The PPS®1350 qualification demonstration
7500h on ground, about 5000h in flight

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Abstract : The PPS® 1350 is a thruster dimensioned for North/South station keeping of satellites in
the range 1 to 4 tons in Geostationary Earth Orbit (1,7t to 6,5t in GTO). With its nominal thrust of
88 mN for 1,5 kW, it follows the on ground qualification program. For the Smart-1 moon mission
(370kg), a thruster of the same definition has already demonstrated almost 5000h in flight with a
maximum thrust of 70 mN with the 1,2 kW allowed to that thruster operation.

This paper discuss the current qualification status of the PPS® 1350. It started during year 2002 with
environmental tests. Life test then began and is still on-going. A first sequence of cycles on/off was
completed before a set of cold cycles conditions in Russia (at OKB Fakel facilities). Then, from
beginning of 2004 to mid 2005, cycles were performed with some interruption mainly to include a
Power Processing Unit. This unit is close to the flight configuration and manufactured by Alcatel-
ETCA (B). A total of 7506h and 5593 cycles was performed.

Results show a good thruster performance above the specified values but in good accordance with
theoretic thrust and power.

This paper will also discuss the thruster performances, in the field of EMC behavior, magnetic
profile, and ion distribution (data measured along the life test). Thermal cartography of the thruster
shows also some information on the phenomenon occurring during thruster start period. As already
observed on most development tests, this thruster shows also similar functional transition mode. In
flight, sometime similar behavior were observed without impact on the satellite. Erosion of the
thruster and cathode are still on-going slowly with a special mention to the cathode that has quite no
visible external erosion.

Nomenclature

\[ \Delta V \] = ideal velocity
\[ \eta \] = efficiency
\[ EP \] = electric propulsion
\[ EP \] = electric propulsion
\[ EMI \] = electromagnetic interference
\[ EMC \] = electromagnetic compatibility
\[ EWSK \] = East West Station Keeping
\[ F \] = thruster thrust

\[ GEO \] = Geostationary Earth Orbit
\[ GTO \] = Geostationary Transfer Orbit
\[ Id \] = discharge current
\[ It \] = total xenon flowrate (anode+cathode)
\[ NSSK \] = North South Station Keeping
\[ PPU \] = Power Processing Unit
\[ TRL \] = Technology Readiness Level
\[ Ud \] = discharge voltage

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I. Introduction

The PPS®1350-G is now in the last phase of its qualification program. The current status of life test is 7506h firing with 5593 cycles. We will first recall the main objectives of this program in terms of mission and performance target and show the overall logic of qualification. The thruster qualification process will be described, and the obtained performances will be discussed. We will also describe some side performance and specific behavior that highlight the missions extensions capabilities of the thruster. There is still some test or demonstration to perform next year that we will also list.

II. Overviews

A. Geostationary satellites needs

Hall effect thruster main advantages are a high Isp with a relatively low electric power consumption. This allow to obtain a significant thrust with the on board power of today’s satellite. One of the commercial satellite constraint remains the availability of the payload, so the power demand of the EP system shall be kept as a fraction of the satellite power. In current configurations, satellite manufacturer uses only one thruster at a time and we estimate the available power to 2 kW maximum.

The PPS®1350-G is designed to cover the current and future needs of satellite propulsion for NSSK. A global overview of such need lead to a ΔV of around 750 m/s for 15 years NSSK in orbit operation. This drive the thruster performance needs : see fig. 1. As hypothesis for this curve, we take a NSSK need of 609 m/s per thruster.

We use one thruster per side (North or South) with a firing angle between north-south axis and earth-satellite axis of 52°. This is one of the options currently studied by satellite manufacturer for heavy satellites (more than 4000 kg).

With a current demonstration of $2.31 \times 10^6$ N.s impulse, and with the above hypothesis, the PPS®1350-G is already compatible with 6000 kg satellite (launch mass) without life margin and 4000 kg satellite with a life margin of 1.5.

Another satellite need is the orbit transfer from GTO to GEO (for classical launch). This lead to a ΔV from 1500 m/s in short impulse strategy to 2300 m/s in continuous thrust strategy. We can see that this continuous thrust strategy has a penalty of roughly 50% ideal velocity increment, but with Xenon plasmic propulsion, specific impulse authorize a five time less consumption than chemical fuel. The resulting gain for transfer from GTO to GEO is to decrease the fuel mass needed to one third of what is currently used for this function with chemical (MMH/N₂O₄ type) propulsion system. Because of the high complexity of chemical bi-liquid propulsion system, it is logic to also consider EP system for that function. The only drawback of such device, the time to achieve the transfer, can be compete by the number of thruster

Figure 1. Thruster impulse need vs. Satellite launch mass

Thruster NSSK impulse demonstration need (dashed curve) depends on margin philosophy requested by the satellite manufacturer. We uses here a standard value of 1.5.
firing simultaneously. As an example, 8 thrusters PPS®1350-G can send a heavy satellite from GTO to GEO in less than 3 months, using 12 kW. To complete the whole propulsion mission EWSK of 2 m/s/year from earth equatorial ellipse and 3 m/s/year from sun annual perturbation, another set of electric thruster must be implemented to have an all electric propulsion system. Other launch strategy (super-GTO, high perigee...) lead to a smaller need of speed increase and thus either save time, either allow bigger satellite.

B. Thruster target performance
Cooperation between OKB Fakel and Snecma lead to create the PPS®1350-G. This thruster, which is an improvement of the SPT 100 thruster, has a functioning point chosen at 350 V, 4.28 A. The PPS®1350-G is designed to deliver 88 mN with the 1500 W electrical power. The total impulse foreseen for qualification program is $2.96 \times 10^6$ N.s at nominal performances. A secondary objective was also to achieve $3.5 \times 10^6$ N.s. We currently do not know the first failure time of such thruster: erosion rate decrease during time to a data close to 0 μm/h (probably more than 11500h will be needed to show any performances degradation).

The target thruster bottom performance is 83 mN with a specific impulse of 1570 s at the 1500 W power level. Of course, this is lower than the thruster real performance (under the nominal functioning point conditions), because of margin taken to include eventual slight modification in flight because of environmental conditions. The SMART-1 experience show a very good behavior and that these margin were large.

C. Thruster qualification logic
To obtain a good demonstration for such “new” technology for western countries, it was decided to realize several models with together on ground and flight demonstration. Two flight opportunities occur for the PPS®1350 with the Stentor CNES program and with the SMART-1 ESA program. Both programs were dedicated to new technology demonstrations. Several on-ground thruster were manufactured to be submitted to the necessary extreme conditions that should never occur in-flight and are only obtained by test.

For the Stentor program, even if the lifetime target was achieved by the thruster, we identify some weaknesses in the design that would limit its lifetime. An improvement campaign was done together with the elaboration of a strategy to obtain the TRL 9 level (flight proven system with mission operation).
This lead to the PPS®1350-G design and to four thruster models:

- the Engineering Model (EM) to demonstrate EMI/EMC compliance and to do some extreme tests
- the demonstration model (DM-R) built by Russian company OKB Fakel to achieve a lifetime of 7180h with 8611 cycles
- the QM model to achieve qualification environmental tests followed by qualification lifetime of the thruster.
- the FM model to demonstrate in-flight performances and the ability to perform transfer functions.

EM, DM-R, QM and FM models are flight standard models except for EM which has only one cathode at flight standard. The other one is just a dummy cathode.

The EM model explore voltage range from 250V up to 1000V, and flow rate from 2.3 mg/s up to 6.4 mg/s.

Currently, the DM-R model performed 7000h with successful compliance to the specifications, the SMART-1 mission with the FM thruster performed 5000h with success at the foreseen level, and the QM performed 7500h with good performances (above the specification).

III. Qualification Process

The model that follow the more stringent process is the QM. It has to perform a first set of on-ground tests as a flight model, then a set of environmental tests at qualification level and a simulation of a flight life test with comfortable margin on the performances in terms of cycles, hours and impulse.

A. Test set up

We will describe here the different functional set-up that were used during the life test.

Two set-up configuration has been used during life test:

- A test bench configuration was used until 4200 hours of firing
- From 4200 to 7500 hours, the life test has been continued with in joint configuration by replacing the test bench power supplies by a PPU (Power Processing Unit).

SET-UP IN TEST BENCH CONFIGURATION

The set-up comprises (Fig 3):

- a main vacuum chamber, in which are placed the PPS 1350-G QM thruster on a thrust balance, the XFCs, the FU, and a mean of characterizing the thruster plume;
- The test bench electrical power supplies for discharge circuit, cathode heater, XFCs command (valves and thermothrottle) and magnet trim (which deliver additional current in the coils when needed)
- a bottle of Xenon simulating the tank;
- a xenon supply assembly equipped with the flow meters and xenon pressure sensors.

Vacuum chamber and pumping system

The main vacuum system comprises a vacuum chamber and its pumping system, an air lock and its pumping system, a valve separating the chamber from the air lock, and a baffle cooled with liquid nitrogen. The extreme vacuum in the 12 m³ chamber is lower than 10⁻⁶ mbar. With a Xenon supply of 5.5 mg/s, the pressure is established at about 1.5.10⁻⁴ mbar. The back of the chamber and the baffle are protected by a carbon wall and the vacuum chamber by a stainless ring.

Xenon supply device

A 60 bar bottle provides the xenon to the fluid circuit. The Xenon pressure is then regulated at the XFC inlet specified value by a mechanical regulator. The Xenon supply device comprises a nitrogen feed line to clean up the overall lines, a xenon feed line, a supply line for the XFC module, and a vacuum circuit for cleaning purposes. The supply line is equipped with a pressure sensor at vacuum chamber sas inlet and a mass flow meter/controller which measures the quantity of xenon flowing through the line to a maximum of 8 mg/s.
**Test acquisition, control and monitoring system**

The unit being tested is controlled and monitored by a computer interfaced by OPTO22 panels, which insures the command of the test bench power supplies, the command of the thrust balance, the control and surveillance, that means check of acquired data, compares them with programmable alarms and display them on computer screen, while commanding appropriate routing if necessary, and the acquisition and retrieval of measurements.

A hardware safety system backs up the software safety mechanisms by cutting off all power supplies.

**Thrust measurement system**

The balance is an important part of the test bench since the thrust measurement is the only parameter giving a mean of precisely determining the specific impulse and the efficiency of stationary plasma thrusters. The balance is a pendulum system of suspension leaf springs with a position follow-up mechanism. It is equipped with a calibration system and a horizontally adjustment system so that the measurement reference datum can be adjusted.

When a thrust force is applied along the axis of the balance, a position sensor detects a variation in the original position of the balance. The balance control loop then command the follow-up mechanism to compensate for the registered deflection in order to balance the force of the thruster undergoing firing. In addition, a balance signal, which reflects the displacement and consequently the load applied to the balance, is generated and is used as measurement signal.

**Mean of characterizing the thruster plume**

An arm equipped with probes (Fig. 4), inside the vacuum chamber is used to characterize the thruster plume. These probes are of two types:

- FARADAY probes to measure ion current density versus divergence angle of the thruster plume.
- RPA (Retarding Potential Analyzer) probes to investigate ion energy in the stationary plasma flow.

A specific EGSE which allows to command the motor for rotation of the arm through the plume and to process data's for determination of the position of the plume center, the divergence and the ions energy.

**SET-UP IN JOINT CONFIGURATION WITH PPU**

Figure 5: PPU-test bench joint configuration

The differences with the former test bench set-up are the following (Fig. 5):

- The test bench power supplies are replaced by a PPU connected to a specific EGSE insuring the following functions:
  - PPU energizing through a Line Impedance Network Simulator (LISN) in order to simulate the satellite power bus
  - PPU command and control
  - PPU telemetry acquisition and storage

This EGSE is commanded by the test control system through a safety rack allowing emergency stop in case of alarm detection.

- The test acquisition system is modified taking into account specific measurements and surveillance's due to the PPU implementation.

As the life test objective is the qualification of the thruster, the PPU is in ambient pressure conditions and not under vacuum. The PPU is at flight standard and provides the power in a close-to-flight manner. It receives also the thruster perturbations and shall perform under that environment.

**B. Environmental qualification tests**

Environmental tests were performed at acceptance level and then at qualification level. Acceptance is as usual 1.5 less than qualification level for sine levels and 1.25 for random level.

Sine Thruster and XFC qualification levels are described in table 1 and table 2.

Random vibration tests levels were described in ref.1, at a level of respectively $13.5 \text{ g}_{\text{RMS}}$ and 10.5 $\text{g}_{\text{RMS}}$ for the thruster and the XFC.

Shock tests were performed at a level of 2000g and 3000g (see table 3).
reference 8) without damage on the thruster and XFC.

<table>
<thead>
<tr>
<th>Mounting Plane</th>
<th>// Mounting Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>Levels</td>
</tr>
<tr>
<td>----------------</td>
<td>--------</td>
</tr>
<tr>
<td>5 – 16</td>
<td>10 mm</td>
</tr>
<tr>
<td>16 – 60</td>
<td>10 g</td>
</tr>
<tr>
<td>60 – 100</td>
<td>8 g</td>
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</tbody>
</table>

Table 2 : XFC qualification level sine

Thermal qualification level of the XFC is at −15°C to +95°C, while the thruster can withstand −57°C to +200°C at its interfaces. No significant anomaly occurs during these tests.

C. Life cycle test

The life cycle tests started in January 2003 by a combined cycles sequence which last 181h : after two tests on the two cathodes, group of cycles of 0h45mn, 2h30mn, and 4h15mn are separated with 20mn off time. The first period of tests last 2900h only perturbed by a few stop of the test facility (pumping system regeneration) where we put the thruster in a small box connected to the main vacuum chamber in order to avoid any atmospheric pressure on the thruster.

51 thruster start at very cold temperature (~45°C) were then performed at OKB Fakel facility. Even if we put the thruster under nitrogen, it is clear that the thruster was impacted by this atmospheric pressure.

At the return of the thruster, we decided to perform 10h firing to clean any gas residual that can be adsorbed in the porous ceramics. Together with a test bench maintenance, this allow to see results a lot more stable after 3000h. Another opening of the test bench with atmospheric pressure on the thruster could not be avoided at 4200h firing, because of the implementation of the flight design of PPU and FU. Since the beginning of December 2004, the thruster fired cycles sequences until it reached 7500h.

The next objectives are to repeat the cold sequence of 51 cycles and to increase the life duration to 9600h and then to 11400h, in order to perform at least 2.91 10^6 N.s, and up to 3.5 10^6 N.s.

IV. Performances

A. Thrust, ISP, power and propulsion performance

Thrust

The evolution of the thrust during life test is presented in the figure 6. Several phases can be noticed:

- From lifetime start to 200 hours, the thrust decreases of about 6 mN and then increases and reaches 92 mN after 400 hours. This has been identified as the signature of the end of outgassing of the thruster.
- Between 400 and 1950 hours, the thrust decreases of about 5 mN, then increases of about 3 mN
- Between 1950 and 2500 hours, fluctuations of thrust can be observed with a decreasing tendency. This was identified as the consequence of the lifetime stop at 1950 hours for

Figure 6. Thrust versus time

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specific intervention on test bench. Then the thrust increases and reaches a stabilized value of 90 mN after 3500 hours of firing. This data is just above what was expected (around 88mN) but coherent with the Xenon mass flow rate which is also just above the expected 5.25 mg/s.

At 4200 hours, following the implementation of a flight design of PPU, a local decrease of thrust is observed during less than 100 hours. This thrust decrease is correlated to a lower discharge current delivered by the PPU (4.24 Amps instead of 4.28 Amps). The difference corresponds to LSB (Lower Significant Bit) on the commanded discharge current of the power supply circuit of the PPU. The setting of the PPU was modified in order to obtain the correct discharge current of 4.28 Amps. Consequently, the value of the thrust came back to its stabilized value before set-up modification.

Globally, the evolution of the thrust of the PPS 1350-G QM during lifetime is similar to the one observed for other Hall effect thrusters if we do not consider the perturbations between 1950 and 3500 hours due to an intervention on the test bench.

After 7500 hours of firing, the total impulse is $2.38 \times 10^6$ N.s.

**ISP**

The evolution of the ISP during life test is presented in the figure 4. This evolution roughly follows the thrust evolution except between 1000 and 1950 hours. During this phase, the decrease of the ISP is not correlated to the increase of the thrust. This was due to a drift of the flowmeter which led to an artificial higher flow rate value. The flowmeter was changed after 1950 hours of firing and the value of the ISP was then correct. The stabilized value of the ISP after 3500 hours is 1650 seconds. The shift before and after 4200 hours is probably due to the calibration of the flowmeter for which a step lower than the measurement uncertainty is observed.

**Power**

During all the lifetime, the global power was constant and fixed to 1500W except for the local accident at 4200 hours, but the corresponding decrease of power (14W) can be considered as negligible. This thruster is also able to other power input as demonstrated on the Smart-1 satellite where 1200 W were used to deliver 67 to 70 mN. In Ref. 1, the thruster show also its ability to work from 600 W to more than 3000 W but no lifetime demonstration exist.

**Propulsion performance**

The evolution of the propulsion performance during life test is presented in the figure 4. The results are presented by considering 4 lifetime periods:

- The first one corresponds to the start of the lifetime until 1950 hours. The great dispersions in terms of thrust and flowrate are correlated both to outgassing period during the first 200 hours of firing and to the drift of the flowmeter between 1000 and 1950 hours.
- The second one starts at 1950 hours and ends at 2900 hours. At this stage, the thruster was submitted to a specific campaign of cold firings. The thrust fluctuations between 1950 to 2500 hours leads to the observed dispersions.
The third one starts at 2900 hours and ends at 4200 hours corresponding to the set-up modification. The increase and the stabilization of the thrust is clearly visible, final dispersions are due to measurements uncertainties.

The fourth one correspond to the lifetime period with PPU. Two families of points are visible and correspond to the 2 values of discharge current encountered during this phase (4.24 Amps and 4.28 Amps). The low dispersions on both families confirm the stabilisation of the performances. One can observe the difference on the flow rate between this phase and the end of lifetime tests in test bench configuration. It must be noticed that this difference is lower than the flow rate measurement uncertainty (typical 0.18 mg/s) and also lower than the difference induced by the adjustment of the PPU discharge current which correspond to the LSB on current value of power supply circuit as mentioned above.

For the whole lifetime, the performances of the thruster are compliant to the specifications, thrust above 83 mN and specific impulse above 1570 s. More than 147 kg of Xenon fed the thruster at this date.

B. Thruster performances: \( \text{Idosc}, \text{Ucrp} \) and efficiency

\( \text{Idosc} \):
This parameter is relative to the amplitude of the Alternative Component created by the hall thruster when operating. This AC value is measured through a transformer located under vacuum. The primary is constituted by the anode current and the peak value of the voltage measured at secondary is called \( \text{Idosc} \). The transformer bandwidth is limited to [1:100] kHz band. Peak values are calibrated in RMS value by using as reference a oscilloscope and a transformer of higher bandwidth. Oscillation measured in stabilized mode (\( \text{Idosc} \) at end of firing) could be correlated with thruster age. The evolution of \( \text{Idosc} \) is very similar to the one observed in SPT100 life test. First phase of very rapid increase occurs during less than 100 hour. The maximum value is reached near 1000 hours. A slow decrease is observed until 2500 hours. Since 2500 hours the value is quite constant near 1 A rms. The step near 4200 hours is a calibration issue between different transformers used. If we except some outgassing effects related to test bench opening, the measured value appear stabilized and constant since 2500 hours.

\( \text{Ucrp} \) evolution:
Hall Thruster are powered with a floating power supply that ensure full galvanic insulation. In one metallic vacuum chamber as the power supply is not ground referenced, the floating voltage is
fixed by hollow cathode operation. The voltage measured between Cathode Reference Point and earth (ground of the test facility) is called U_{crp}. Its value is mainly dependant of the cathode operation and has a mean value around −13 V dc for cathode A. Little changes due to thermal influence and cathode age are observable in this mean value. Cathode B, that has only a small number of hours of operation, exhibit a voltage near −15 V. A ripple of some volts is superposed on this DC value. Amplitude of this ripple is mainly dependant of Idosc amplitude. The quite constant DC value is different from flight experiences results. For spacecraft SMART1, the DC value of U_{crp} show several volts of variation. A simple explanation is that the coupling of one potential through plasma is totally different between the spacecraft environment and the test bench one. For U_{crp} it is clear that we must handle with care measurements obtained in vacuum chamber.

**Efficiency**

The evolution of the thruster efficiency during life test is presented in the figure 6. This efficiency is defined as follows:

\[ \eta = \frac{F^2}{2mUdld} \]

This evolution is similar to the ISP evolution. Especially, the efficiency is underestimated between 1000 and 1950 hours due to the above-mentioned drift of the flowmeter which leads to a higher flow rate value.

The thruster efficiency is stabilized at 50% after 3000 hours of firing.

### Table 3. Ion energy versus time

<table>
<thead>
<tr>
<th>Firing time (hours)</th>
<th>Mean ion energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>119</td>
<td>278</td>
</tr>
<tr>
<td>2317</td>
<td>270</td>
</tr>
<tr>
<td>2822</td>
<td>270</td>
</tr>
<tr>
<td>4227</td>
<td>267</td>
</tr>
</tbody>
</table>

**C. EMC behavior / Ion distribution / Magnetic profile**

**EMC Behavior**

The fact that thruster start-up transients create peaks of several hundred of Amps\(^{33}\), and long wires present in test facility and satellite, explain that we paid a special attention to the level of electromagnetic emissions. Conducted emissions between power supply and thruster are measured for all currents and voltages every 2000 hours. Two noticeable points are:

- amplitudes are strongly dependant of the amplitude of the oscillations, (parameter \(\text{Idosc}\)).
- inside cathode, voltage between electrodes, is much lower for cathode A (quasi continuously used) than for cathode B.

Life test has confirmed the efficiency and stability of filters inserted between the power supply and the thruster. Even with 1 Amps of oscillations, conducted emission...
send to power supply are reduced to some tens of mA.

Ion distribution

The evolution of the divergence angle of the ion beam during life test is presented in the figure 7. This angle corresponds to the half cone angle containing 90% of the whole ion current. Between about 600 and 3200 hours, the angle softly spreads from 40 to 43.3° and then comes back to 38 - 40° until 5000 hours. Table 3 present the evolution of the ion mean energy, which remains quasi-constant on the whole lifetime.

Magnetic profile

We perform two magnetic profile verifications. The first one was at beginning of life during the acceptance tests and the second one at 4200h, during the PPU integration period. We do not experiment any evolution of the two profiles.

V. Specific behaviors

A. Transient variation of thrust

During the lifetime, the first minutes of thruster firing show evolutions that were not foreseen. The flow rate decreased without clear explanation after some minutes of firing only when the thruster was starting in cold conditions. It comes back to the nominal date after some more minutes. This occurs after the first 1000h of firing and cycling. The foreseen corrective action during lifetime has been activated : after added an extra magnet current (by TC as already foreseen in the Stentor type PPU) the magnet field in the thruster during cold start change and the starting period becomes for all the parameters as quiet and flat as during the beginning of operation. We never experienced thruster stop or flame out during the whole life test, even during oscillation starting period.

B. Erosion rate

The erosion of the ceramic walls of the thruster has been determined by measuring the remaining thickness of both internal and external walls of the chamber. The measurement is very accurate until 1200 hours. After this duration, the erosion presents non-regular shape with wavelets which reduces the accuracy as the determination is based on mean values between top and bottom.

The evolution of the erosion during life test is presented in the figure 9. Several curves are presented corresponding to 4 models of PPS 1350. The erosion for the 4 thrusters is very similar which confirms a good reproducibility of the behavior of the PPS 1350 during lifetime.

The figure 10 presents the thruster after 7000 hours of firing. The absence of significant erosion on both cathodes must be noticed. Their disposition, which has been optimized during the thruster design, is a major contributor to this low erosion.
VI. End of qualification

A. Measure Electromagnetic Emissions
The objective is to measure radiated emissions of thruster. Electromagnetic emission measurements requires to place antennas in a facility designed for vacuum environment with a thruster firing. In tests already performed antennas are shielded from plasma with a Kapton tent or thruster is fired in a specific fiber-glass chamber. Of course other elements of the set-up like PPU, FU, harness have to be as much as possible representative from flight ones, at least from EMC point of view.

Before emission measurements the thruster has to be outgassed. For the thruster the influence of outgassing still present in conducted emissions level after several hours of firing is also a lesson learned.

As thruster's geometry and power level are very similar between SPT100 and PPS®1350, we didn’t expect major difference in term of emissions from previous results obtained with SPT100.

B. 7500h to 11400h
This part of the qualification test is dedicated to evaluate the robustness of the thruster and to show the ability to deliver \(3.5 \times 10^6\) N.s that allow the use of this thruster for heavy satellites. A set of cold tests will be done and the end of lifetime (after 9600h) will be done through quasi continuous thrust.

Up to now, the first failure time is unknown but two area are particularly observed: the chamber and the cathode. We expect to see the first smooth decrease of performances, either by beginning of degradation of the polar pieces after enough chamber erosions, either by cathode degradation through leakage or emissive part erosion. When will this occurs? Will we discover other type of degradation?

VII. Conclusion

The main performance of the PPS®1350-G thruster is now demonstrated along the needed life duration for NSSK of commercial satellites. The good behavior observed make it eligible for missions of high \(\Delta V\) and high impulse. The use of one thruster on the Smart-1 probe show that low mass, high \(\Delta V\) and affordable missions can be achieved.

TRL level of the PPS®1350-G thruster is between 8 and 9. The 9-level is achieved for missions such as Smart-1 (5000h, 845 cycles, 67mN) and the 8-level is achieved for commercial application of less than 5000h operation per thruster. There is still to formally finish the EMC/EMI tests and to have a thruster in operational conditions on a commercial satellite to complete the 9-level. This is one of the aim of the Alphabus-v1 program currently under discussions.

We now intend to extend the life duration to a total impulse of \(3.5 \times 10^6\) N.s and to demonstrate the capability of such type of thruster to fire simultaneously in group of up to 8 thrusters step by step. This will allow to fulfill commercial and scientific missions with satellites using only electric propulsion.

Acknowledgement

This work was supported by CNES, ESA/ESTEC, and SNECMA that we particularly thanks. We also thanks ALCATEL for its expertise in specifying the satellite needs, OKB Fakel for the design and tests expertise of hall effect thrusters, ALCATEL-ETCA for their support in the field of power processing units and all the teams of Sncema Villaroche Nord site that allow the concept, design, manufacturing and tests of the thrusters and subsystems around during this last 10 years. This work wouldn’t be possible without the Russian and French scientific community support all along the development phases. We also want to thanks them for their help to implement the knowledge of Hall Effect Thruster.
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