PPS®1350-G Qualification status 10500 h

IEPC-2007-164

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

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Abstract: The PPS®1350-G Hall Effect Thruster continued its qualification process to achieve 10500h and 7300 cycles. This paper summarize the obtained results and main observations for this rare end of life thruster. After a quick overlook of the 2002-2007 steps, it presents all along the lifetime the following parameters with their evolutions : thrust, flow rate, specific impulse, discharge current, discharge current oscillations, efficiency, erosion pattern, cathode parameters. The first end of life expertise will also be discussed. The success of this lifetime qualification at 3.3 10^6 N.s opens new spacecraft propulsion opportunities for high ΔV missions.

Nomenclature

ΔV	=	speed increment, m/s
η	=	efficiency
F	=	thrust level, N
g_0	=	specific gravity at sea level, 9.81 m/s²
Id	=	discharge current, A
Isp	=	specific impulse, s
$\dot{m}$	=	flow rate, kg/s
Ud	=	discharge voltage, V

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I. Introduction

THE PPS®1350-G is a Hall Effect Thruster mainly designed for North-South Station Keeping of geostationary spacecraft. After several years of prototype testing and optimization[1,8], the qualification program of the PPS®1350-G thruster started in 2001 and included several thrusters with emphasis on one of them which followed a complete environmental and lifetime test. With an average thrust between 89 10^{-3} N and 90 10^{-3} N, and an average specific impulse above 1650 s, the thruster demonstrated a total impulse of 3.39 10^{6} N.s under various and extreme environmental conditions. On the same cathode, the thruster demonstrate also a capability of more than 7200 cycles. We will detail the qualification phases and show the performances obtained. Designed mainly for geostationary mission, the thruster demonstrates flexible capability confirmed both by the Smart-1 ESA successful experience and by ground research tests.

II. Qualification model campaign

The PPS®1350-G thruster is issued from a Snecma/Fakel technology program[1,3] of the end of last century. Advanced design has been implemented to improve the initial capability of the PPS®1350, which was initially built for the STENTOR program[2] needs. In cooperation with prime contractors such as Thales-Alenia-Space and EADS-Astrium, new objectives have been refined in terms of total impulse and cycles. At nominal functioning point, its main performance parameters are :

Thrust :	89 10^{-3} N
Discharge Voltage :	350 V
Discharge Current :	4.28 A
Specific impulse :	1650 s
Efficiency	50 %
(including hollow cathode flow and coil current)	
Mass :	4.4 kg

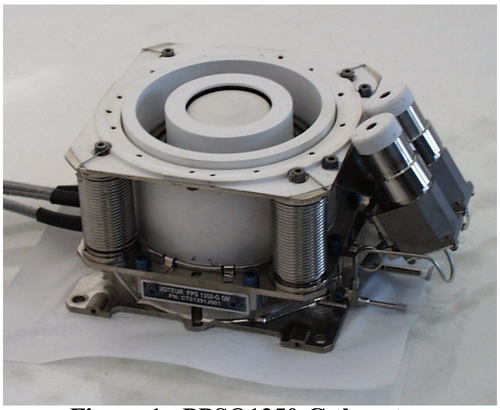

Figure 1. PPS®1350-G thruster.

A. Qualification Model Thruster life

The qualification model followed a classical initial sequence representative to the on ground life before launch with thermal cycling and vibration cycles at qualification level and time.

The different steps of that sequence were performed in 2002 :

- Reference performance under vacuum (with electrical control, and with thrust, discharge power at different functioning points)
- Qualification thermal cycling (-57°C, +200°C), 12 cycles were performed with ignition on the two cathodes at the high and low level of temperature
- Thrust vector control
- Additional firing tests
- Qualification vibrations (up to 38 g sine, 13.5 g_{RMS} random)
- Shocks
- Reference performance under vacuum similar to initial test that confirm no noticeable change in the thruster performance.

The second sequence were dedicated to a lifetime with margin demonstration. The steps were achieved end of the year 2006 (10530h lifetime). The following major events happens :

- life test up to 2900h, the first opening of the vacuum chamber occurs to transfer the thruster into a large thermal range facility. Tests were performed at EDB Fakel facility.
- 50 thermal cold start. Then, the thruster was sent back to Snecma Villaroche plant in the same facility than initial tests.
- life test up to 4200h

- implementation of a Filter Unit and a Power Processing Unit flight representative from Thales-Alenia-Space. As the filter unit (electrical element in-between thruster and the power processing unit, dedicated to oscillation attenuation) was inside the vacuum chamber, the thruster see a third time the atmosphere for a short period.

- life test up to 7964h, up to now, the sequence was the same with a macro sequence as follow : 99 firing during 0h45, 22 firing during 2h30 and 11 firing during 4h15. These macro sequences were separated by one firing on the each cathode to avoid on the redundant cathode the negative effect of test bench back sputtering. The next sequence was done to cumulate the cycles at higher rate, with macro sequences as follow : 195 short cycles, 6 medium cycles and 3 long cycles.

- life test up to 8500h, the thruster was then transferred to a large thermal range vacuum chamber just beside the life test chamber in Snecma Villaroche plant. We limited the atmospheric contact with that old thruster down to less than 4h.

- 50 Thermal cold start test, then again, the thruster was quickly transferred to the life test vacuum chamber.

- life test up to 9200h. The life test initial goals were obtained, and seeing the performance of the thruster, it was decided to continue on long firing sequence to simulate either end of life orbit extraction of the satellite, either orbit topping at the beginning of life of the satellite. Usually, such a mission happens during the beginning of thruster life, but the potential need was identified late in the qualification program by our customers. The sequence optimization lead to cumulate the long firing at the end of the life test.

- long firing cycle tests up to 10530h, these firing were respectively with duration of 264 h, 34 h, 190 h, 287 h, 368 h, 95 h, 95 h. The different stops occurs because of tests bench needs (Xenon bottle change, cold plate regenerations, electrical maintenance, vacuum pump maintenance).

To achieve the lifetime in a reasonable timeframe, most of the off thrust time between two on thrust sequences were limited to 20 mn during life test period.

The first sequence of 7964h of firing cumulated 2.38 10^6 Ns total impulse, the second sequence with 1236 h firing (0.397 10^6 Ns impulse), and the third sequence allow to achieve 3.39 10^6 Ns impulse.

B. Thrust and total impulse performance

All along the life test, thrust has been measured at end of each firing cycle. This was needed because of the measurement method which was used : the thrust balance is sensitive to thermal effect and the continuous measurement show that data changed all along the firing with no relation to real thrust, specially for short firing time. A calibration is done after each firing cycle with a non thermal sensitive method : the use of metallic mass immediately after end of firing. The data obtained are consistent with theory and largely above initial specifications at 83 10^{-3} N. An average thrust of 89.4 10^{-3} N is observed. It is preferable for spacecraft system calculation to include uncertainties for absolute data at a level of +/-2.5 10^{-3} N for the thrust balance. At the beginning of the life test, a short duration with low thrust (down to 86 10^{-3} N) is observed and is correlated with end of out-gassing of the thruster on short duration firing. The different low thrust observed are linked to test bench long stops. At the end of the life test, as there is only one calibration per firing, we have only a few point because of the sequence of long firing but, looking to the continuous measurement, after a period of around 3h (thermal stabilisation of thrust balance), there is no change in the observed data. Between 8500h and 9000h, measurement noise increased because of a thrust balance failure that was repaired at 9000h. The general behavior of the thrust (slight decrease, then slow growing) has been observed already on different models. During the life test, the thrust was usually stable and constant for each firing.

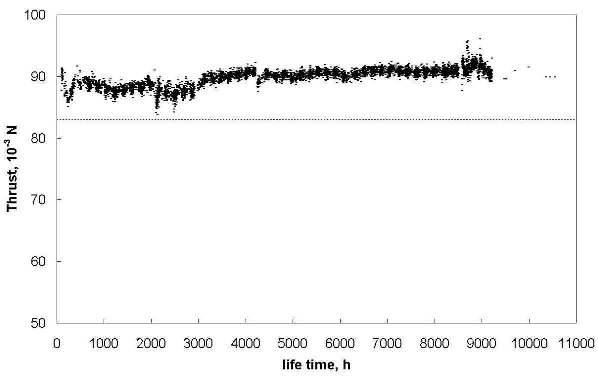

Figure 3. PPS®1350-G thrust

The total impulse seen by the thruster has been calculated with the average measure. It is evaluated to 3.39 10^6 Ns. The total number of cycles was 7309 cycles. The lifetime was done with the main cathode until full coverage of the 7200 cycle specification at 9200h. Then the test continued on the redundant cathode until the end of the life test. A final verification firing on each cathode was performed.

C. Specific impulse, flow rate

All along the lifetime, the flow rate was measured with high accuracy. The thruster shows a small increase of flow rate during the first 2000h and then a stabilization occurs with a slow decrease at the end of life. The use of the second cathode one time every 180h does not show fundamental differences in flow rate and thruster performance.

On figure 4, The top curve is a measure of flow rate through accurate flow meter. The lower curve is a combination of inlet pressure and Smart-1 model of Xenon Flow Controller. Between 1300h and 1900h of firing, the flow rate measurement started drifting. A repair occurs but the data was kept as is on figure 4.

Specific impulse specification was to be above 1570s at any time. Observed average is above 1650s and the level increases at the end of life up to around 1700s both because of thrust slight increase and flow rate slight decrease.

$$Isp = \frac{F}{\left(\dot{m}_{anode} + \dot{m}_{cathode}\right) \cdot g_0}$$

Both anode and cathode flow rate gives the thruster specific impulse.

Between 1300h and 1900h, the impact of the flow meter drift conduct to a slight under estimation of the specific impulse real value. Between 8500h and 9000h, the impact of the thrust balance data uncertainties creates a greater specific impulse uncertainties. We can see that before and after that period, specific impulse is similar : the thruster didn't change its performance in between.

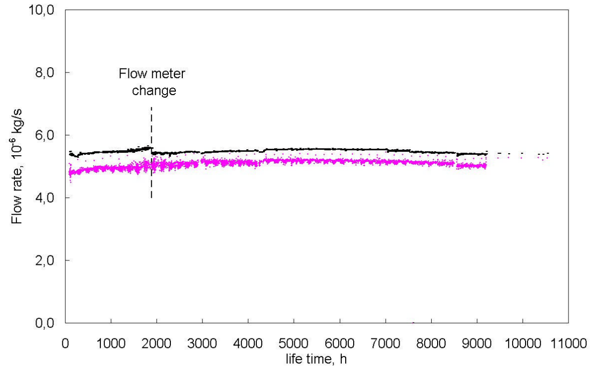

Figure 4. PPS®1350-G flow rate.

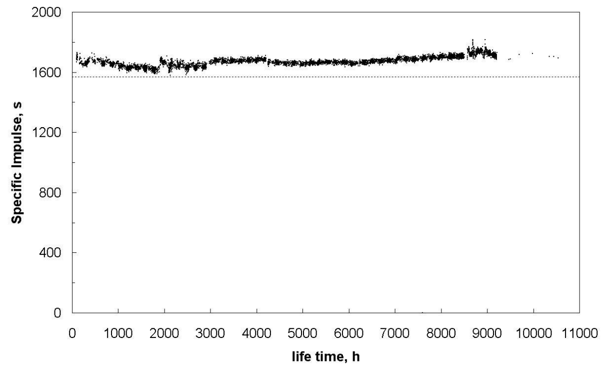

Figure 5. PPS®1350-G specific impulse.

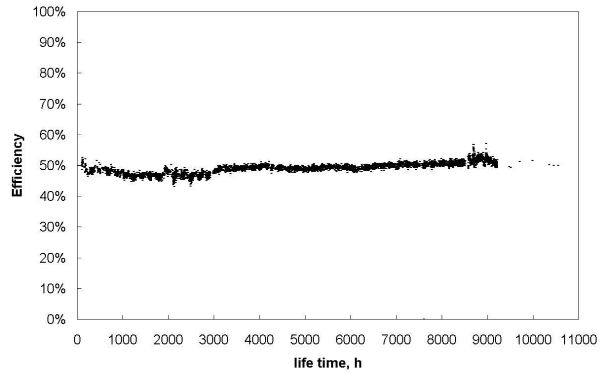

Figure 6. PPS®1350-G efficiency.

D. Efficiency, current oscillation

Efficiency includes the anode and cathode flow rate as well as power dissipation in the magnet. It shows a level consistent with theory at around 50% all along the life. The minimum observed of 46% was during the flow meter drift and during re-start after very long stop of the thruster (several days) probably due to test bench conditions.

$$\eta = \frac{F^2}{2 \cdot \left(\dot{m}_{anode} + \dot{m}_{cathode}\right) \cdot Id \cdot Ud}$$

End of life efficiency was above 50%. the small decrease at beginning of life is a combination of real electrical efficiency decrease during high erosion rate and mass flow rate over estimation due to measurement drift.

Current oscillations is a parameter that was measured in the last electronic loop which includes the discharge and the capacitor of the filter. It is an inductive measure with a bandwidth up to 1 MHz. The measurements were done in two different areas before and after 4200h firing because of a new flight standard filter unit implementation. We verified by oscilloscope that the real data on the last electrical loop were identical before and after implementation of the FU. A similar profile of the current oscillation has been observed for each HET tested for a long period in that power range. This is probably linked to the initial high speed erosion of the outlet of the ceramic chamber.

E. Cathode parameters

During the lifetime, the cathode delivers the electrons and a good evaluation of the behavior of the cathode efficiency is to look at the cathode reference potential. All along the life, reference potential stand in the range –12V to –18V with a usual value between –14V and –16V, until the end of the test.

On figure 8, we can see the redundant cathode firing each 180h below the average of the main cathode firing. This show a slightly more inefficient electron extraction that can be correlated with the Xenon Flow Controller which is from a different definition, dispatching a different amount of Xenon through the cathode.

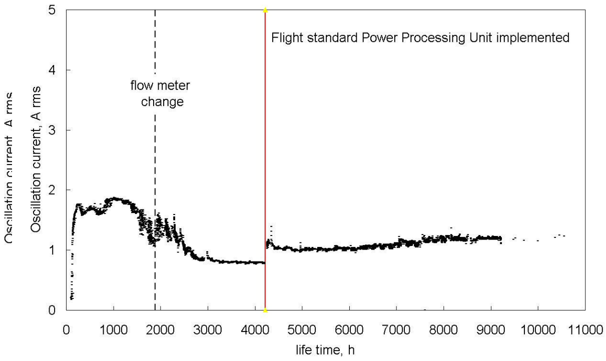

Figure 7. PPS®1350-G Oscillation current.

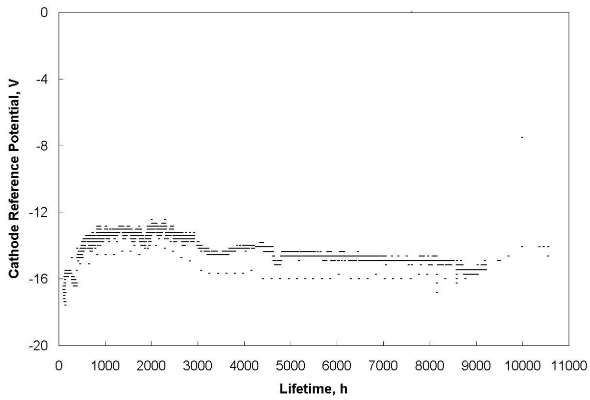

Figure 8. PPS®1350-G Cathode reference potential

F. Thermal behavior

During life test, two sets of 50 firing in cold conditions were performed. The thruster was left in a liquid nitrogen cooled box and supported by a plate regulated at temperature down to –45°C. The engine was then switch on for half an hour after opening of the front door of the box.

Cold operations demonstrated a good behavior of the performances of the thruster and show a starting transient period with a smaller electrical efficiency. It has been demonstrated that a slight tuning of the magnet level (as foreseen in the thruster command) makes the performance return to nominal behavior. As soon as thermal stability of the thruster is achieved, a full return to the nominal point is done with nominal performances of the thruster.

On hot conditions, the thruster demonstrates its capability to start and run at 200°C at the plate interface.

G. Erosion

During lifetime, erosion rate started with a low rate at nearly 6 10^{-6} m/h. Then we confirm that the erosion rate decreases down to around 0.1 10^{-6} m/h for a thruster of 5500h age, a value even below initial extrapolation that confirm that the ionization and the acceleration of ions are done mainly in the central beam and that secondary ions or atoms with energy high enough to erode are in very low amount above 45° angle direction. This is coherent with observation of ion energy profile measured. Cathodes are particularly well preserved, see figure 9.

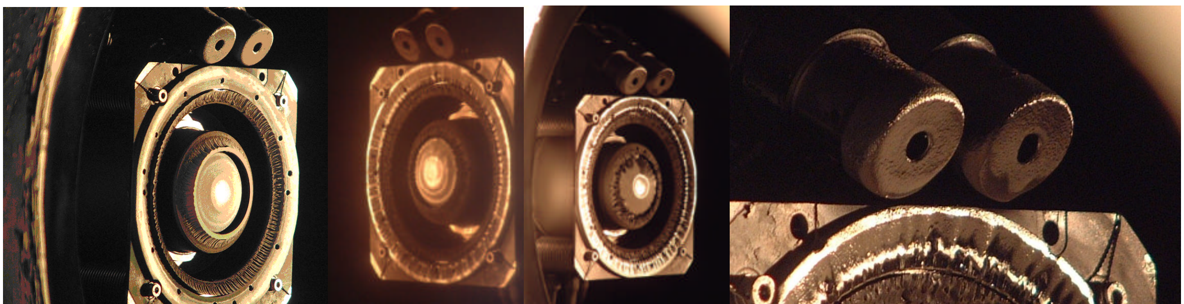

Figure 9. PPS®1350-G erosion pictures.

Thruster age respectively : 2000h firing,6000h firing, 10530h firing, zoom on cathodes at 10530h

H. Ion distribution, thrust direction

Ion energy distribution was measured every 2000h and shows no evolution throughout the lifetime. Thrust direction stayed within the specified 1 degree cone from initial vector as shown in figure 10. For latitude position, the step observed at 4200h is linked to the balance refurbishment, in fact the maximum latitude evolution is below the measured value of almost 1 degree.

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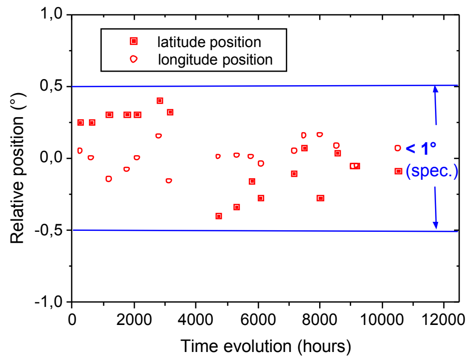

Figure 10. PPS®1350-G thrust direction evolution.

I. Performance summary

The performance of the thruster at beginning of life, 1000h, 2000h, 4000h, 6000h, 8000h, and 10000h are compliant with the expected behavior and the theory. Data at 10000h firing show a hot thruster performance (data of the 368h long firing, 28h after start).

Performance	Initial	1000h	2000h	4000h	6000h	8000h	10000h(*)
Discharge voltage	351 V	352 V	353 V	353 V	350 V	350 V	350 V
Discharge current	4.28 A	4.27 A	4.29 A	4.28 A	4.29 A	4.28 A	4.29 A
Total xenon flow rate	5.32 mg/s	5.45 mg/s	5.44 mg/s	5.48 mg/s	5.54 mg/s	5.46 mg/s	5.41 mg/s
Thrust	89,1 10^{-3} N	88 10^{-3} N	91 10^{-3} N	91.1 10^{-3} N	90.4 10^{-3} N	90.6 10^{-3} N	91.5 10^{-3} N
Specific Impulse	1706 s	1647 s	1707 s	1693 s	1662 s	1693 s	1725 s
Efficiency	49.6 %	47.2 %	50.4 %	50.1 %	49.1 %	50.2 %	51.5 %

Table 1. PPS®1350-G thruster typical performance.
(*) data taken during long firing sequence

J. Test with polluted Xenon

The Alphabus requirement specifies the quality level of the xenon. To demonstrate the ability of the thruster to operate along the life with such quality (the cathode is the most sensitive part affected by the pollution, oxygen is the main pollutant), xenon for life test should have been of a worse or equal quality. In reality, the xenon quality was better. Consequently, to demonstrate compliance with the requirement, one of the last xenon bottle was voluntarily polluted and the life test was performed with that bottle with the objective to obtain on average a level of pollution equal to the specification. Since 8654h, 542 hours have been performed with polluted xenon. The table 2

	Requirement in ppm Xenon N45 (99.995% pure Xe)	Demonstrated (in ppm)	
		At 9196 h	Reduced to 5500 h
H2O	< 3 ppm	2.54	4,25
O2	< 3 ppm	2.21	3,70
N2	< 10 ppm	7.21	12,06
H2	< 2 ppm	1.34	2,24
Kr	< 30 ppm	19.88	33,24
CO2 + CO	< 2 ppm	1.43	2,39
CH4 + CnHm	< 1 ppm	0.68	1,14
CF4 (R14)	< 1 ppm	0.67	1,12

Table 2. Xenon PPS®1350-G.
N45 class Xenon is obtained when 5500h is considered (in flight real use of the thruster).

summarizes xenon pollution level that has been demonstrated with K1 cathode. We are close to the specified level but a little below for the 9200h firing. As far as the use in flight will be around 5500h firing, there is in fact some positive margin, see Table 2.

K. Transient start

During the life time, a transient start phenomenon occurs after 2000h firing for cold start. We observed that during the thermal transient start period, the thruster had performance similar in specific impulse but needed more power. With a control loop based on current discharge, it results in a temporary decrease of thrust. We demonstrated that this decrease is limited and the thrust is never below 70% of the nominal thrust. This decrease is also limited in time to short duration (less than 10 mn). This phenomenon is linked in time within thermal transient start (typically 15 mn) we observed with a thermal camera that the ceramics temperature grows faster to reach the thermal equilibrium when the phenomenon occurs. We also demonstrated that a simple tuning of the magnet level during the first 15mn firing makes this phenomenon disappeared. Other demonstrated way to suppress the phenomenon is to decrease the voltage level during the transient start. It is important to note that such a phenomenon was not observed in flight for Smart-1.

L. End of Life expertise

After first control of the thruster, we identify a loss of insulation of the magnet wire to the electrical ground. Observations shows that this is due to a plasma penetration close to the center coil of the thruster that create an erosion of the last wire coil. This happens very late in the thruster life and in fact didn't affect the thruster performance in terms of thrust and efficiency. This is due to the floating concept of the electrical supply. We are now close to the end of life of this design and the destructive expertise is planned.

III. Conclusion

The PPS®1350-G demonstration is now completed for NSSK missions. It shows a constant performance throughout life time always in accordance with theory. This is the first HET above 10000h firing that follows a complete qualification process with extreme mechanical and thermal environment and with a complete life on ground simulation. The very good behavior of this thruster allow to use that thruster for needs up to 3.39 10^6 N.s impulse, at 89.4 +/-2.5 10^{-3} N average with 1500W inlet power.

Acknowledgments

This work has been supported by ESA/ESTEC and CNES with SNECMA participation. Qualification team thanks all the research and technology teams from Russia and France that help understanding of this thruster.

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