

Development Status of the PPS[®]5000 Hall Thruster Unit

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Abstract: The 5-kW PPS[®]5000 Hall thruster is currently under qualification at Safran. The thruster development logic was adapted to meet the severe time-to-market constraints placed on the program. This challenged the current long-development times typical of Electric Propulsion and demanded elaborate risk management. The approach relied on the extensive heritage gained from existing product lines, as well as on partial overlapping of standard development logics backed by parallel iterations between hardware model testing and analyses. This paper reviews the PPS[®]5000 pre-development background and the main development activities. An overview of the PPS[®]5000 design is presented, and the paper concludes with a description of the on-going qualification program and status.

Nomenclature

ARTES	=	Advanced Research in Telecommunications Systems
EP	=	Electric Propulsion
I_{tt}	=	Thermosthrottle current, A
PPU	=	Power Processing Unit
SK	=	Station Keeping
XFC	=	Xenon Flow Controller
ΔV	=	Velocity increment, m/s

I. Introduction

ELECTRIC propulsion (EP) devices have been under research and development at Safran since the late 1960's.¹ In the late 1990's, the Safran activities started concentrating on Hall thruster technology. The steady effort maintained since has resulted in three successful thruster qualification programs to date (PPS[®]1350; SPT-100; and PPS[®]1350-G) and another two currently on-going (PPS[®]1350-E and PPS[®]5000). This also resulted in the delivery of EP hardware or subsystems totaling 73 flight thrusters to date, with production ongoing. At the time of writing, EP

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thrusters or subsystems provided by Safran have already been integrated on a total of 14 different spacecraft: 13 communications satellites, and ESA's *Smart-1* lunar probe. A significant production ramp-up must be achieved in 2018, and this is illustrated by the upcoming inauguration of a new facility building in the Safran Vernon operations, Normandy, France, at the end of 2017. The current Hall thruster product line includes four thrusters, at different stages of maturity: first, the flight-proven PPS®1350 and its three subsequent versions (–G, –S and –E). Next, at both ends of the power and thrust spectrum, two thrusters are at an early stage of development or at Technology Demonstrator stage, respectively: one for low power applications (200-700 W), and the other for high power applications (20 kW). Finally, the PPS®5000 is a 5-kW-class Hall thruster currently under qualification, with firm orders for the production of flight models.² This range of thruster applications is illustrated in Figure 1. This paper describes the current development and qualification status of the PPS®5000 program. Section II will cover the predevelopment background for the thruster system, and Section III will present the development logic. A general overview of the flight design will be presented in Section IV. Finally, Section V presents the qualification program and qualification status for the PPS®5000 thruster unit.

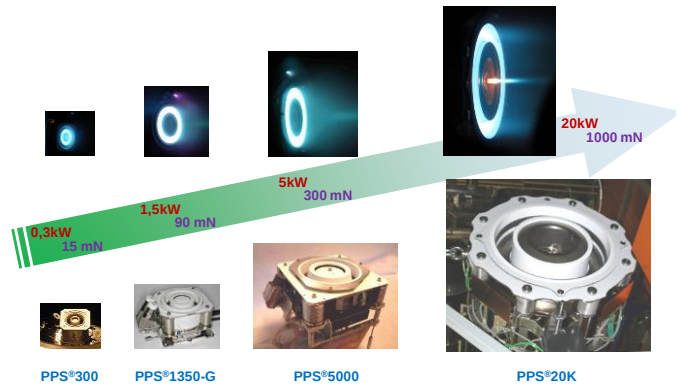


Figure 1. Safran Hall-effect thruster family.

II. Predevelopment Background

The PPS®5000 design was initiated by a three-year predevelopment activity started in 2000, with the objective of reducing manufacturing costs and increasing robustness with respect to varying mission constraints. In fact, it was recognized that the then-likely penetration of EP on the commercial market, in conjunction with the emergence of a broadening offer for launch services, would lead the market toward “all-electric” spacecraft where most, or essentially all, propulsive maneuvers would be assigned to the EP system. In fact, because the orbit-raising ΔV represents more than 2/3 of the total mission ΔV , this mission phase is a strong driver of the performance requirements specification for the EP system.

The introduction of electric propulsion for orbit raising of geostationary satellites, on top of the conventional SK mission, therefore has three main technical consequences when compared to previous-generation EP systems devoted to North-South SK operations:

- 1) An increase of the power available to the EP system, because the payload is not yet in service during orbit raising;
- 2) An increase of the total impulse capability required from the EP system; and
- 3) A large variability of operating points and throttling profiles required from the thrusters.

On top of the above main technical consequences but key to any new developments, cost-effectiveness is a mandatory feature dictated by the increased competition generated by this new market.

The pre-development of the 5-kW-class PPS®5000 Hall (stationary plasma) thruster was a response to this shifting need in terms of electric propulsion capability. The key objectives of the PPS®5000 development were therefore three-fold:

- Meet the evolving technical requirements of the Customers;
- Achieve a cost-competitive solution;
- Meet the stringent time-to-market constraints imposed by the stakeholders.

The PPS®5000 design was optimized with specific patented features³ to handle large thermal loads, and as such presents significant differences with respect to previous-generation HET designs. The early feasibility assessments of a 5-kW-class plasma thruster therefore led first to the design, manufacture and testing of a 1:1-scale Technology Demonstrator model, the PPS®X000. This model was tested over a wide range of conditions and served as a technology testbed to trade different magnetic configurations and mature the key technologies and thermal architecture anticipated for the flight design.⁴⁻⁸

A first iteration of the PPS®5000 flight design was proposed for the *Alphabus* (extended range) pre-development activities under an ESA ARTES-8 contract. After the PDR milestone in 2004, however, the PPS®5000 development was placed on hold in large part because of the combination of two trends: first, a revision of the near-term *Alphabus*

propulsive needs to lower total impulse requirements; and second, the extension of the PPS®1350-G life qualification test, such that the PPS®1350-G became capable of meeting the near- to mid-term need of the *Alphabus* program. Indeed, the first spacecraft based on the *Alphabus* platform, known as *Alphasat* or *Inmarsat XL*, was launched in July 2013 with a flight-set of four PPS®1350-G thrusters.⁹

Yet, CNES and ESA Research & Technology Programs helped support both a second round of design optimization in 2006, and further testing of PPS®X000 configurations between 2006 and 2014.^{10,11}

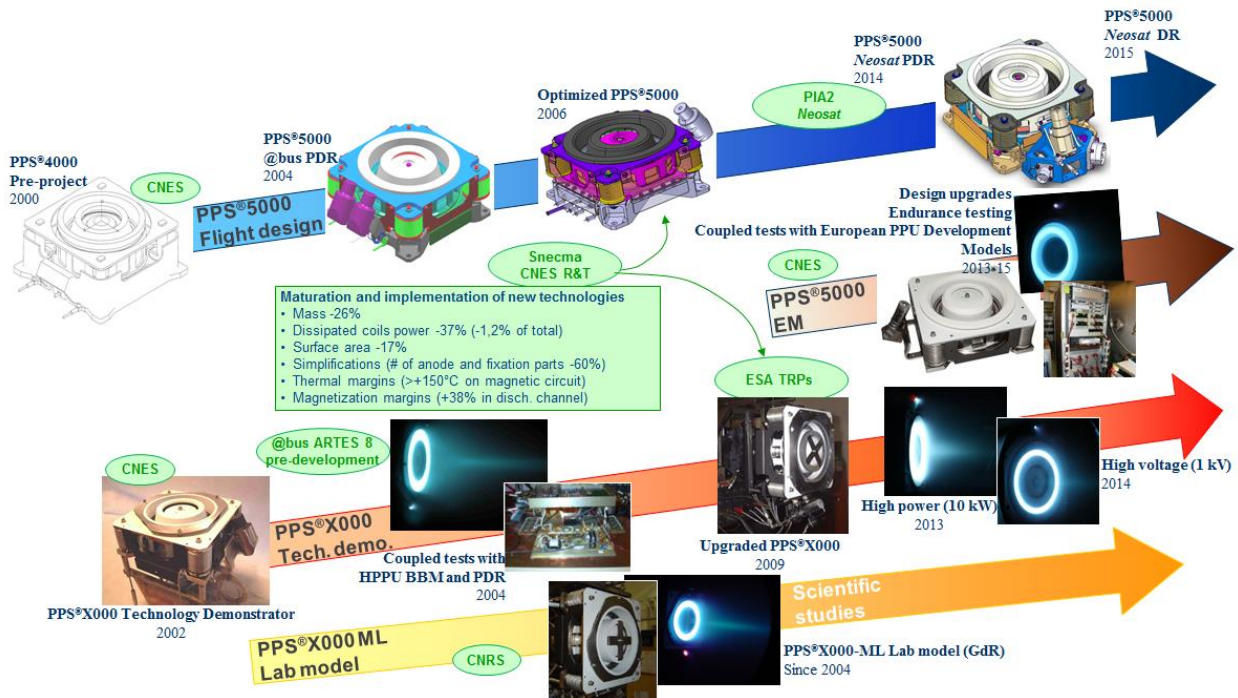


Figure 2. PPS®5000 pre-development background.

The low-level activity during the dormant phase of more than 8 years between the PDR for *Alphabus* in 2004 and the development kickoff in 2013 still achieved important results. It led to improving the magnetic design features; to further assessing the design margins; and to exploring the domain of stable thruster operation under varying conditions. What is meant by “stable thruster operation” is that the performance and discharge modes remain stable in time, e.g., they do not require tuning of control parameters, such as magnet current setting, with time as the discharge channel profile evolves due to erosion, or back-sputtered deposits accumulate in the discharge channel. An overview chart of the pre-development history is provided in Figure 2.

To illustrate the efforts to aggressively explore the operating domain and assess the design margins, two short-duration (200-hr) wear tests were performed on specific configurations of the PPS®X000 Technology Demonstrator model: one in 2013 at 8 kW and 300 V of discharge power and voltage, respectively; and another in 2014 near 5 kW and 1 kV. As an example, Figure 3 shows the evolution of thrust and specific impulse for the 1-kV test.

Overall, the PPS®X000 Technology Demonstrator has cumulated nearly 2,600

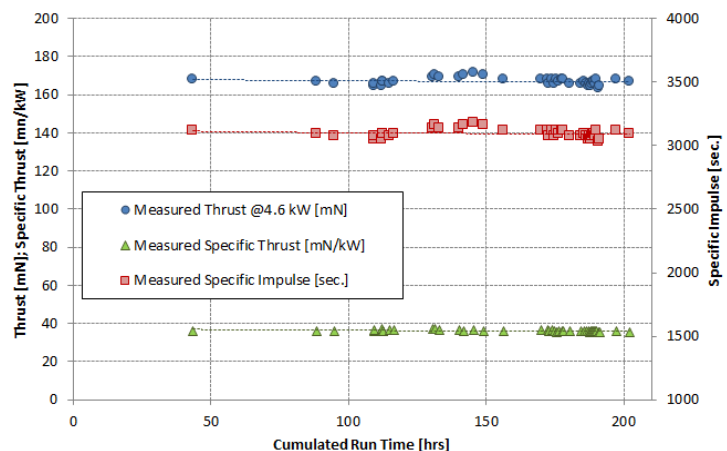


Figure 3. PPS®X000 performance during 200-hr wear test at 5 kW and 1 kV of discharge power and voltage, respectively.

hours of testing. Another, lab-model version was built by CNRS, the French National Center for Scientific Research, to support scientific studies: the PPS®X000-ML.^{13,14}

While not mandatory at this stage of the development, assessing the design margins over such a large range of operating conditions was important in order to identify and understand the main failure modes, and to maintain growth potential for future opportunities on the same design. Indeed, because development times and costs for long-lifetime EP devices are so high, ensuring that a qualified, flight-proven design has growth potential to adapt to future market demands through a relatively faster delta-qualification program is an important aspect. For example, the qualified, flight-proven 1.5-kW PPS®1350-G is currently undergoing a qualification program to operate essentially the same thruster design – the PPS®1350-E – at 2.5 kW with the same total impulse capability of 3.4 MN.s.^{2, 12}

III. Thruster Unit Development

A. Development Logic

The development of the PPS®5000 was approved to resume in January 2013, following the approval of the *Neosat* program¹⁵ under ARTES element 14 at the European ministerial conference of November 2012 in Naples. Because the design had evolved since the *Alphabus* Preliminary Design Review (PDR), as shown in Figure 2, and because of the new set of technical requirements specifications for the new program, a new PDR was to be prepared and held for *Neosat*. By then, the time-to-market constraints had become severe and an aggressive design-to-time approach had to be implemented in the project management. This, however, is in contradiction with the development cycle durations historically associated with EP, so a new approach was needed.

In response to this context therefore, the PPS®5000 development logic features a significant overlap between the standard development Phases B (preliminary design), C (critical design) and D (qualification), as represented in Figure 4. This overlap is illustrated in several ways, and can only rely on an unwavering willingness to take the corresponding industrial risk.

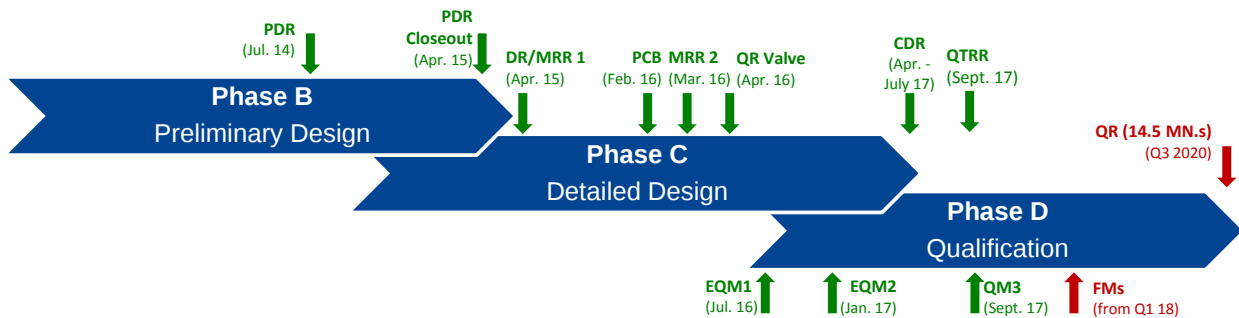


Figure 4. PPS®5000 development logic.

First, the detailed design of the flight unit had to be initiated well before closeout of the Preliminary Design Review (PDR), i.e., well before requirements freeze. This was necessary because in the context of the generic *Neosat* program, requirements freeze itself took about two years, including repeated co-engineering sessions with the stakeholders of the *Neosat* program which included spacecraft prime contractors as well as the agencies CNES and ESA. Safran could not afford to wait for full completion of this process to initiate critical (detailed) design and start the procurement of long lead items. In fact, less than a month after PDR closeout, a first Manufacturing Readiness Review (MRR) associated with an (intermediate) Design Review (DR) was held to authorize manufacture of qualification-standard parts and subassemblies. The Parts Control Board (PCB) and Materials and Processes Control Board (MPCB) were progressively held to accompany the increase in maturity of the manufacturing file.

Second, following completion of the MRR process, manufacturing of the first qualification-standard units to flight design proceeded well before CDR (Critical Design Review) closeout. In fact, the two first qualification hardware units, EQM1 and EQM2 (Engineering Qualification Models) were manufactured well before the CDR was held. Likewise, the primary qualification unit, QM3, came out of production just two months after closure of the CDR and formal design freeze.

Finally, testing of qualification-standard units (EQM1 and EQM2), which would normally occur in Phase D, began well before the CDR and in fact participated in the design justification for the CDR. Flight Model production was also initiated before CDR closeout, and flight hardware deliveries will occur well before completion of the full life test objectives.

Such a challenging development logic, and validation and verification process, can only be accepted and implemented if it is based on intensive, solid configuration management, as well as dedicated risk management.

B. Configuration Management

The PPS®5000 design will be presented in Section IV. The thruster unit comprises a thruster and a Xenon Flow Controller (XFC). The thruster itself comprises an anode subassembly, and a cathode subassembly. The XFC comprises a dual-valve subassembly. The product tree is represented in Figure 5.

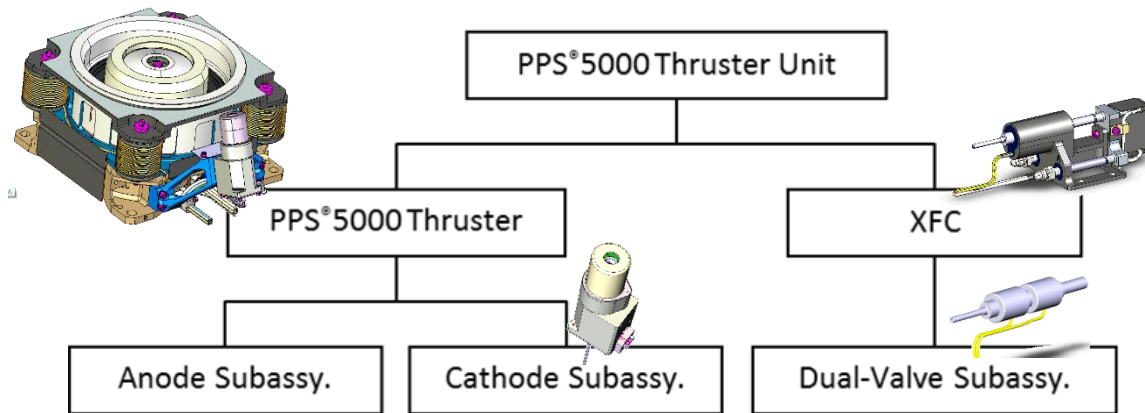


Figure 5. PPS®5000 product tree.

Initiating hardware manufacture for qualification-standard parts with the above logic posed significant challenges. One of them is that configuration management was extremely resource-intensive because hardware parts were launched in production before full design closure. Launching qualification-standard parts in production requires a design reference, which in turn mandates a formal change process whenever an evolution in the design must be introduced as a result of, e.g., the evolving design justification, process development, or refined material property characterization, all of which were progressing in parallel. In other words, strict configuration control had to be applied at an early phase, when agility and design evolutions were still necessary.

C. Risk Management

Risk management was another key aspect subtended by the selected, time-to-market driven development logic. For instance, anticipating parts procurement and qualification hardware manufacture before requirements freeze or detailed design justification meant that parts or complete subassemblies could be lost or rendered non-representative of the final design. Likewise, initiating manufacture of complete flight hardware units even before Qualification Test Readiness Review (QTRR) of the primary (QM3) qualification unit induces a significant industrial risk. Safran was willing to take the associated development risk based on an appropriate risk-mitigation approach.

In part, the significant pre-development background detailed in Section II was a contributor to the development risk mitigation. However, a specific aspect of the risk management relied on a progressive approach to the representativeness of development models: hardware models were manufactured very early on, first with a low fidelity to retire limited risks, e.g., verifying the robustness of a ceramic-to-metal junction. As the flight design progressed, increasingly representative hardware models were manufactured and tested in parallel to corresponding improvement loops in the maturity of the software models and material property characterization, e.g., over a progressively expanded temperature domain. This is illustrated in a simplified way by the PDR-DR-CDR review sequence of Figure 4. Section III D below presents the main hardware models built in support of this development logic.

D. Development Hardware Models

First and over the course of 2013, an Engineering Model for the PPS®5000 was designed, built and tested in order to finalize the design features, and confirm lifetime potential and magnet settings for thruster stability over life and

over the final targeted operating domain. This was necessary in part because most of the PPS®X000 Technology Demonstrator testing had been carried out at high voltage. As part of this development program, the PPS®5000 EM has cumulated 4,145 hours of testing. This included a PPU/thruster coupling test in mid-June 2014,¹⁶ and about 3,500 hours of testing in high-thrust, high power mode, i.e., operating at 300 V and 5 kW of discharge voltage and power, respectively.

In summary then, over 7,000 hours of testing were cumulated on the lab model, Technology Demonstrator model, and Engineering Model for the PPS®5000 design. This was key in correcting the last issues and retiring the main residual risks associated with the functional design before finalizing the PPS®5000 flight design. An overview of this functional test heritage is provided in Figure 6.



PPS®X000		Hours
Preliminary testing		231
Life test @5kW/700V		357
Life test @5kW/550V		1026
Wear tests in extreme modes		811
Additional characterization		139
		2563
PPS®X000-ML		Est. 300
PPS®5000 EM		
Characterizations / coupled test		614
Life testing @5kW/300V		3531
		4145
Total:		7008

Figure 6. PPS®X000 EM, and summary of functional test heritage on PPS®X000 and PPS®5000 EM.

The justification to the mechanical (dynamic and quasi-static) and thermomechanical loads stemming from the technical requirements is another very important aspect of EP development, and a source of very significant development risks. To progressively retire the associated risks, different hardware models with increasing fidelity to the flight design were built. For the thruster for example, a low-fidelity Structural Model (StM) for the anode subassembly, called StM A0, was built and tested in 2014. This model was submitted to mechanical shock as well as thermal (hot) cycles in order to verify the mechanical integration of the central ceramic discharge channel. Once a first detailed flight-design reference was established, within three months of the PDR closeout, a high-fidelity Structural and Thermal Model (STM A1) was then built. It was actually found to be more effective to launch STM A1 in production as per that flight-design reference, than produce a separate, STM-specific design. Deviations were accepted for, e.g., internal surface finishes or minor dimensional discrepancies in order to obtain (and test) the STM A1 sooner than the first qualification-standard unit, EQM1. In fact ultimately, the STM A1 was fitted with the proper fluid and electrical interfaces and with a cathode, and became a fully-functional, highly representative thruster used for facility commissioning or even acceptance-testing of a flight (PFM) thruster module assembly of Safran responsibility in January 2017.

A similar approach was followed for the cathode: Structural Models StMK0, followed by StMK 1 then StM K2, represented increasingly high-fidelity models dedicated to structural verification by testing. Because the XFC is a relatively simpler unit, only a (highly reconfigurable) functional breadboard (or BBM) was used to verify the functional design, before a STM-EM model could be manufactured, again to the flight design reference. This means that again, the XFC STM-EM ended up being a fully-functional, highly representative unit built to the flight design, and was the unique precursor to the qualification unit. An overview of the main hardware models and their main purpose is provided in Table 1 and in Table 2.

Additional (local) hardware models were used for, e.g., cross-correlation of the thermal models or for dedicated mechanical environment testing of component junctions or subassemblies whenever software modelling could not establish sufficient margins to cover the residual uncertainties. Uncertainties could be generated by the limits in modeling, e.g., for brazed junctions, but also from insufficient material property characterization in extreme temperatures at any given time. In such instances, local hardware models were built and tested to establish the necessary confidence in the design.

Table 1. Main hardware models for the PPS®5000 development: anode subassembly and XFC.

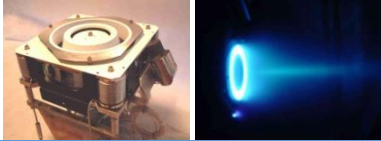
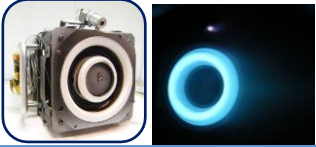
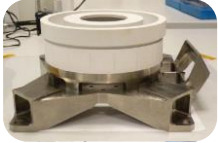
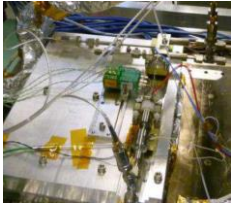
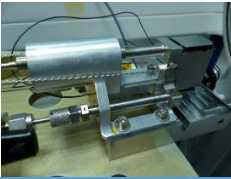
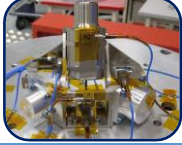
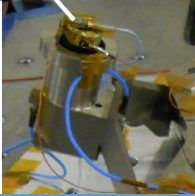
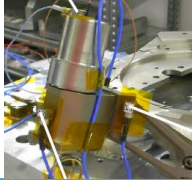
Hardware Model		Purpose
Anode Subassembly		
PPS®X000		• Technology (internal architecture) validation • Exploration of magnetic configurations
PPS®X000-ML		• Scientific studies • Exploration of domain, alternate propellants • Plasma diagnostics
PPS®5000 EM		• Performance characterization • Endurance testing • Plume characterization • Functionally representative
StM A0		• Shock testing • Thermal cycling • Representative of discharge chamber mechanical mount
STM A1		• Shock, thermal cycling, & vibration testing • Designed for instrumentation (thermal & mech.) • Validation of design and assembly procedures • Component-level testing of instrumented inner coil for early cross-checking of thermal model • Cross-checking of thermal & mechanical models • Fully representative of flight design, acceptance firing-test of flight (PFM) thruster module assembly.
Xenon Flow Controller		
BBM		• Exploration of configurations • Performance characterization, including flow restrictors • Validation of functional design, incl. 3D effects • Cross-checking of fluid models • Functionally representative
STM-EM		• Vibration, shock, thermal cycle testing • Cross-checking of mechanical, thermal models • Subsystem testing as needed • High representativeness

Table 2. Main hardware models for the PPS®5000 development: cathodes.

Hardware Model		Purpose
Cathode Subassembly		
STM K0		• Vibration testing • Cross-checking of mechanical model
BBM1	 	• Performance characterization • Endurance testing • Plume characterization • Destructive Physical Analysis • Functionally representative
BBM2		• Performance characterization • Designed for instrumentation • Cross-checking of thermal model • Functionally representative
StM K1		• Vibration testing • Cross-checking of mechanical model • Moderate representativeness
StM K2		• Vibration and shock testing • Cross-checking of mechanical model • Validation of mechanical design • High representativeness

This was especially true for thermomechanical fatigue justification. Indeed, design margins to thermomechanical cycles cannot be established by qualification life testing alone on the anode subassembly because applying all ON/OFF cycles with representative thermal cycle depth and dynamics would take too long and would not necessarily capture all local worst cases. Therefore, the justification by analysis is key, and it was supported by local hardware models whenever necessary. For instance, this was the case for the xenon line junction to the anode. A hardware model was built and cycled to the required 6,255 operational cycles multiplied by the required safety factor of 4 for fatigue analysis, that is, the hardware model was cycled 25,000 times in representative-temperature conditions because analyses alone could not conclude to an acceptable residual risk level.

IV. PPS®5000 Hall Thruster Unit Design

The flight-design PPS®5000 thruster and XFC are depicted in Figure 7. The as-measured mass of the qualification hardware is 11.54 kg for the thruster (QM3) without harness; and 0.335 kg for the XFC (EQM1) including a 2-m harness.

The cathode and XFC developments are further detailed in companion papers presented at this conference: Ref. 17 and Ref. 18, respectively. This section provides a brief overview of the main design features of the PPS®5000.

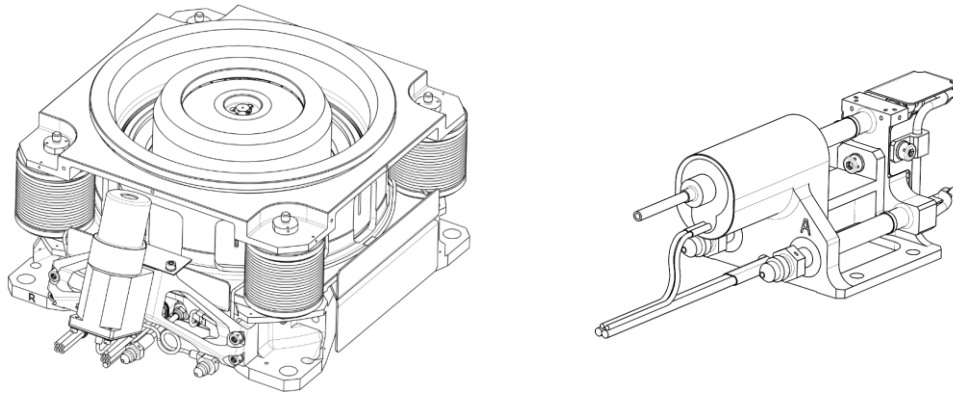


Figure 7. Flight design of PPS®5000 thruster and XFC.

A. Thruster

The thruster design is sized for 5 kW of discharge power and has demonstrated significant thermal margins over the course of the extensive testing performed over the course of the pre-development (Section II) and development (Section III) activities. This is permitted by an internal architecture that differs significantly from that of the previous-generation PPS®1350 and PPS®1350-G designs. The architecture and performance was verified by testing on the PPS®X000 Technology Demonstrator model and PPS®5000 Engineering Model. In fact, most of the design features proposed and tested on the PPS®X000 in the early 2000's were retained in the 2017 flight design.

The thruster was designed to a lifetime requirement corresponding to a minimum total impulse capability of 11.7 MN.s, with the objective of reaching 14.5 MN.s. This amounts to a total xenon throughput of 825 kg. Long-lifetime capability is a key feature of modern designs, and for the PPS®5000 the approach, presented in 2005,⁸ is to ensure that the erosion pattern developed on the discharge ceramic walls remains in a region completely downstream of the magnetic pole pieces. Although it will converge to a very low value over time, the erosion rate remains finite but the key feature here is that there is no measurable pole piece erosion. This was demonstrated both in the last 2500-hr PPS®5000 EM partial life test, and in the recent EQM1 life test over 1,700 hours at 5 kW of discharge power. This is visible in Figure 8, where the black deposits all over the thruster (including cathode and pole pieces) and coming from the carbon tiles in the facility indicate that erosion is limited to the discharge channel walls, as expected. The erosion rates coincided with the predictions established from PPS®X000 and PPS®5000 EM testing and propagated by modeling.⁸



Figure 8. PPS®5000 EQM1 after 1,700 hours of operation at 5 kW of discharge power.

In the context of a generic development, it was important to converge on a design that would be robust to varying spacecraft interface requirements. As a consequence and throughout the design process and thermal analyses, the justification was established on the basis of a (theoretical) adiabatic interface in hot conditions. This means that the thruster was to sustain a perfectly (mathematically) decoupled interface with the spacecraft, both conductively and radiatively even when operating at full power. This is rendered possible by the presence of a thermal drain connected to lateral radiators on all sides of the thruster. This proved decisive already for the first case of a flight-design accommodation: when Safran took responsibility for the design, development and manufacture of a thruster module assembly for the PPS®5000 in late 2014, this possibility was leveraged to converge on a module design that would reject as little heat as could practically be achieved on a real design. The first (PFM) flight model for this module was acceptance-tested in January 2017 and achieves a total power dissipation (conductive and radiative, including XFC) to the spacecraft interface of just 22 W with the thruster operating at 4.5 kW of discharge power. By comparison, the Thruster Module Assembly (TMA) design developed by Safran in the late 90's had to evacuate 20 W by a conductive path to the satellite interface in order to maintain an acceptable temperature for the 1.35-kW thrusters.¹⁹

B. Cathode

The 20-A cathode development for the PPS®5000 application is described in Ref. 17. In this Section, only the main design approach is recalled.

During the entire pre-development period until the spring of 2014, the assumption had been to procure the cathode from an outside source. Several suppliers were considered and different cathodes were tested on the PPS®X000 and PPS®5000 EM. This approach was revisited in early 2014, and the decision was made to kick off the development of an internal solution.

Because this significant change intervened late in the development, an opposite approach was taken to that of the overall thruster anode subassembly design: while the anode subassembly was based on a novel internal architecture and magnetic design, the cathode was directly scaled up from the flight-proven, long-lifetime PPS®1350 cathode design with minimal changes. In particular, the sizing by modelling had as an objective to ensure that the same temperature ranges were conserved between the 5-A PPS®1350 cathode design, and the scaled-up 20-A PPS®5000 cathode design. This allowed to conserve the material and processes heritage of the PPS®1350 cathode.

Within 9 months of the programmatic decision, a first functional BreadBoard Model of the cathode, BBM1, was fitted onto the PPS®5000 EM thruster (Table 2) and underwent characterization testing over the entire functional domain, followed by close to 1,600 hours of successful partial life testing at 16.7 A of emission current. This test was followed by a Destructive Physical Analysis to observe the progress of potential internal failure modes. The BBM1 cathode was then replaced by a BBM2 in order to enable further thruster testing and internal cathode temperature measurements for thermal model correlation. The EQM1 cathode functional design was then frozen.

C. XFC

The main challenge to the XFC design¹⁸ was to accommodate the increased throttling range of the PPS®5000 compared to that of the PPS®1350, extend the thermal qualification range, and reduce manufacturing costs. The design remained based on the same principle as that of the PPS®1350.

The component controlling the flow in the XFC is an electrically resistive capillary tube called thermothrottle. The electrical current I_{tt} flowing through the thermothrottle governs the heat released into the gas flow, which changes the Reynolds number as a consequence of the temperature-dependence of viscosity for xenon. The net result is that an increased I_{tt} and therefore an increased capillary tube temperature leads to a reduced Xe flow rate. The total flow is then passively split between the anode and cathode by means of calibrated orifices. A functional schematic of the XFC is shown in Figure 9.

While the working principle of the PPS®1350 XFC was retained, the architecture of the flow controller was entirely revisited for ease of manufacture. This was very successful and to date, on top of the STM-EM unit built to flight standard except for a surface finish, two EQM units, one Proto-Flight Model (PFM) and two Flight Models (FM) have already been produced, with other FMs currently nearing completion. The XFC design is visible in Figure 7, and the qualification unit is shown in Figure 10.

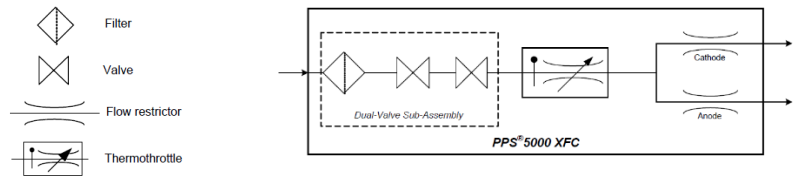


Figure 9. XFC functional schematic.

V. Qualification Program and Status

A. Qualification Program Overview

Qualification of the Thruster Unit to the technical requirements specification derived from the *Neosat* requirements is now underway. Prior to initiating the qualification test sequence on the thruster, two qualification-standard models, EQM1 (Figure 10) and EQM2, were produced and tested in order to finalize the design verification for those areas that were not fully covered by testing of the development hardware models described in Section III D.

More specifically, EQM1 is considered a secondary qualification unit because it has been, and will be, subject to tests that contribute to the qualification program and the V&V (Validation & Verification) logic, including at EP subsystem level, but do not need to be performed on the primary qualification unit because they do not contribute to thruster ageing. Those tests include subsystem End-to-End tests such as PPU coupling tests with different PPU options, but also multi-thruster firing tests, fine plume characterization, Electro-Magnetic Interference (EMI) characterization or Electro-Static Discharge (ESD) susceptibility tests. In addition to supporting the above tests, the EQM1 thruster was submitted to full acceptance as well as qualification-level mechanical environment tests including quasi-static, harmonic and random vibration tests, as well as shock tests. This unit also underwent thermal vacuum cycles in order to commission Safran's LIC test facility ahead of the qualification program. This was followed by qualification ESD

testing. Finally, the EQM1 thruster completed a partial life test of 1,700 hours at full power (including a stretch at 5.5 kW of discharge power) in order to build confidence in thruster performance and plasma discharge stability ahead of the life qualification test on QM3, the primary qualification thruster.

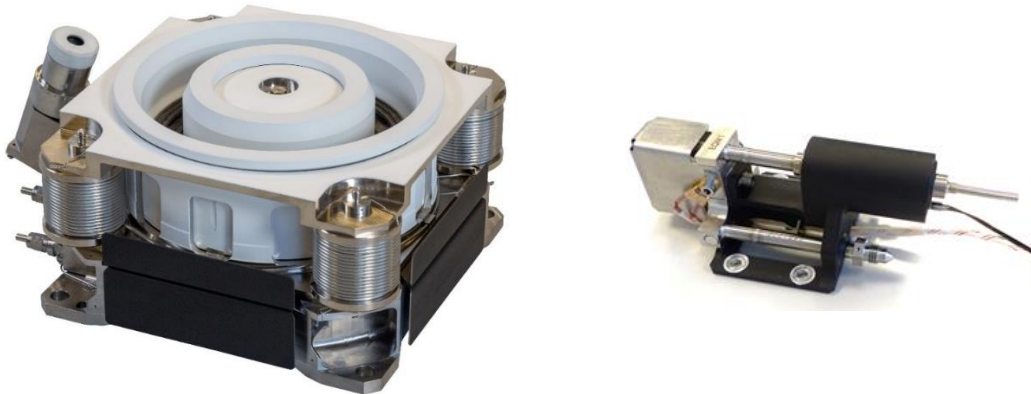


Figure 10. Thruster and XFC qualification hardware (EQM1).

The EQM2 unit was the second model fully built to qualification standards. Like EQM1, this unit underwent full acceptance as well as the complete suite of qualification-level mechanical environment tests. Both EQM1 and EQM2 therefore helped identify and resolve identified weaknesses in the design ahead of the QM3 test campaign. A specific value-added of EQM2 was that, following the above test sequence, the thruster underwent a second random vibration test sequence, but this time to experience a Power Spectrum Density (PSD) 3 dB above the qualification levels. This was a higher-risk test sequence designed to provide additional confidence on design areas where analyses alone could not decisively conclude on robustness margins. Lastly, EQM2 will also be available to qualification-accompaniment tests such as PPU coupling tests and multi-thruster firing tests.

Finally, we recall that the first Thruster Unit built to the flight design, albeit with lower quality standards and to an earlier design reference, was the STM A1 (Table 1). Together, STM A1, EQM1 and EQM2 have cumulated close to 2,000 hours of testing. This is in addition to the more than 7,000 hours of test time cumulated on the PPS®X000 and PPS®5000 EM thrusters (Figure 6), so that together about 9,000 hours of test heritage on representative models were available ahead of the QM3 qualification test campaign.

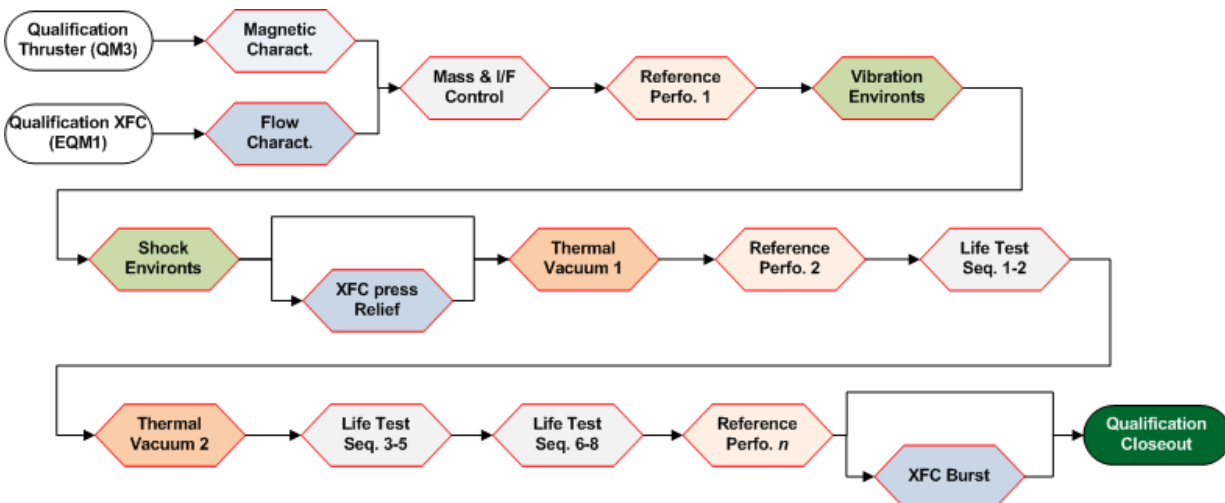


Figure 11. Thruster Unit qualification test sequence summary.

A simplified diagram representing the qualification test sequence is shown in Figure 11. This sequence lists only the main steps that the primary qualification hardware (thruster QM3 and XFC EQM1) will undergo. At the time of

writing, the XFC has already successfully passed all mechanical environment tests. Meanwhile, the thruster has completed Reference Performance #1 and is currently being readied for mechanical environment testing.

B. Mechanical Environments

The mechanical environment tests comprise mostly high-level sine (harmonic) loads, quasi-static loads, random vibration loads, and shock tests. To illustrate the levels in the technical requirements specification, the PSD input loads applicable to the thruster out-of-plane are shown in Figure 12. The specified PSD spectrum amounts to a total root-mean-square acceleration of 18.3 g_{rms} in-plane, and 19.1 g_{rms} out-of-plane. Hardware models STM A1, EQM1, and EQM2 all three experienced even higher loads. The loads applicable to the XFC can be found in Ref.18.

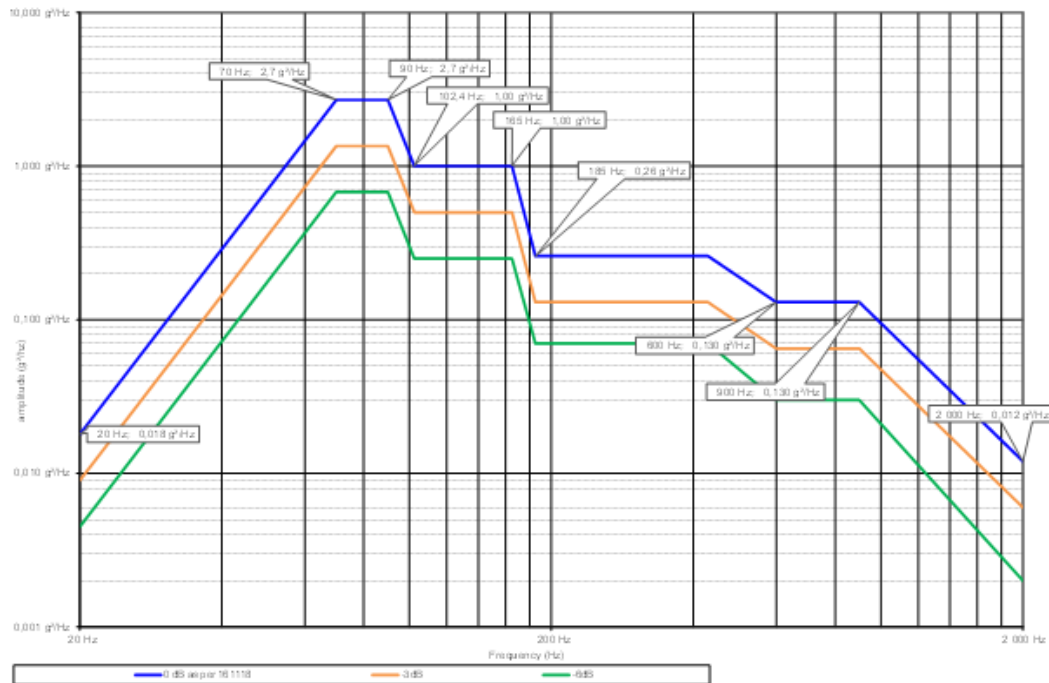


Figure 12. Random vibration PSD requirement for the thruster (out-of-plane).

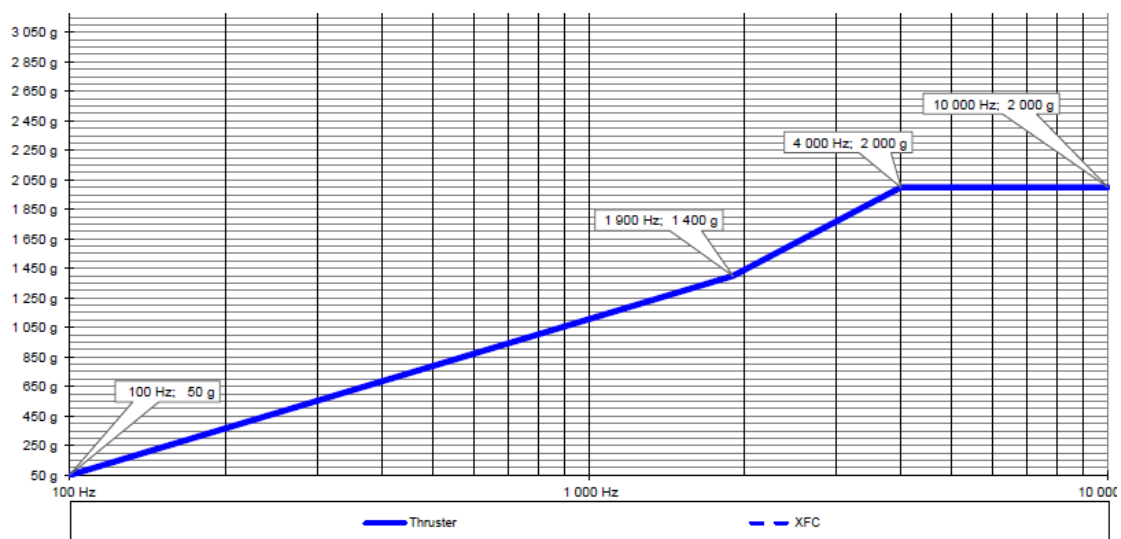


Figure 13. Shock Response Spectrum applicable to the thruster and XFC (out of plane).

Shock testing is performed as per the requirement of Figure 13. Each shock is repeated three times per axis.

C. Thermal Vacuum Cycling

As shown in Figure 11, a thermal vacuum cycling sequence will be performed twice on the primary qualification thruster. The first time will be right after the mechanical environment tests; and the second time will be during the life test.

The temperature qualification limits for the thruster and XFC are shown in Table 3. The temperatures are given at the Temperature Reference Point (TRP). Note that the notion of TRP typically makes sense for relatively homogeneous spacecraft equipments such as, e.g., electronics boxes. For a highly dissipative unit such as a Hall-effect thruster, where temperatures may range from a couple hundred degrees up to perhaps 1,700°C at the core of the cathode with extremely large gradients, the notion of (regulated) Temperature Reference Point actually makes little sense. For this reason, the TRP temperature on the thruster is not regulated during (hot) thermal cycles and the thruster is allowed to heat up from its own power dissipation, just like it would during its mission. It is recalled that for high power thrusters, a strong decoupling is sought between the thruster and the spacecraft interface. Therefore, the same arrangement must be replicated during ground tests. As a consequence, the test interface in the LIC facility replicates that of the most decoupled flight-design interface that could be achieved. This means further that the maximum TRP temperature is driven by the highest thermal decoupling possible, combined with running the thruster at maximum power. Thus, the hottest temperatures will essentially be reached every cycle during the life-test sequence that is long enough for thermal stabilization, and where the thruster operates at full power. Heating the thruster interface to yet higher temperatures therefore makes little technical sense, except for formally generating qualification margins at the interface. However, internal temperatures are not significantly impacted by interface heating.

The primary purpose of the thermal vacuum cycles therefore is to verify the thruster cold-start capability, and to verify the robustness of the design to large thermal gradients over a few cycles. As discussed in Section III D, thermal vacuum cycling tests cannot support the justification to cycled, thermo-mechanical fatigue. Indeed, performing a large number of full-excursion thermal cycles is simply impractical because each cool-down then warm-up cycle takes more than 24 hours. This means that, in order to perform the required 9,415 ON-OFF cycles including qualification margin, a total of 26 years would be necessary.

D. Life Test

The thruster life test will cover the operating domain plotted in Figure 14. This is driven by limitations associated with the available PPU options. Operating time will be essentially split between the 5 kW/300 V, and the 4.5 kW/375 V operating points. All ten operating points shown in Figure 14 will however be visited and characterized all along the life test.

With this plan, the complete life test will achieve a total delivered impulse of 14.5 MN.s. This will amount to a total xenon throughput of 825 kg and a total processed energy of 269 MJ. Following the currently projected throttle profile, this will be done over a total operating time of 15,762 hours and 9,415 ON/OFF cycles. The corresponding projected life test profile over time is shown in Figure 15.

As discussed in Sections IV.A and V.A, the EQM1 thruster was submitted to the first leg of the life test with several objectives. The first objective was to

Table 3. Thruster and XFC temperatures requirements (at TRP).

	Min. Temperature		Max. Temperature	
	XFC	Thruster	XFC	Thruster
Qualification	-40°C	-65°C	+110°C	+310°C
Acceptance	-35°C	-60°C	+105°C	+305°C
Flight	-30°C	-55°C	+100°C	+300°C

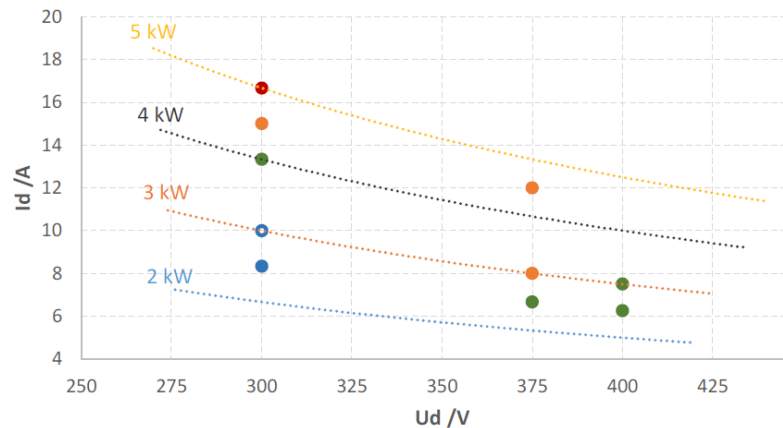


Figure 14. PPS®5000 operating domain during qualification.

obtain additional confirmation of the performance and plasma discharge stability with time on a fully-representative, flight design thruster ahead of the qualification life test. The second objective was to age a qualification-standard thruster so as to be able to perform fine plume characterization and EMI testing on a fully representative test hardware unit in aged conditions. Lastly, this provided a final verification opportunity for the behavior of the test facility as a whole and an opportunity to introduce and commission late, minor improvements to the test setup.

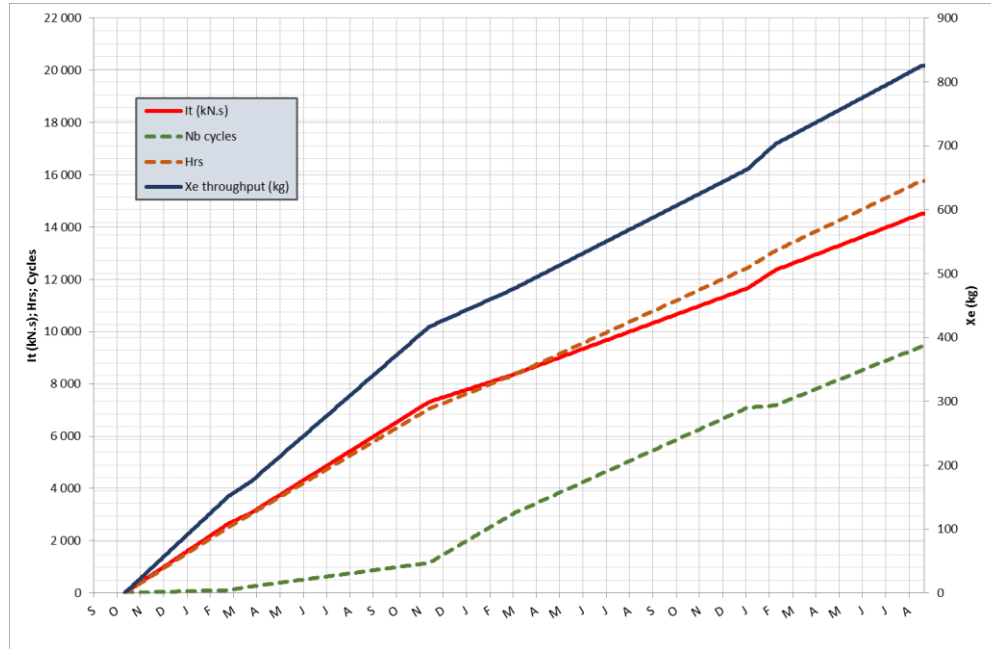


Figure 15. Life qualification test profile. Each tick mark on the x-axis corresponds to one month.

Over the course of this partial life test, the EQM1 thruster (coupled with the EQM2 XFC) reached a total of 1,687 hours of operation. The test was only terminated at the QTRR when it became time to integrate the QM3 thruster into the facility to begin the primary qualification test sequence.

Thruster performance was mapped over the 10 operating points represented in Figure 14 at regular intervals all along the life test. The performance is shown in Figure 16 for three operating points at 300 V; 375 V, and 400 V of discharge voltage, respectively.

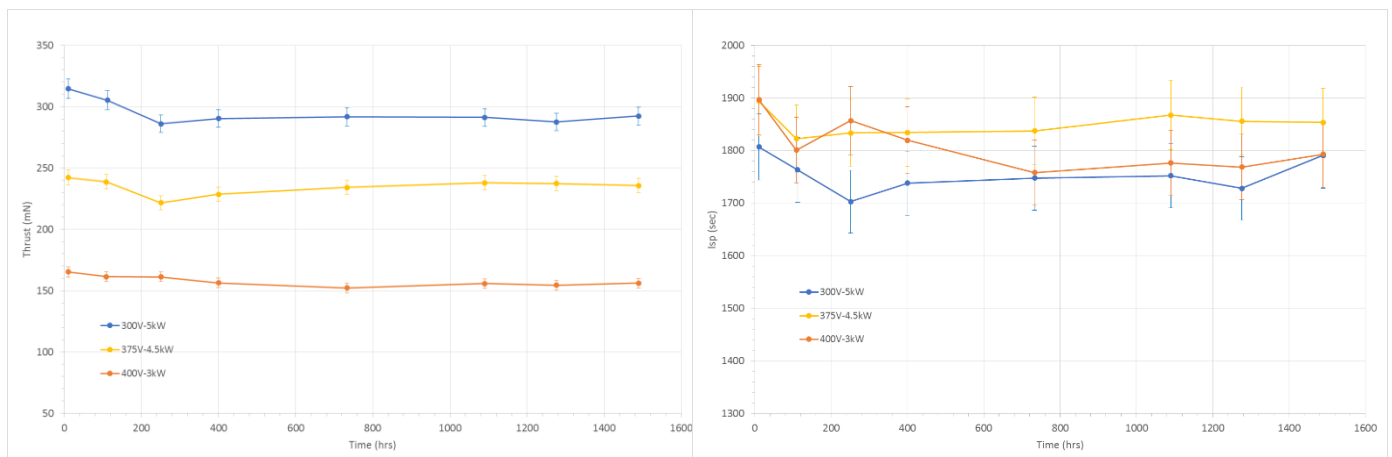


Figure 16. EQM1 performance during pre-qualification partial life test.

VI. Conclusion

The PPS®5000 Hall Thruster Unit has begun qualification testing, following an accelerated development program which mandated significant adaptations to standard development logics. In particular, a first functional model of the cathode was fitted on the thruster for 1,600 hours of testing, just nine months after the decision was made to develop the cathode in-house. The project relied on a number of hardware test models, combined with detailed analyses in intermediate correlation steps in parallel with the maturation of the detailed design. Overall, a total of close to 9,000 hours of testing on several models have been cumulated to support an extensive program of progressive risk mitigation that addressed performance and plasma stability over time, as well as degradation mechanisms including cathode wear or discharge channel erosion.

Prior to engaging qualification, two qualification-standard thrusters, EQM1 and EQM2, were built and tested, with emphasis on mechanical environment testing cumulated with a partial life test.

The Thruster and XFC have now entered the qualification phase. The Thruster has passed the first performance characterization sequence, and at the time of writing is being readied for mechanical environment tests. The XFC has already moved ahead along the test sequence, and has already successfully undergone all mechanical tests, plus a dedicated pressure-relief test. Several XFC flight units have already been produced, and production of the first thruster Flight Models (FM) is underway.

To date, the PPS®5000 has been jointly selected by the European Space Agency, Thales Alenia Space, and Airbus Defense and Space for the *Neosat* new-generation telecommunications satellite platforms. The PPS®5000 has also been selected by Boeing for commercial satellite applications featuring simultaneous operation of three PPS®5000 Thruster Units, and by OHB for the *Electra* new-generation platform.

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