SMART-1 PRIMARY ELECTRIC PROPULSION SUB-SYSTEM THE FLIGHT MODEL

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ABSTRACT :

Onboard the ESA SMART-1 spacecraft, (Small Mission for Advanced Research and Technology), the Primary Electric Propulsion sub-System (EPS) must operate at optimum performance under limited power available and with a variable power feature. As EPS Contractor for ESTEC, SNECMA will present in detail the major's features of the complete electric propulsion system, as well as the development efforts of each main component.

The development tests of the PPS®-1350 hall-plasma thruster, including an extensive number of start-up tests in the whole useful operational domain have been performed. This paper presents the development status of the system, and describes the new approach for having a limited inrush power when the thruster is switched on.

The tests campaign has been successful and the results obtained during the campaign have been fully taken into account in an optimisation process for providing the foreseen performances of the SMART-1 mission. Those performances are the thrust, the total xenon flow, the specific impulse and the additional magnet trim current.

These new features of primary electric propulsion subsystem and especially the low-power start-up and variable power features can be also a significant added value for any commercial application using electric propulsion for station-keeping and/or orbit transfer.

1 - INTRODUCTION

Although High Specific Impulse Thrusters have already propelled numerous satellites in the frame of station-keeping missions, their use for orbit transfer and deep space missions has only recently begun, bringing out a need for new thrust strategies.
The Snecma PPS®1350-G is primarily intended for North South station keeping of Geo-stationary satellites. For that kind of application, the spacecraft available power is much higher than the PPU maximum power demand, so there is no risk to overload the spacecraft power bus.

In the case of SMART 1 [1], on the contrary, the PPU power could exceed the total spacecraft power. In addition, the thruster shall be able to work with less than half its nominal power. To fulfil these requirements, it was necessary to modify the thruster / PPU interfaces and to validate these modifications by tests.
Our discussion will mainly be focused on a Hall Effect Thruster (also called Plasma or Stationary Plasma Thruster) as these are the most mature technologies currently available for propulsion systems with a specific impulse in the range 1000-3000s.

2 - SMART-1 ELECTRIC PROPULSION SUBSYSTEM (EPS)

The SMART 1 power is supplied by two solar panels enabling the plasma thruster to operate at 1190 W max at beginning of life [2].

In some cases, (e. g. failure of one solar wing in addition to the solar cells) 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.

This holds true also for missions involving variable sun distances.

The whole EPS is designed for the three following main functions [3]:
- ✓ Xenon system
- ✓ Electrical power system and thruster
- ✓ Digital interface and communication system

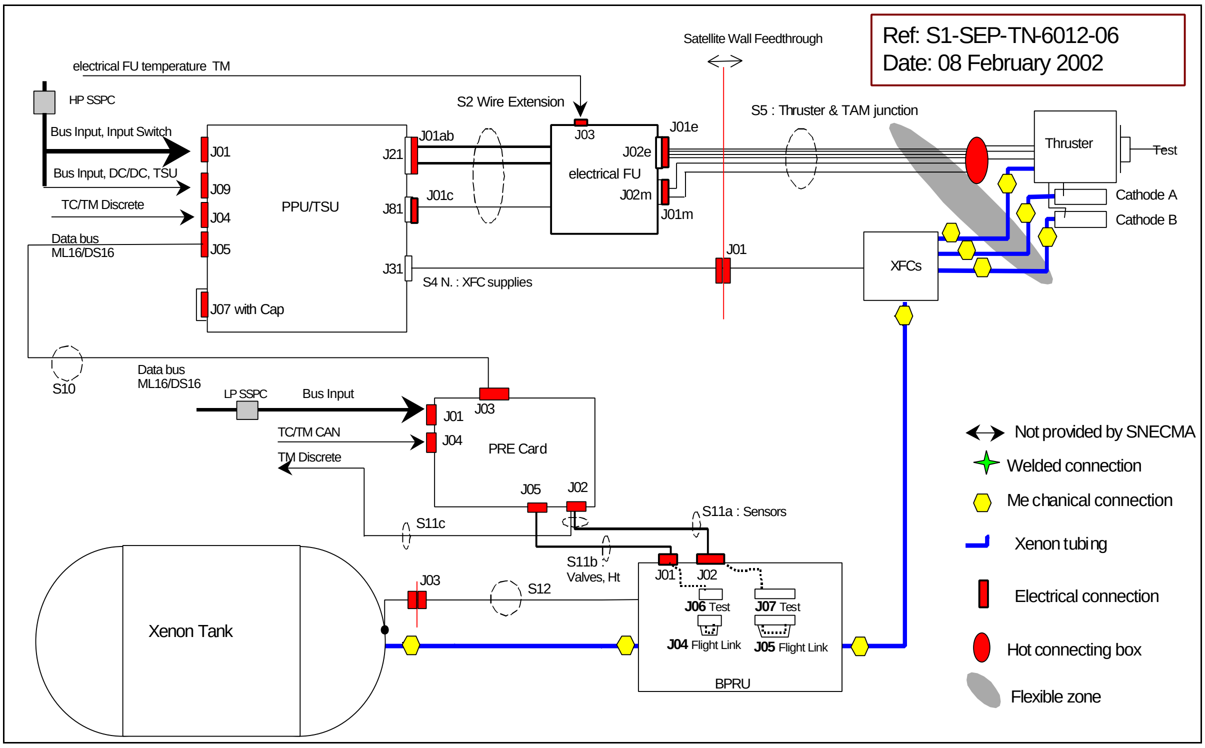

Figure 1. EPS functional diagram: the xenon system feed the thruster cathodes and anode

The **xenon system** is composed of a main composite over wrapped Xenon Tank which store the gas under high pressure, a pressure regulator called Bang-Bang Regulation Unit (BPRU) designed by Snecma Moteurs and Iberespacio (Spain) which deliver the xenon under constant pressure to the adjustable flow regulator called Xenon Flow Control (XFC) which “in fine” deliver the rated flow of xenon to the thruster anode and cathode. For redundancy reasons, the XFC feeds one of the two cathodes A or B depending on the command coming from the switch unit of the Power Processing Unit / Thruster Switch Unit, Figure 2.
The constant pressure delivered by the BPRU is controlled by the simple and robust algorithm loop located into the Pressure Regulation Electronic Card.

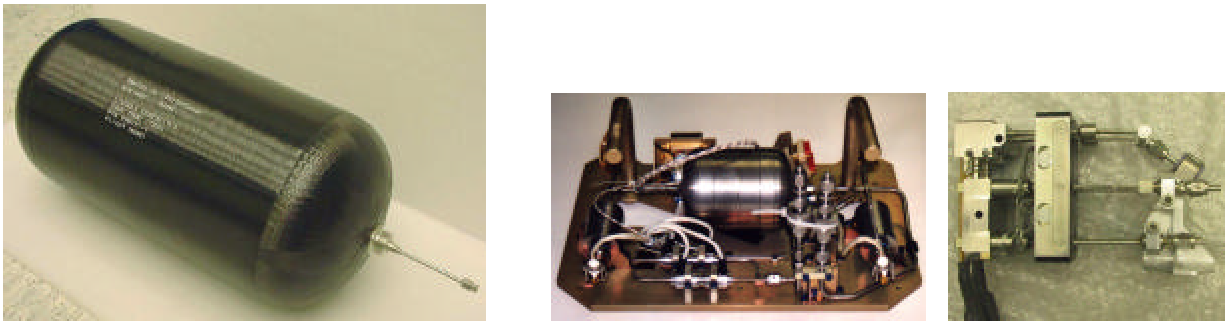

Figure 2. Flight model hardware: tank, BPRU and XFC

The **electrical power system and thruster** 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, into the voltage required by the thruster (from 220 up to 350 Volts). 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. .

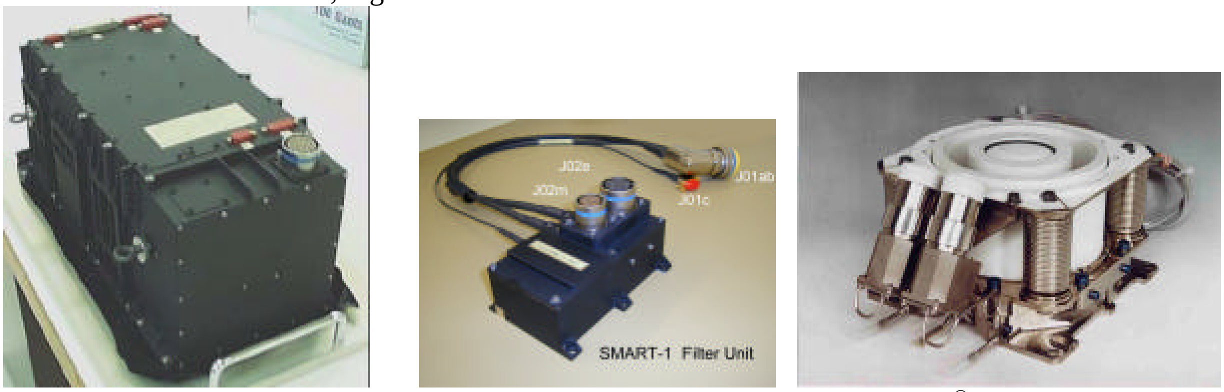

Figure 3. Flight model hardware: PPU, FU and thruster PPS®1350-G

In order to deliver a constant thrust, a simple and robust algorithm loop is integrated into the PPU/TSU and generate the analogic control signal to the XFC [4].

The **digital interface and communication system** is composed of one main interface located into the PRE Card designed by Atermes (France), Figure 4. . The commands and telemetry's dealing with the regulation of the xenon pressure are directly processed by the micro processor of the PRECard. The commands and telemetry's dealing with the thruster and PPU/TSU are first converted into simpler messages and then send to the digital interface of the PPU/TSU for further processing into the microprocessor of the PPU/TSU.

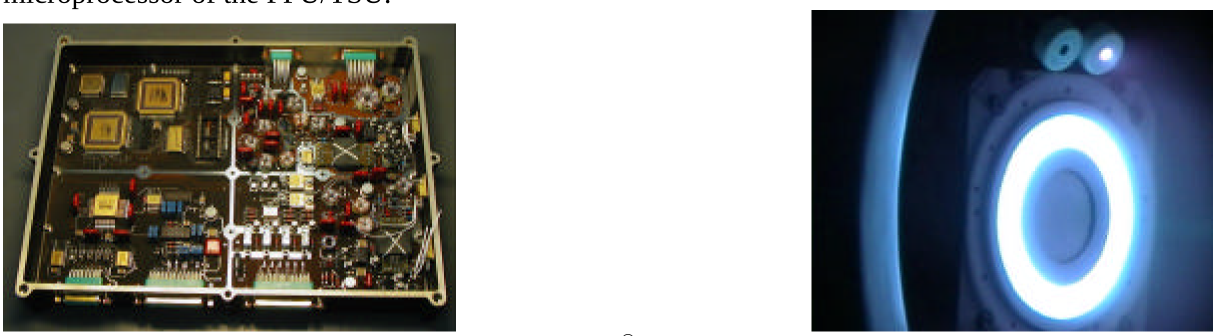

Figure 4. PRE Card hardware, Thruster PPS®1350-G Flight model during the acceptance test:

Each software of the PRE Card and PPU/TSU includes the "automatic mode" subroutines. With such feature, the ignition of the thruster requires only a few set of commands: first, a selection of the main or redundant branches and initialisation parameters, then it is needed to sent the command "automatic exec" in order to perform automatically the xenon pressure regulation algorithm loop and the thruster ignition sequence and after its ignition, the further xenon flow control algorithm loop.

That last loop is performed also automatically by the PPU/TSU in the following way: the goal is to maintain almost constant the thrust delivered by the thruster.
However, it has been shown that it is sufficient to keep constant the Discharge Current , abbreviated "Id" , in order to keep the thrust constant.
On the other hand, it has been shown that the current Id vary quasi linearly with the xenon flow. A device called thermothrottle (a capillary tubing able to be heated when connected to a current source) integrated into the XFC (see Figure 6.)act as a xenon mass flow regulator: the xenon mass flow depends on the current deliver to the thermothrottle (current abbreviated "Ith").
Thus the loop is the following: the PPU/TSU read simply the level of the current Id and its algorithm compute the required xenon flow and generate the required current Ith to be sent to the XFC, Figure 5. .

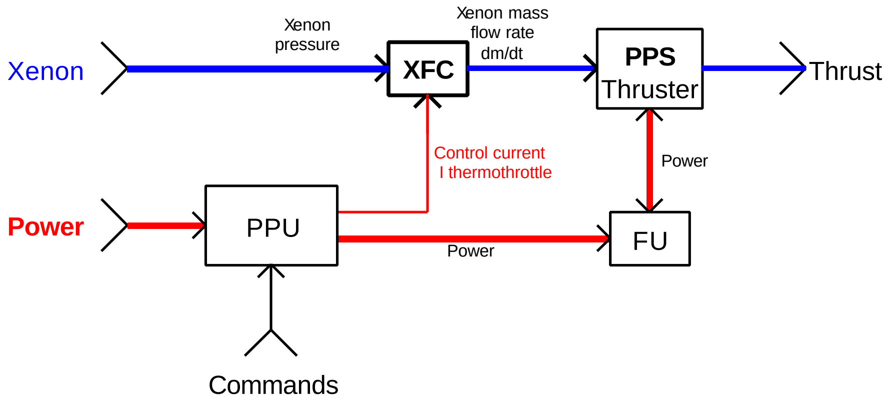

Figure 5. Xenon flow regulation loop

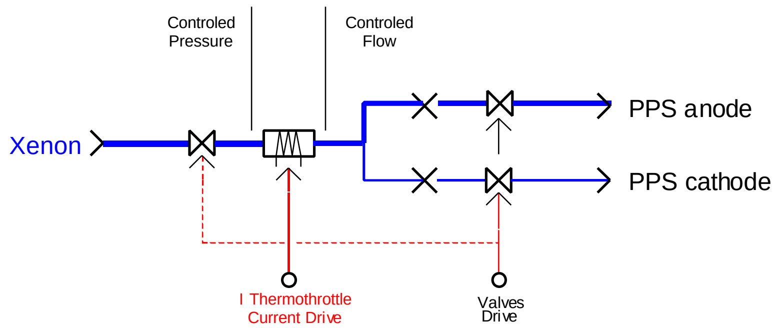

Figure 6. Xenon flow Controller functional diagram

2.1 - 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 degradation as well as non probable electrical failures.
The user can sent, at any time, a "Nominal power set" parameter command to the EPS in order that the thruster use more or less electrical power and to produce more or less thrust. Such command is taken into account by the PPU/TSU to fix the PPU/TSU characteristic. The transient between two settings points is performed by the PPU/TSU in an automatic fashion at a rate of change of about 15 Watt per second. The range of power at thruster level vary from 462 W up to 1190 W [5].
Taking into account the natural losses into the PPU/TSU as well as comfortable power margins, the range of the Nominal power set parameter is varying from 649.3 W to 1417.8 W. The exact power used by EPS is slightly lower than the Nominal power set parameter. Thus, the user will be able, after in-flight characterisation, to sent the maximum "Nominal power set" command to the EPS even if the available power is less than 1417.8 W, in order to get the maximum thrust and performance from the EPS.
The lowest value is the software default Nominal Power set value. It is used to perform the thruster ignition in automatic mode.

There are 117 steps of Nominal power set parameter available, i.e each step of Nominal power set is equal to 6.625 W. In the common electric characteristic plane of the thruster (plane Ud, Id), all the corresponding points are aligned along a single straight line, which is also almost the diagonal of that plane.

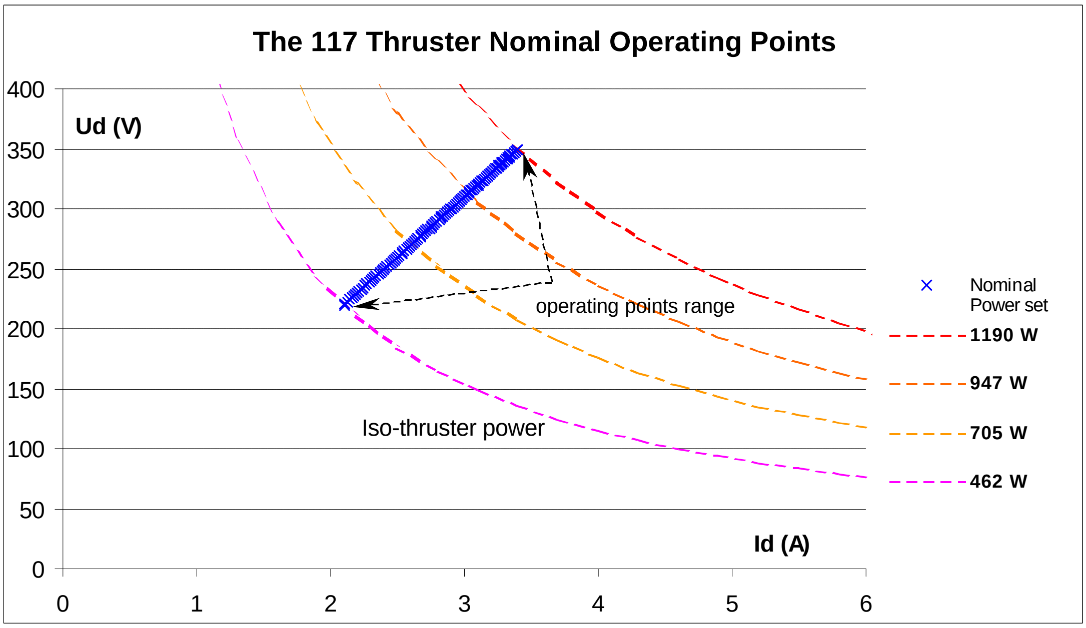

Figure 7. The diagonal with the 117 steps of the variable power feature of Smart-1given by the Nominal Power Set parameter. The EPS Power at thruster level is of course **Ud*Id**, some iso-Power hyperbola are shown.

2.2 - THRUSTER AND PPU CHARACTERISTICS

2.2.1 - *Thruster characteristics*

The xenon mass flow is the main parameter of the thruster. It fix the ions current and further the discharge current Id. So, the characteristics for some fixed xenon mass flow is roughly a set of vertical lines in the plane Ud, Id. The influence of other parameters, as the additional magnet current provided to the coils, are not really relevant with respect to this characteristic. Such characteristics are in fact similar to the ones of electronic component such as a high power diode…

The tests performed in the frame of the Smart-1 program[7], as explained here after, have produced the following characteristic, Figure 8.

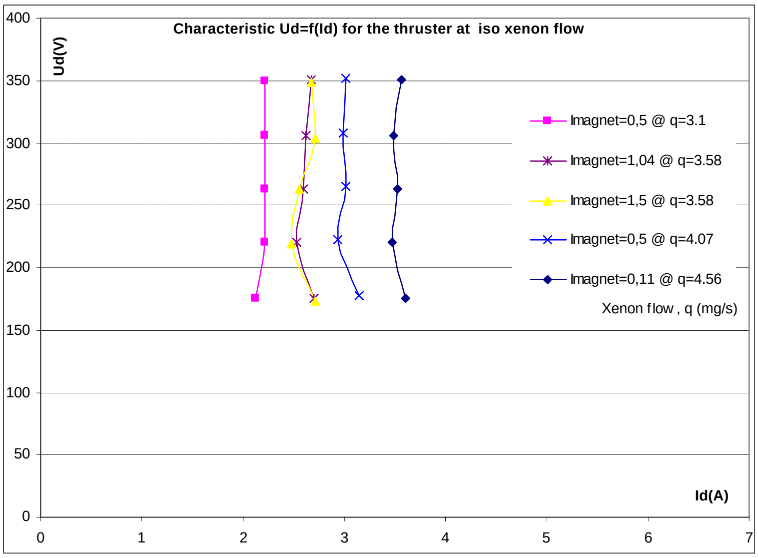

Figure 8. Thruster characteristics, power at thruster level is of course Id*Ud

2.2.2 - *PPU/TSU characteristics*

As the thruster characteristic is similar to the one of a diode, the thruster itself cannot fix the voltage of the discharge, and of course the discharge power cannot be fixed alone. Thus it is required that the PPU/TSU provides a characteristic with a constant voltage. In order to never exceed the maximum power, the end of the characteristics follows a decreasing voltage slope wrt. the current increase. Each PPU/TSU characteristic is uniquely determined with the Nominal power set parameter. The maximum value of the parameter indicate to the PPU to reach the maximum Voltage, Figure 9. .

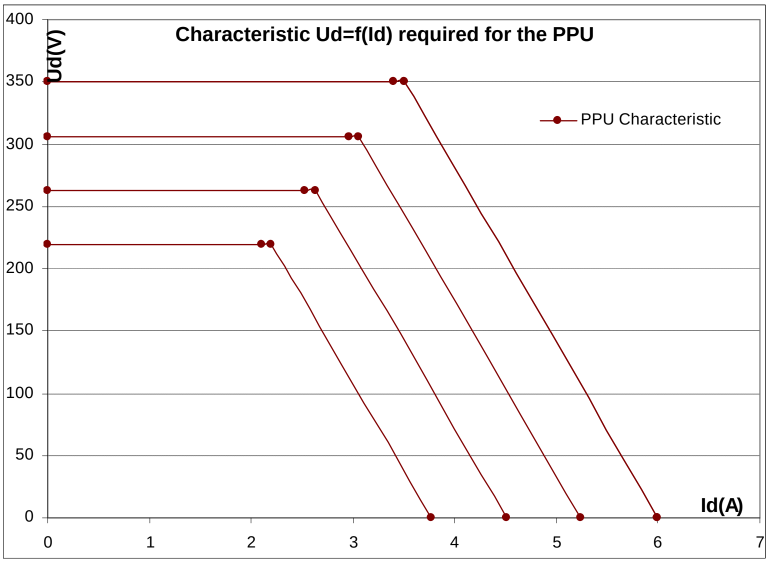

Figure 9. PPU/TSU characteristics, only some of the 117 characteristics are shown

Finally, when the thruster is connected to the PPU/XFC the working points are given by the intersection of the two characteristics, the one of the thruster for a **fixed xenon flow** (or as said before Id), and the one of the PPU/TSU for a **fixed voltage** (or Nominal power set parameter).The diagonal Smart-1 is located near the knee of each of the PPU/TSU characteristics, Figure 10. .

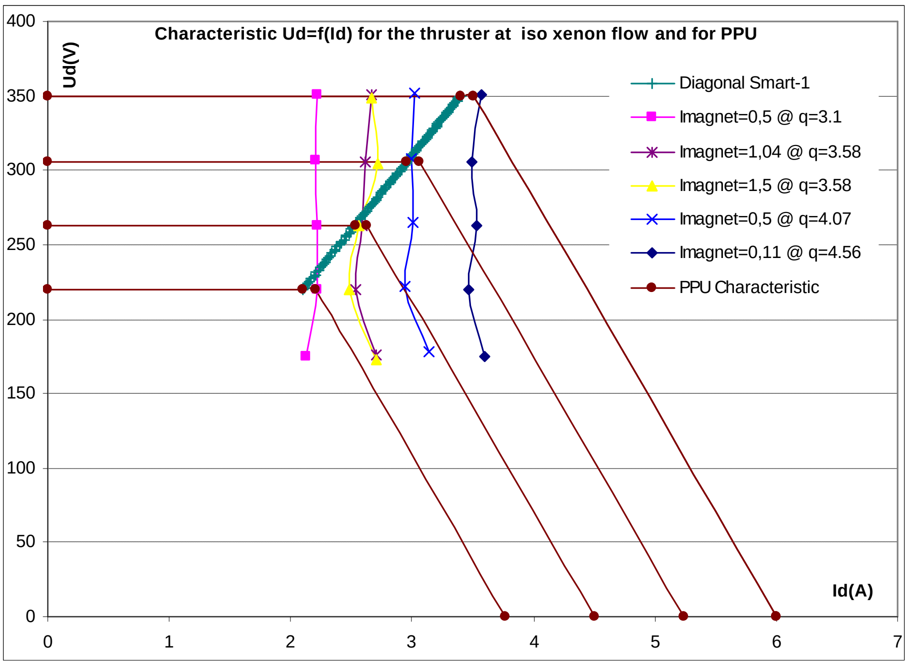

Figure 10. The whole characteristic of PPU/TSU, thruster with the Smart-1 diagonal

3 - GOVERNING LAWS

Before to present the experimental data, we shall introduce the electric propulsion laws in order to minimise the number of characteristic data to be extracted from the tests.

3.1 - THRUST

The thrust provided by the plasma ejection is computed from the momentum conservation law. The momentum given by electrons is neglected due to their very low mass compares to ion mass [6]
The resulting expression of the module of the thrust is:

$$F = \bar{v}_{i_x} \cdot \dot{m}_i \qquad [1.]$$

with $\dot{m}_{prop}$: mass flow rate of propellant in kg/s,

$\bar{v}_{i_x}$: average exhaust ion axial velocity in m/s.

3.2 - SPECIFIC IMPULSE

The major thruster performance is the specific impulse. It is the ratio of the amount of impulse produced per unit of expelled mass. It is usually given in seconds (while ***g_0.Isp*** is expressed in m/s), and is then written:

$$g_0.Isp = \frac{F}{\dot{m}_{prop}} \qquad [2.]$$

with F: thrust in newton,
$g_0 = 9.80665\ m.s^{-2}$.

For Ion and Plasma Thrusters, the Specific Impulse can be expressed as a function of $\bar{v}_{i_x}$:

$$g_0.Isp = \bar{v}_{i_x} \cdot \frac{\dot{m}_i}{\dot{m}_{prop}} \approx \bar{v}_{i_x} \qquad [3.]$$

with $\dot{m}_i$: mass flow rate of ions.

This means that the specific impulse ***g_0.Isp*** is almost equal to the mean ions velocity.
This is a common approximation which is justified by the fact that generally most of the propellant (more than 90 %) is ionised and the fraction of propellant lost in the cathode is low (hollow cathode technology require that some propellant be used to enhance electron emission process).

3.3 - TOTAL EFFICIENCY

The total efficiency of an Electric Thruster is given by:

$$h_t = \frac{1}{2} \frac{F^2}{\dot{m}_{prop} \cdot P} \qquad [4.]$$

with P: total electric thruster input power (given by the PPU to the thruster).

The efficiency is generally around 50%. The causes of losses are numerous, and include:

- Thermal losses
- Ionisation and atom excitation losses
- Jet divergence
- Non-uniformity of exhaust ion kinetic energies
- Electron temperature in the beam
- Fraction of propellant used in the cathode (hollow cathodes)
- Non-ionised propellant

3.4 - SPECIFIC POWER

The specific power expresses the power requirement per unit of thrust.
The previous relationship [4]can be turned into:

$$\frac{P}{F} = \frac{1}{2}\frac{g_0.Isp}{h_t}$$ **[5.]**

which shows that the specific power is almost a linear function of the specific impulse, provided that the efficiency does not vary too much.

3.5 - MINIMUM DATA FOR THE CHARACTERISATION OF AN ELECTRIC THRUSTER

As a conclusion, this chapter show that two data only can characterise any electric thruster:
- ✓ the data of the **thrust** versus the Power
- ✓ the data of the xenon **mass flow** rate versus the same power

The specific impulse can be considered by the user as an intermediate variable only and is just proportional to the ratio of the two previous data.

4 - CHARACTERISATION TEST REULTS

The objectives of the tests [7] were to optimise the operational parameters in a vacuum facility at low discharge power, and specially the variable "Magnet Trim" current used to adjust the magnetic field inside the thruster in order to maximise thrust, efficiency and the specific impulse. Those results serve as a reference for the set up of the operational flight parameters of the thruster as well as a base of the simulation software. The number of cycles performed is 70.
In addition, the ionic jet has been explored 4 times, at low power conditions, in order to be able to give the jet characterisation for the satellite Diagnostic Package.

4.1 - TEST SET-UP

The thruster can only work in a vacuum chamber. The high level of vacuum is performed thanks to a specific set of pumping devices. During the characterisation tests, the thruster is mounted on a specific thrust measurement device, and is connected to the xenon feed tubing’s as well as to the electrical harness.

The ions are exhausted from the thruster at a high velocity, 20 km/s in an area called “plume”. All the kinetic energy of those ions is converted into thermal energy in the specific ion target.

The test facility devices like the high voltage and power unit, the xenon pressure regulator and the xenon mass flow rate regulator as well all the measurement and digital acquisition / command complete the set-up. The jet measurement probes are shown Figure 12.

Contrary to the real use of the thruster into the EPS, the goal of the test being to characterise the thruster behaviour, the internal loops of the EPS are open in the tests set-up. For example, the xenon mass flow is regulated independently from the discharge current Id and deliver the xenon at a rate defined into the test facility software.

4.2 - TEST SEQUENCE DEFINITION

Since the number of points to be tested was large, the test sequence has been optimised in order to save time and cost as follow :
For each four set value of flow-rates , it has been decided to not to switch off the thruster between each change either Voltage or current Imagnet .
To avoid any loss in thrust measurement accuracy, it has been added three or four reference identical set points chosen on the main diagonal and those points were used as calibration of thrust during the entire sweep in Ud-Imag of one pre-set flow-rate .
Since the thrust measurement balance is sensitive to thermal change and because it's the main source of thrust signal drift , it has been introduced also a preliminary warm-up firing test of three hours just before the characterisation in order to get the best thermal stabilisation of the experimental set-up.
Finally, a firing test of 15 minutes on the same reference set point between the warm-up firing and the characterisation firing has been added.
After that the change of the flow-rate allows to perform the intermediate diagonal point .

In summary , each long run of testing can be detailed as follows, as shown on Figure 11.

Event	GOAL
Three hours warm-up test	Thermal stabilisation
Reference set point 15 minutes	Thrust calibration
Three - four hours characterisation test	Characterisation
Intermediate flow-rate 15 minutes characterisation	Characterisation

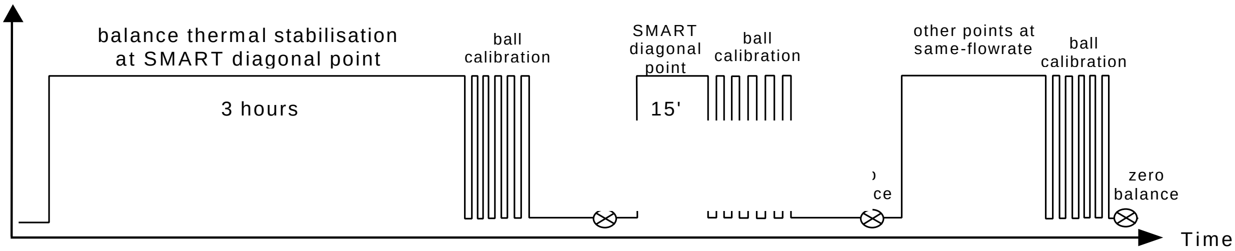

Figure 11. Long run test sequence, definition of same flow-rate firing sequence.

5 - TESTS RESULTS

The test has been performed mid-June 2000. After the thruster has been set-up inside the vacuum chamber, the test sequence has been started. The main parameter are shown on Figure 13.

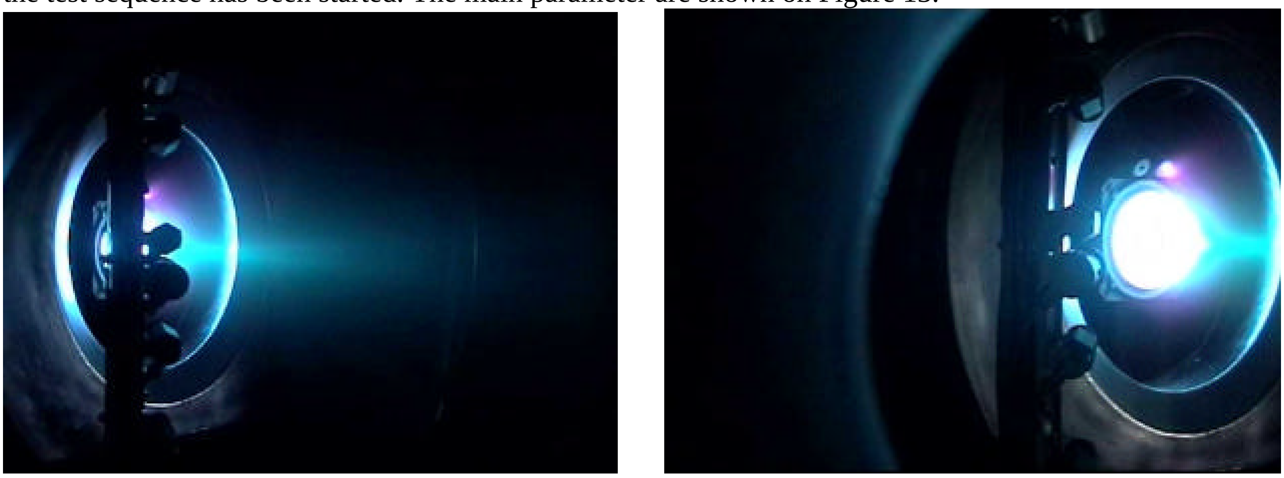
Figure 12. Firing sequence with jet probes measurements.

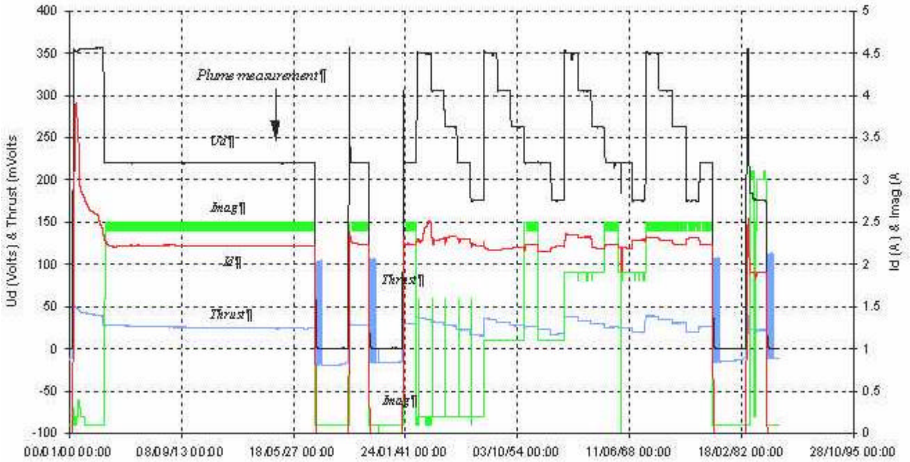

Figure 13. A typical characterisation test Sequence, with multiple operational points.

Dispersion on the thrust measurements

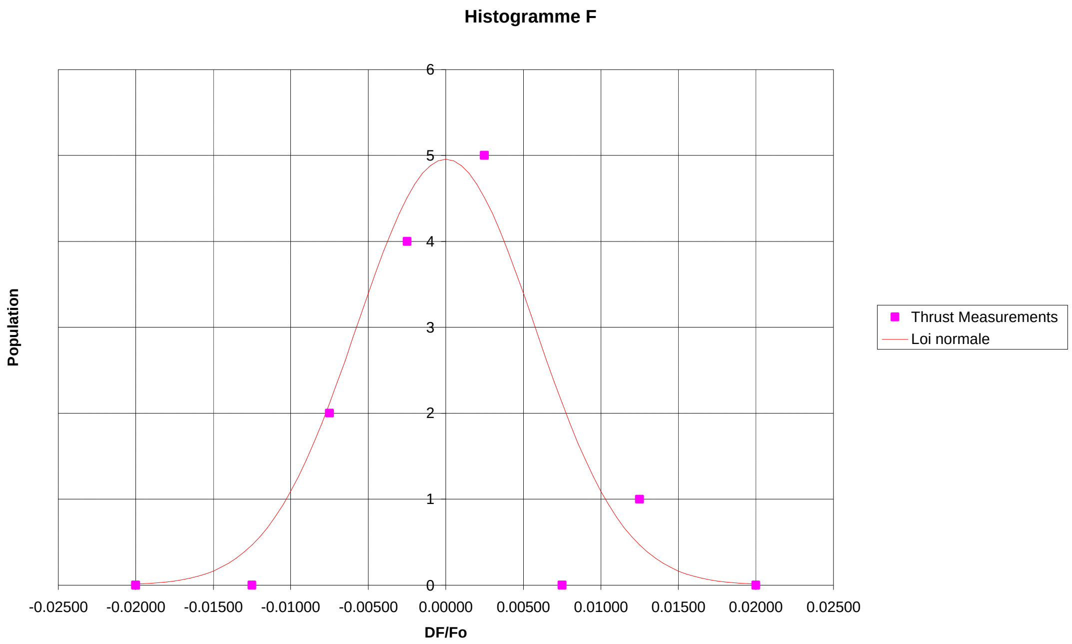

Figure 14. Show of the dispersion on 4 sets of 3 identical measurements performed on the first diagonal, Standard deviation σ expressed as $\Delta F / Fo$ is 0.00575.
The overall thrust accuracy measurement at 3σ is $\pm 1.7\%$.

6 - PERFORMANCE DATA REDUCTION: PERFORMANCE LEAST SQUARES FIT ON THE FIRST DIAGONAL SMART-1 LAW

In order to obtain the first diagonal performance law versus power , we performed a data fit with the following laws:

$$F(N) = 0.9162 \cdot (1 - e^{-\frac{\dot{m}}{1.791}}) \cdot \dot{m} \cdot 0.9225 \cdot \sqrt{\frac{2Ne}{M} \cdot (Ud - Uo)} \qquad \textbf{[6.]}$$

with $175V \le Ud \le 350V$ and $Uo = 64V$ and 0.9225 is the anode part of total flow-rate; N: Avogadro number; e: electric charge of the electron, in coulomb; M: molecular mass of the ion (=the neutral atom of xenon) in kg.

$$\dot{m}(kg/s) = \frac{IdUd \cdot 10^{-6}}{7.10 + 0.918 \cdot Ud} + 0.837 \cdot 10^{-6} \qquad \textbf{[7.]}$$

with $175V \le Ud \le 350V$ and $2.1A \le Id \le 3.6A$
With these relations , we calculate from the measurements, by limited development versus Ud ad Id, the thruster performances exactly on the diagonal and we fit after that with standard method on a polynomial of degree 2 .
The following results [8] are obtained versus power (input power of the thruster) :

$$\boxed{\dot{m}(mg/s) = -0.3716\, P^2 + 2.545 \cdot P + 1.935} \qquad \textbf{[8.]}$$

$$\boxed{F(mN) = -5.10 \cdot P^2 + 60.94 \cdot P + 4.68} \qquad \textbf{[9.]}$$

where $P = (Ud + Umag) \cdot Id$ is the Power at thruster level, expressed in kW and 0.46<P<1.5 kW.

6.1 - Performance Least Squares Fit with Highest Isp

The diagonal can be considered as a robust optimised high thrust setting points of the EPS. However, the performances data reduction show a non optimum use of the thruster on the first diagonal.

From the thruster point of view , it seems to be more convenient , in terms of highest Isp , to work at the same highest voltage of 350 Volts covered by the characterisation ; obviously , higher voltages would deliver higher Isp .

The comparison with the first diagonal law of the specific impulse and the thrust obtained is given in Figure 15.

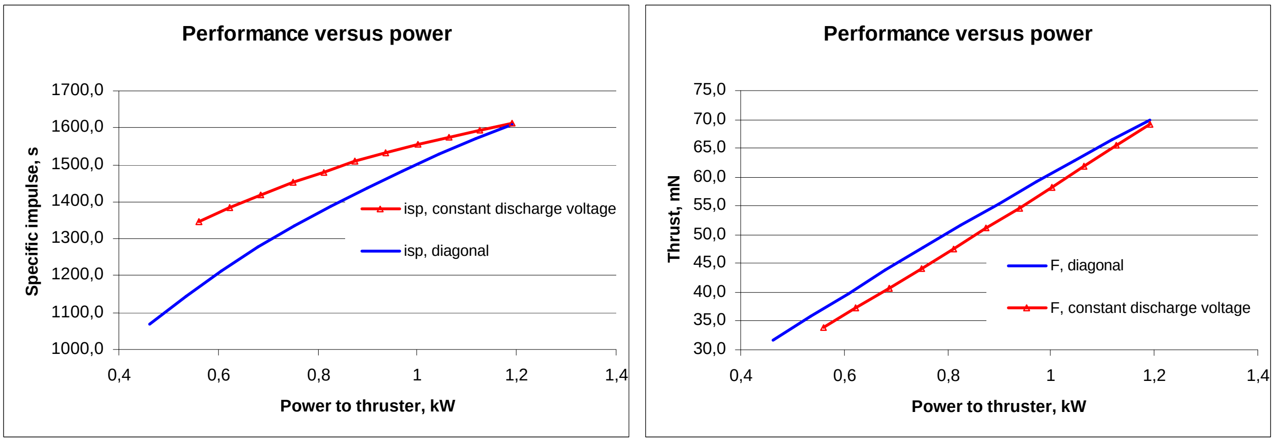

Figure 15. Specific impulse and thrust versus power diagonal case and 350 volts case.

The development programm timing allowed to take into account in the PPU/TSU software of the Flight model the above data fit computation on the first diagonal, directely in a loockup table.

7 - ACCEPTANCE TESTS

The Smart-1 components acceptance tests have been performed at their manufacturing plants by each sub-contractor. Special attention were taken wrt. the tank environmental tests with fluid simulant the real xenon gas, and the protoflight PPU/TSU which was not completely considered as an off the shelf component due to the new features added to it (mainly the variable power feature).

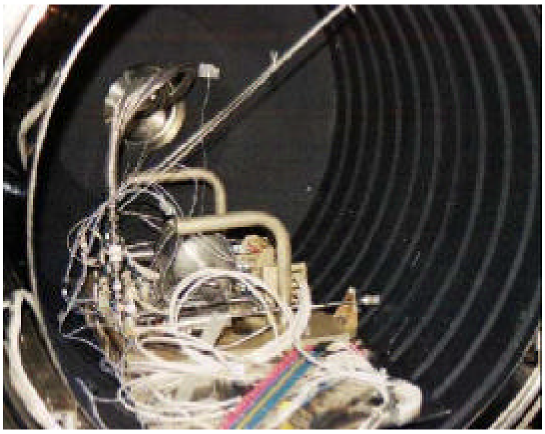

Figure 16. BPRU thermal vacuum functional tests with real xenon gas, at Madrid INTA facility

The pressure regulation unit BPRU, composed of off the shelf components, has been protoflight acceptance tested by Iberespacio (Spain) at the Madrid INTA facilities, Figure 16. Before that campaign, a complete serie of characterisation tests with real gas xenon has been performed on the base of a detailed modelisation using the power full software EcosimPro (http://www.ecosimpro.com/).

The results of those tests showed that the mathematical model didn't requires any update to keep the right accuracy.

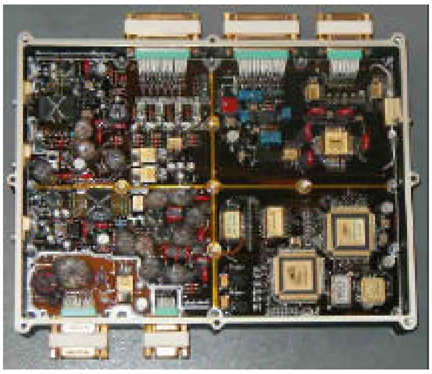

Figure 17. PRE Card FM after fuctional tests at Atermes (with savers connectors)

The Electronic PRE Card FM has been strictly only acceptance tested (including shock test and thermal vacuum campaign performed by Swedish Space Corporation in Solna, Stockholm) because the completion of the qualification model tests performed by the Atermes, France, didn't shows any deviation wrt. the requirements Figure 17.

The PPS® 1350-G[9] Flight model of Smart-1 has been acceptance tested during a first serie of two acceptance test campaigns:

First, a common acceptance test campaign including magnet measurement, start ON and performance measurement, environmental tests,… has been performed in order to establish the manufacturing quality.

The second FM campaign was a coupled test campaign with other FM devices: FM PPU/TSU and FM FU. The test sequences (at different power levels, Figure 18.) were fully checked during that campaign, as well as the right behaviour of the FM devices in real conditions (with the real thruster instead of the usual thruster simulators). The results of that campaign can be considered as the Reference State of the EPS.

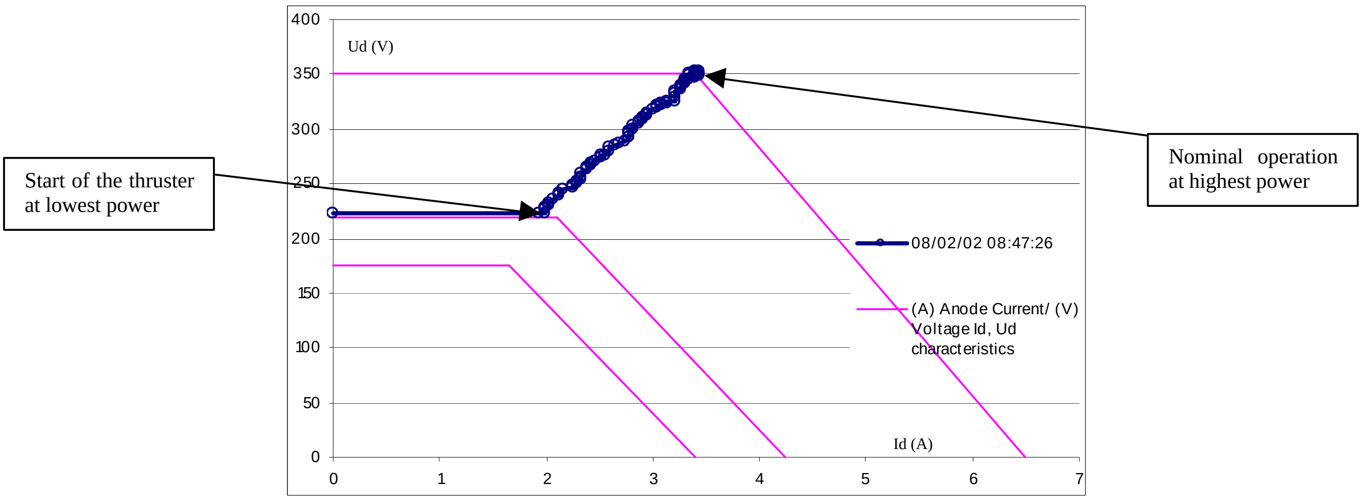

Figure 18. Typical PPS® 1350-G FM firing at maximum power, starting at low power and following (automatically via the PPU software) the Smart-1 Diagonal

8 - END TO END TESTS

Finally, the test of the thruster, at satellite level (End to End tests) has been successfully performed by the Swedish Space Corporation (SSC), the Smart-1 prime contractor, in an adequate

ESTEC vacuum test facility (large enough for the whole satellite) [10]. For the EPS, the goal of that tests was the right behaviour of the whole System, including the sequences foreseen for the xenon lines venting and the behaviour of the xenon pressure regulation. Moreover, the compliance between the different system of the satellite has been checked particularly during the two thruster firing (firing using first the nominal branch, and second firing using the redundant branch). The results of that campaign can be considered as the Reference State of the EPS into the satellite. The End to End tests performed act as a final tests: its success has also shown the satellite robustness.

9 - CONCLUSION

The paper presents the Smart-1 Electric Propulsion Sub-system Flight Model as well as the main feature of the system and the tests performed.

Because during its travel to the Moon, the Smart-1 probe electrical power can be decreased, the characterisation of the performances provided by the EPS has been performed. The data have been fully taken into account in the EPS software. For Smart-1, the nominal philosophy available for the user is the first diagonal (where voltage and current of the discharge are decrease together when the input power decrease) which maximise the thrust. The user can use up to 117 steps on the diagonal in an automatic mode, with a thruster power in the range 462 W to 1190 W. The thrust vary between 30 and 70 mN and the Specific impulse vary from 1060 to 1600 s.

On the base of the tests campaign, as described here above, performed in the frame of the Smart-1 program, the thruster PPS® 1350-G has shown its ability for application as a Main Propulsion subSystem.

ACKNOWLEDGEMENTS

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BIBLIOGRAPHIE / BIBLIOGRAPHY

[1] G. Saccoccia, D. Estublier, G. Racca " SMART-1: A Technology Demonstration Mission for Science Using Electric Propulsion", AIAA-98-3330, 34 th AIAA/SAE/ASME/ASEE Joint Propulsion Conference and Exhibit, July 13th-15th, 1998 / Cleveland, OH.

[2] C. Koppel, M. Lyszyk, D. Valentian,, "PPS 1350 With Variable Power Feature for SMART-1", AIAA 2000-3427, 36th AIAA/ASME/SAE/ASEE Joint Propulsion, Conference and Exhibit, 17th-19th July 2000, Huntsville, Alabama.

[3] S1-SEP-ICD-6001 **,** SMART-1, Eps Interface Control Document.

[4] H. Declercq, C.Rijm, E. Bourguignon, T. Scalais, V. Lempereur, "High Power Processing Unit For Stationary Plasma Thruster", Propulsion des Véhicules Spatiaux / Spacecraft Propulsion, October 10th–13th 2000, Cannes, France.

[5] S1-SEP-RS-6001 69, SMART-1, Power Processing Unit (Ppu) Requirement Specification.

[6] C. Koppel, S. Barral, " High specific Impulse Thrusters Behaviour", ATELIER CNES "TRAJECTOIRES A POUSSEE FAIBLE" 7-8 mars 2000, Toulouse.

[7] S1-SEP-TR-6002, SMART-1, Low Power PPS®1350 Characterisation Test Report.

[8] C. Koppel, O. Secheresse, "Performances and Thrust modelisation of a Hall effect thruster", LOTUS 2, LOW THRUST TRAJECTORIES CNES Workshop, 18 – 20 juin 2002.

[9] P. Dumazert, S. Lagardère-Verdier, F. Marchandise, C. Koppel, P. Garnero " PPS®-1350-G Qualification Status, March 2003" 28th IEPC 2003-0270, 17-21 March 2003, Toulouse, France.

[10] D. Etsublier, C. Koppel, "SMART-1 End-to-end test: Final results and lesson learned" 28th IEPC 2003-0303, 17-21 March 2003, Toulouse, France.