimized in order to measure the real pressure instead of spikes of pressure necessary induced by the Bang-Bang valves opening. The low-pressure transducer particularly has been located after the plenum volume. As it can been seen later in the paper, the response of the pressure transducer after a valve activation is very pure contrary to some other location [2, 4].

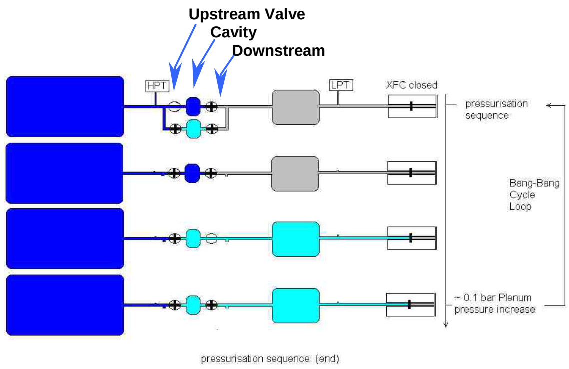


Figure 8. BPRU sketch of the robust concept

B. Bang-Bang process

The nominal status of the valves is that there are all closed, even in automatic regulation mode.

When the outlet pressure of the BPRU decrease below the Preset Pressure value, the bang-bang valves are actuated in the following manner, fig.8:

- The upstream valve is opened

- The internal cavity between the two valves of the Bang-Bang assembly begins to be filled by the xenon gas from the tank
- Duration of the upstream opening is T1 seconds.
- This upstream valve is then closed.
- After a while of T2 seconds, the downstream valve is opened.
- The plenum tank pressure start to increase
- After T3 seconds, the downstream valve is then closed.

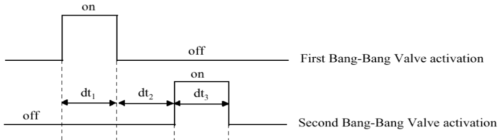


Figure 9. Bang Bang Valve Cycle Timing

- The Bang-Bang valves are all closed and a new cycle can be executed on request.

As described here before, we can see that never in the process, there exist a direct communication between the high pressure tank and the low pressure side of the BPRU: there is at least one valve fully closed between the two parts, fig. 9. Moreover most of the time all the valves are closed between the two parts (ie always two valves are closed). This particular feature makes that concept of pressurisation very robust, and not sensitive to any timing discrepancy (which is very important for other concept based on the Pulse Width Modulation (PWM)).

III. Functional modelisation

The rather simple concept of pressurization Bang-Bang has been fully checked in the course of the design thanks to adequate simulation software. EcosimPro software has been selected for its reliability, its modular approach and its very valuable feature of symbolic treatment of the equations as well as the automatic resolution of the differential equations. The code written by Iberespacio (Spain) is thus understandable by any Engineer having rudimental basis in the language used. Moreover, the acceptance of the software was very facilitated by the great readability and in real time modification even for adding a differential equation. This is of course also true if any for maintenance purpose.

The sketch of the modelisation, directly coming from the software is presented in fig. 10. The model is divided in two parts: the fluid (gaseous) thermodynamic system based on a real gas xenon characteristic –in light blue color in the figure- , and the thermal part conductive and irradiative in vacuum and weightlessness – in red color in the figure-. The two parts are properly interconnected together for a global modelisation of the whole system in its environment. The same model with some formal equations added was able to simulate the functional behavior with the

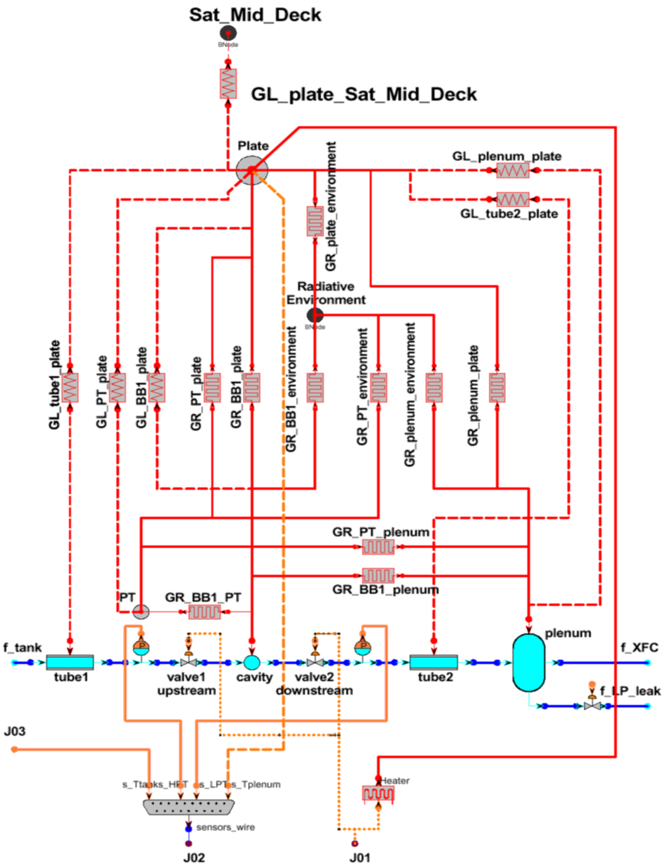


Figure 10. BPRU Functional modelisation on EcosimPro

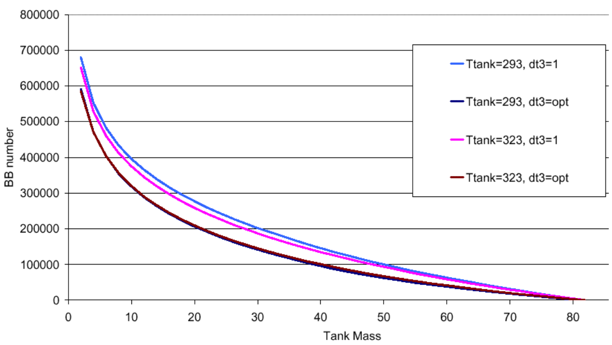


Figure 11. BPRU EcosimPro model output: Number of Bang-Bang cycles

natural convection effects on earth into the cavity and tanks as well as around the external skin of those mechanical parts.

Among all the model outputs (temperatures, flows, pressures, timings), an important output to report here is the number of the valves activation forecasted by the model. The model predicts a range for the number of bang-bang cycles around 650 000 for the complete use of xenon, fig. 11. The model give for the time of writing, 32 kg of xenon used, a prediction for various cases in the range between 60 000 and 105 000. The in flight cumulated number is strictly in line with the forecast.

IV. Integration of the BPRU modelisation into the EPS model EPOS

EPOS is the acronym of Electric Propulsion Operation Software. The model, developed by Iberespacio, is a simulation model of the whole EPS (including PPU, Thruster, Electronic Card, xenon tank, XFC and BPRU) has been widely used by the team of ESOC Darmstadt[7] in order to learn how the satellite, and particularly the EPS, answer to the procedures for controlling the satellite. This software delivers a safe check of the procedures when updated.

The software chosen to produce EPOS was still EcosimPro for the same reasons as mentioned here before. The part relative to the BPRU simulation didn't require any additional work because the functional model was fully compliant with the architecture of EPOS as well as simulation time constrains, and hence the full BPRU EcosimPro model was included into EPOS. A sketch of EPOS is presented in fig. 12.

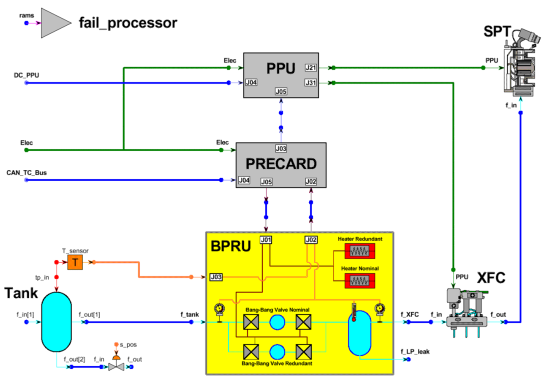


Figure 12. EPOS an EPS simulation software which includes the functional modelisation of the BPRU, on EcosimPro

V. Acceptance Tests

The pressure regulation unit BPRU, composed of off-the-shelf components, has been protoflight acceptance tested by Iberespacio at the Madrid INTA facilities (Spain). Before that final campaign, a BPRU characterisation-mapping campaign with xenon has been performed with the support of a detailed modelisation using the powerful software EcosimPro. The test results showed the very good predictive accuracy of the mathematical model. The acceptance test sequence includes the environmental mechanical tests (vibration random and sinus) and the shock tests, see figure 13.

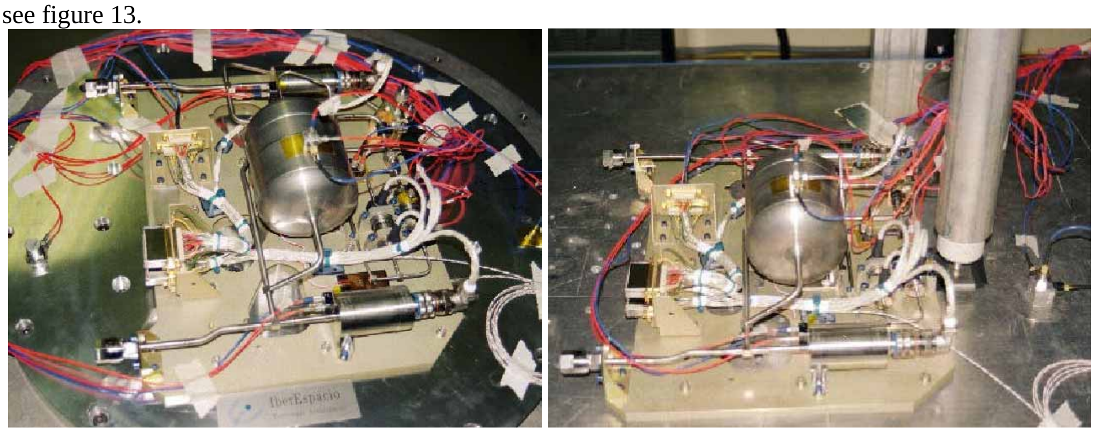


Figure 13. BPRU during the vibration sinus, random and shock tests of the acceptance tests sequence performed by INTA /Iberespacio

The last functional test was performed in a thermal vacuum facility, see figure 14, with xenon input at different pressure levels and xenon output.

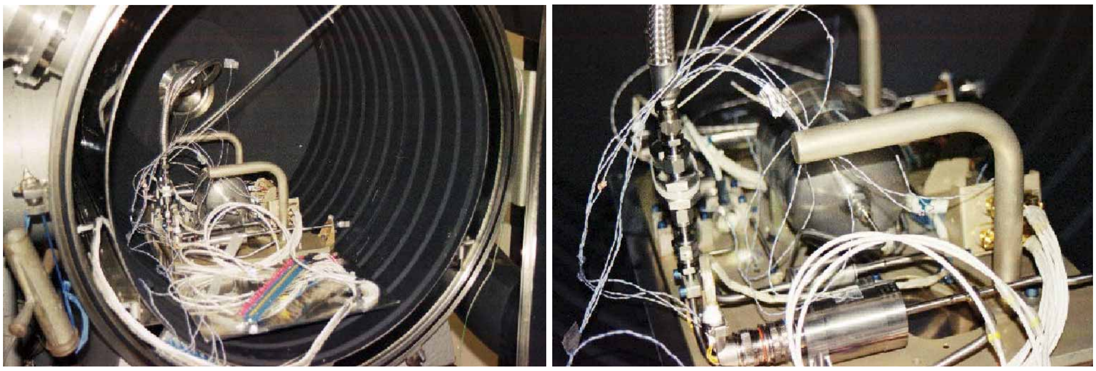


Figure 14. BPRU during the thermal vacuum acceptance tests with xenon, INTA facility

VI. In flight behaviour

At the time of writing the cumulated firing hours of the EPS reached the 2000 hours last April 16th. The number of Bang-Bang activation reached at that time a figure of 100 000. The total number of activation is estimated by EcosimPro around 650 000, that means that at 2 000 hours, 15% of the life of the BPRU has been completed. On the other hand, the xenon mass used is 32 kg after 2 000 hours of EPS firing. At loading, the EPS tank was loaded with 82.5 kg of xenon, ie 39 % of the xenon mass has been used. This is an other feature of the BPRU, the progression of the Bang-Bang cycles is slower than proportional at the beginning of life than the overall xenon mass regulated.

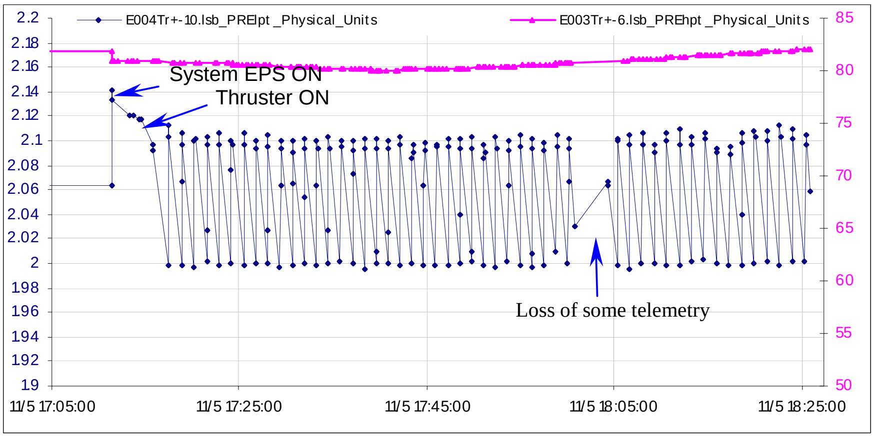


Figure 15. Behaviour of the pressure regulation, in flight, May 2004, duration 80 minutes: Pressure steps between 1.995 bar and 2.11 bar (ie +- 0.058 bar) occurs at each Bang-Bang cycle. *The High pressure around 82 bar shows slow variations.*

A. Typical measurements

The typical measurements in flight from the BPRU are presented in the following figures 15. The regulation of the pressure is performed between 2.11 bar and 1.995 bar (ie +- 0.058 bar). The corresponding simulation output presented fig. 16, shows a very similar behaviour.

One shall mention that the slight decrease of the pressure measurement immediately after the system has been powered ON is due to the warming time of the pressure transducer and its electronic.

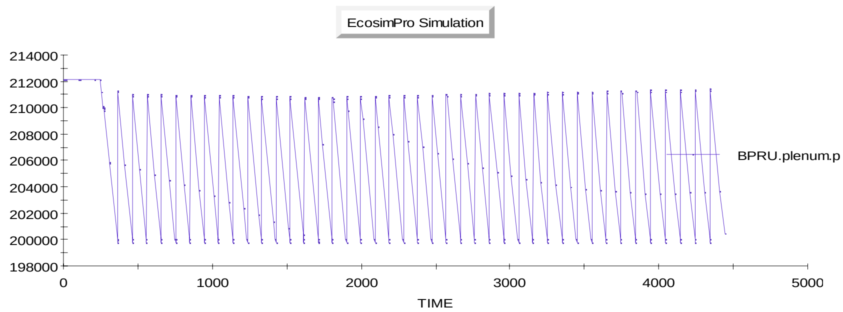


Figure 16. EcosimPro simulation of the pressure steps with the inputs coming from the flight data: Behaviours are very similar with fig. 15, as expected

An interesting point to mention is that the BPRU system of telemetry allows discriminating the loss of telemetries from a wrong behaviour: on the figure 15, one suspects that there are some Bang-Bang cycle missing due to a wrong behaviour of the system or simply a loss of availability of the telemetry. In the first case, the duration between the Bang-Bang cycles should vary a lot; 2 times for example. The confirmation of the right hypothesis is given by the value of the Time between Bang-Bang telemetry (TimeBB) in flight that shows, fig. 17, that absolutely no variation of that duration occurs at that time.

This confirms that the loss of some telemetries was the right assumption.

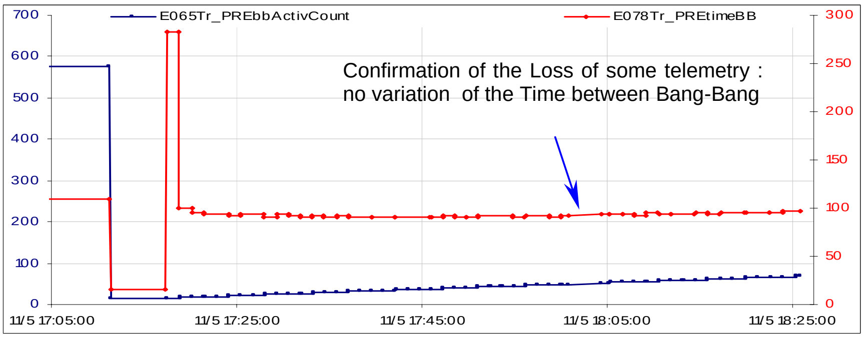


Figure 17. Behaviour of the pressure regulation and the characteristic of the system: the time between each Bang-Bang cycle: *except for the first value that depends on the initial state, the Time between Bang-Bang is a real characteristic of the system. The health check of the system rely on that value.*

The computation of TimeBB is also very useful for the check of the behaviour of the regulation system. The system detects if the current value of TimeBB stay in line with the look-up table computed by the simulation model. An out of limit from the table would means:

- If TimeBB is too short with respect to the table: one of the valve poppet could jam
- If TimeBB is too long: a weakness in the poppet/seat leak tightness of the downstream valve may occur.

Such check is performed automatically by the software of the regulation after an adjustable period of inhibition in the automatic mode. The period of inhibition is needed because the first value depends on the initial state of the system (temperature, pressure into the plenum from the previous use). In case of check positive, the only action is to use the redundant branch of the Bang-Bang valves. This case didn't happens up to now, the system behaves flawlessness.

The settings of the pressure regulation are mainly the timing parameters (duration of opening of the valves) and the target parameter of the regulation. The pressure step has been adjusted, during the satellite commissioning phase, by decreasing the duration for the downstream valve opening pulse. While the xenon mass consumption progress, it was possible to increase that same settings in February 2004. This characteristic is a very valuable feature of the "digital" regulation system. Of course, this is not possible when using a classical mechanical regulator…

B. Second level check (virtual redundant pressure transducer)

As mentioned before, the minimized number of pressure transducers in the BPRU cannot not provide the status of the pressure transducer itself. It may derive slowly from its nominal status or have some other catastrophic failure like a loss of the measure. The next plot, fig. 18 shows the results of the virtual redundant pressure transducer implemented aboard the

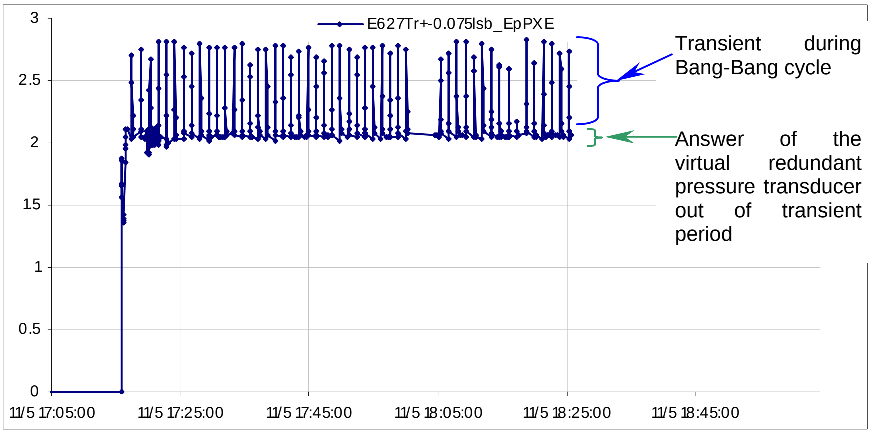


Figure 18. Virtual redundant pressure transducer telemetry: the values given by the computations are fully in line with the real transducer telemetry (out of the transient periods).

spacecraft. The graph gives the pressure computed from the Discharge current of the thruster and takes into account the Thermothrottle current used to control the Discharge current loop. The results are very comparable to the one given by the low-pressure transducer (except during the transient period when the bang-bang cycle is activated, because the time constant of the Thermothrottle capillary tube is not taken into account). This parameter is checked since the beginning of the flight operation and no discrepancy have been seen between the two low pressure transducers (the real one and the virtual one). This show the right behaviour of the real low pressure transducer.

VII. Conclusion

This paper presented the SMART-1 Bang-bang Pressure Regulation Unit (BPRU) of the Electric Propulsion Sub-System and the behaviour in flight. On the basis of the various SMART-1 test campaigns, the BPRU has demonstrated the capabilities for providing the xenon regulated pressure with the required accuracy.

After more than 2230 hours in flight, the behaviour of the BPRU is nominal.

The system has proven its ability for being integrated into the Electric propulsion subsystem. The essential characteristics of the BPRU is that by concept, it relies on sequential opening and closure of valves which makes it very robust because at no time, there are any risks of over pressurisation of the low pressure side of the system.

Acknowledgments

The overall SMART-1 EPS activities have been performed in the frame of an ESTEC/TOS-MPE TRP Contract, and the EPS has been delivered to the Project as Customer Furnished Equipment.

References

[1] Saccoccia G., Estublier D., Racca G. " SMART-1: A Technology Demonstration Mission for Science Using Electric Propulsion", *AIAA-98-3330, 34th Joint Propulsion Conference*, July 1998, Cleveland, OH.

[2] Bushway E., Engelbrecht C., and Ganapathi G. “NSTAR Ion Engine Xenon Feed System: Introduction to system design and development,” IEPC 97-044, Aug. 1997

[3] Koppel C., Lyszyk M., Valentian D., “PPS 1350 With Variable Power Feature for SMART-1”, *AIAA 2000-3427, 36th Joint Propulsion, Conference and Exhibit*, 17th-19th July 2000, Huntsville, Alabama.

[4] Ganapathi G and Engelbrecht C. “Performance of the Xenon Feed System on Deep Space One,” Journal of Spacecraft and Rockets, Vol. 37, N°3, Mat-June 2000.

[5] Estublier D., Koppel C., “SMART-1 End-to-end test: Final results and lesson learned” *28th IEPC* 2003-0303, Toulouse, France.

[6] Koppel C., Estublier D. “The Smart-1 Electric Propulsion Sub-System” AIAA-2003-4545

[7] Milligan D., Gestal D., Estublier D., Koppel C., “SMART1 Electric Propulsion Operations” AIAA-2004-3436