Qualification 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 life test has reached the 9,000-hr milestone, with the thruster delivering a total impulse of almost 9 MN.s. In parallel to the ongoing qualification life test on the primary qualification unit, additional test campaigns are being conducted with other qualification-standard hardware. These parallel activities are in support of the qualification as risk-mitigation actions, or as system-compatibility verifications. This paper reviews the PPS®5000 general design and the overall development and qualification logic. A more detailed discussion focuses on the on-going life test. A first Qualification Review is scheduled in the last Quarter of 2019. The paper concludes with a first look at series production of flight-hardware in the context of the necessary production ramp-up.

Nomenclature

EOR	=	Electric Orbit Raising
F	=	Thrust, mN
I_{sp}	=	Specific impulse, s
PPU	=	Power Processing Unit
SK	=	Station Keeping
XFC	=	Xenon Flow Controller
ΔV	=	Velocity increment, m/s

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I. Introduction

THE PPS®5000 is s 5-kW Hall thruster system designed and developed by Safran. Its qualification status has reached a milestone which makes it available for flight missions. Industrial production is ramping up, and the first flight sets have already been delivered to Customers.

The PPS®5000 qualification program is the latest in a series of ambitious, successful qualification campaigns that resulted in flight applications for the SPT-100 in Europe, and for the PPS®1350. Based on this long-standing heritage,[1] Safran has delivered EP hardware or subsystems totaling 87 flight thrusters to date, with more scheduled before the end of this year. These thrusters or subsystems were delivered to six different spacecraft manufacturers and for integration on a variety of platforms, from commercial to exploration.

After the flight proven thrusters in the mid-power range (1.3-1.5kW), the PPS®5000 is the next thruster to enter commercial production at Safran. In the meantime, Safran is actively conducting the development of the low-power PPS®X00 (pronounced “X-hundred”), a Hall thruster sized to cover the power range 200 W to 1000 W with a long lifetime. The PPS®X00 is specifically designed as a compact, highly cost-effective thruster for LEO missions and constellations. Its development status is detailed in paper Ref. 2 to be presented at this conference. Finally, the PPS®20k is a technology demonstrator for high power applications up to 20 kW. An overview of the Safran thrusters portfolio is available in Ref. 3 and is illustrated in Figure 1.

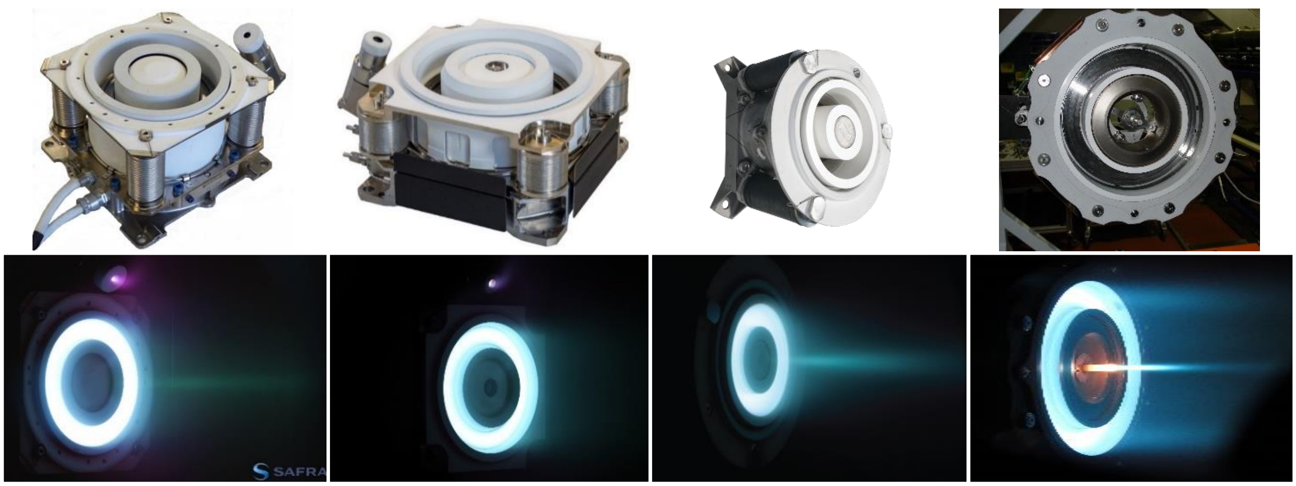

Figure 1. Safran Hall thrusters, from left to right: the commercially available PPS®1350 and PPS®5000; the PPS®X00 under active development; and the PPS®20k technology demonstrator.

The core of the current market driving the PPS®5000 development & qualification program is constituted by “all-electric” geostationary commercial satellites, where essentially all propulsive maneuvers are performed using EP. Because the orbit-raising ΔV represents more than two thirds of the total mission ΔV, this mission phase is the key driver of the performance requirements specification for the EP system of all-electric commercial satellites.

Compared to the first generation of comsat EP systems developed for Station Keeping (SK) operations only, the advent of Electric Orbit Raising (EOR) for geostationary satellites has three important technical consequences:

1) The power available to the EP system is increased, because the payload is not yet in service during orbit raising;
2) The total impulse capability required from the EP system also increases dramatically; and
3) A large variability of operating points and throttling profiles becomes necessary.

On top of this, cost-effectiveness is an increasingly important feature dictated by the growing competition generated by this new market.

The development background and time-to-market logic of the PPS®5000 development have been discussed in more details in Refs. 4 and 5. Overviews of the thruster design and qualification logic are provided in Sections II and III, respectively. This paper then focuses on the status of the qualification life test in Section IV. Section V will present key results from a qualification accompaniment program to support entry into production. Finally, Section VI will briefly discuss the first industrial phase for production of flight hardware.

II. PPS®5000 Design Overview

The thruster unit comprises the thruster itself, as well as the Xenon Flow Controller (XFC). The thruster comprises an anode subassembly and a cathode subassembly. The XFC includes a dual-valve subassembly. The product tree is represented in Figure 3.

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

The cathode and XFC developments were discussed in Ref. 9 and Ref. 10, respectively. This section provides a brief overview of the main design features of the PPS®5000.

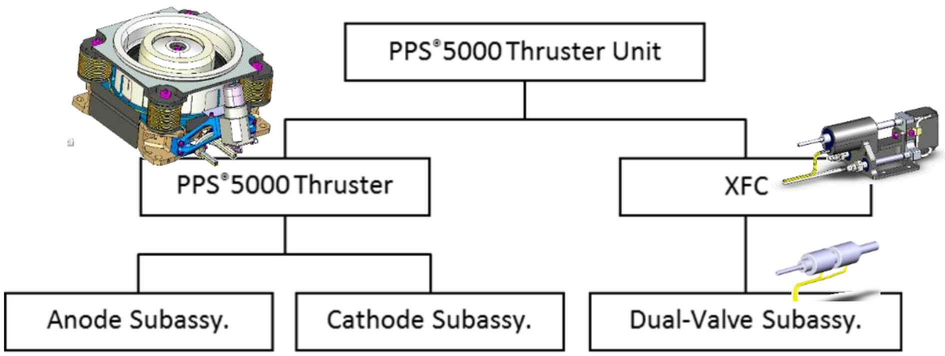

Figure 3. PPS®5000 product tree.

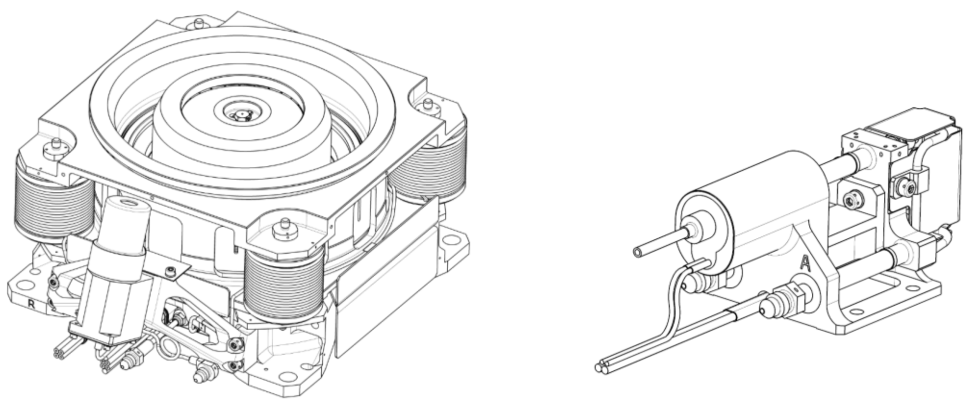

Figure 2. Flight design of PPS®5000 thruster and XFC.

A. Thermal design

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 and development activities. This design has also been demonstrated to possess growth potential and development units were tested to higher power.[4,5] If fact, the EQM1 (primary qualification) thruster was operated to thermal steady-state at 5.5 kW during the life qualification testing.

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 thermal robustness was leveraged to converge on a complete module design that would reject as little heat as could practically be achieved on a real design. A flight-design thruster module assembly achieved by test 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.[6]

This growth potential 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 implemented and tested on the PPS®X000 in the early 2000's were retained in the 2017 flight design.

B. Lifetime potential

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,[7] 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 ceramic erosion rate remains finite but the key objective here is to protect the pole pieces from any measureable erosion. This magnetic design concept and recent validation at the PPS®1350 scale are detailed in paper Ref. 8 presented at this conference.

This approach to long-life design was verified for the PPS®5000 in a 2500-hr partial life test on the PPS®5000 Engineering Model (EM). After the first part of the EQM1 qualification life test, the thruster was removed from vacuum for other specific testing, and this provided an opportunity for direct inspection. The thruster, which at this point had been operated for a total 1,700 hours at 5 kW of discharge power, is visible in Figure 4. In the same Figure, a picture of the thruster during its on-going qualification life test is shown, after a total of 8703 hrs, mostly at 5 kW. The black deposits observed all over the thruster (including cathode and pole pieces) originate from the carbon tiles in the facility and indicate that erosion is limited to the discharge channel walls, as expected. It can also be observed that the ignitor electrode on the cathode shows very limited erosion.

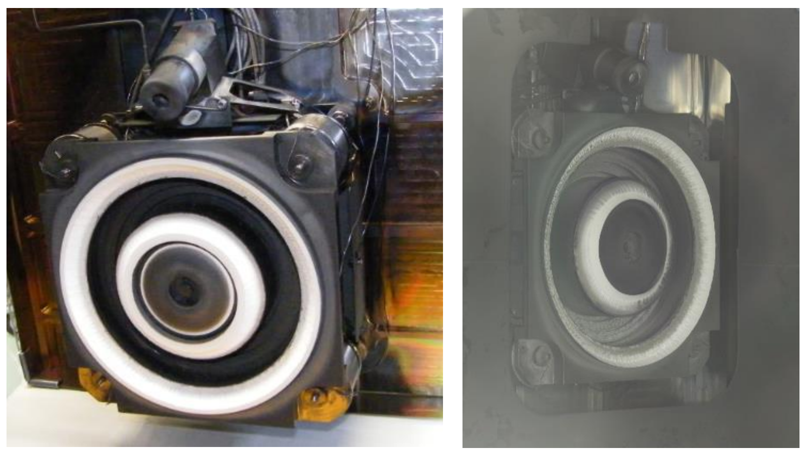

Figure 4. PPS®5000 EQM1 during qualification life testing at 5 kW outside vacuum after 1,700 hours of operation (left); and in LIC life test chamber after 8,703 hrs of operation (right).

C. Cathode

The 20-A cathode development for the PPS®5000 application is described in Ref. 9. In this Section, only the main design approach is recalled. A PPS®5000 cathode readied for a standalone test is shown in Figure 5

For programmatic reasons, the decision for Safran to develop the cathode internally intervened late in the thruster development. Therefore, 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 objective in sizing the cathode using a multi-physics model was 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 materials and manufacturing process heritage of the PPS®1350 cathode. The cathode is based on a lanthanum hexaboride (LaB_6) emissive unit and is capable of self-heated steady-state operation down to 5 A.

Figure 5. PPS®5000 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 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 (DPA) to observe the progress of potential internal failure modes. The BBM1 cathode was then replaced by a BBM2 instrumented with internal thermocouples in order to permit further thruster testing and internal cathode temperature measurements for thermal model correlation. The PPS®5000 cathode functional design was then frozen. The mechanical design was closed subsequently after mechanical testing of structurally representative models.

D. XFC

The main challenge to the XFC design[10] 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.

While the working principle of the PPS®1350 XFC was retained, the architecture of the flow controller was entirely revisited for ease of manufacture. As represented in Figure 6, the XFC architecture is based on three main subassemblies: the Dual-Valve subassembly, which features a filter and two cutoff valves in series; the thermothrottle subassembly, to ensure the flow-control function; and the flow restrictor subassembly, to split the output flow between the anode and cathode output branches. The qualification unit itself is shown in Figure 7.

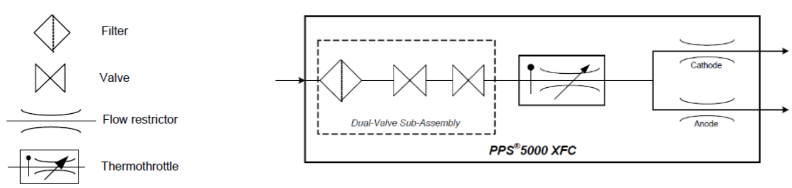

Figure 6. XFC-5000 functional schematic.

The development of the XFC started with the Dual-Valve sub-assembly. This subassembly was developed and qualified independently from the XFC and re-used the valve already qualified for the PPS®1350 application. Over the course of its qualification program, the Dual-Valve sub-assembly was submitted to functional tests; mechanical and thermal environmental tests; and life test, before being integrated at XFC level for upper-level qualification. The Dual-Valve qualification was pronounced in early 2016.

III. Qualification Program Overview

A. Development logic

With the support of CNES, the French Space Agency, the development of the PPS®5000 was approved to start fully in 2013 following the approval of the *Neosat* program.[11,12] Because of the severe time-to-market constraints placed on the PPS®5000 development, an aggressive design-to-time approach had to be implemented in the project management. Indeed, the development cycle durations historically associated with EP hardware development was clearly not acceptable in the current context and a more aggressive approach was necessary.

The amount of overlap introduced between the typical design phases of a “textbook” project has been described before.[4,5] The implications of parallelizing the activities related to requirements freeze, detailed design, manufacturing of a qualification-standard unit, and entry into commercial production lead to considerable challenges which had to be overcome by strong configuration and risk management, and unwavering resolve at all levels of management.

B. Qualification Status

The PPS®5000 qualification is borne by the EQM1 thruster unit (thruster and XFC), shown in Figure 7. As discussed in Ref. 5, other qualification-standard units were built and tested to support a comprehensive parallel test program including risk mitigation, Electromagnetic Interference (EMI) characterization, detailed plume characterization, or system-compatibility tests such as PPU coupling or dual-firing configuration tests.[5] For instance, a total of 10 PPU coupling test campaigns have been supported to date by PPS®5000 development or qualification models, covering different PPU options and different system configurations.

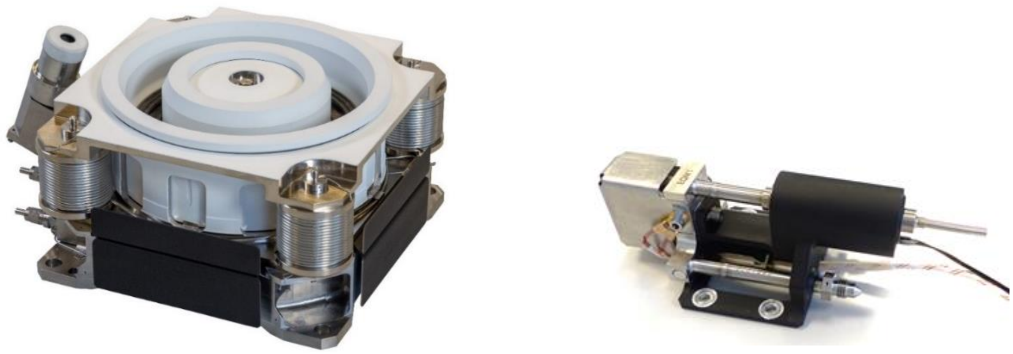

Figure 7. Thruster and XFC primary qualification hardware (EQM1).

In addition, and in keeping with industrial practices, e.g., in the Ariane launch-vehicle propulsion "world", a Qualification Accompaniment Model (QAM) was introduced in the V&V (Validation & Verification) activities to capture the minor design improvements that were introduced for mechanical robustness purposes between the EQM1 Manufacturing Readiness Review (MRR) closeout in March 2016 and the acceptance testing of the first flight model (PFM) in the summer of 2018. These improvements were without impact on the functional design, and addressed aspects related to industrialization and robustness of production. The additional purpose of this QA Model was therefore to further demonstrate and establish the frozen production capabilities after manufacture of the three qualification-standard thrusters (EQM1 through EQM3) and in accompaniment of the first flight units (FMs) manufactured from 2018 on. The QA Model therefore was only to undergo the qualification test sequence of Figure 8 up to life testing (but limited to a 1000-hr wear test).

The distribution of test activities in the V&V logic is summarized in Table 1. All qualification-standard units (EQM1, EQM2 and EQM3) underwent acceptance testing as well as the complete suite of qualification-level mechanical environment tests: quasi-static; harmonic and random vibration tests; as well as shock tests. A specific added value of EQM2 was that, following the above test sequence, the thruster underwent a second random vibration test sequence, but this time a Power Spectrum Density (PSD) 3 dB above the qualification levels was applied. 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 and EQM3 remain available to support qualification-accompaniment tests such as PPU coupling tests and multi-thruster firing tests.

A simplified diagram representing the qualification test sequence is shown in Figure 8. This sequence lists only the main steps followed by the primary qualification hardware (EQM1 thruster and XFC). For instance, additional intermediate inspections and verifications are performed between the main blocks represented in Figure 8. Also, additional tests are performed on other units in support of the overall qualification or as risk reduction ahead of the life test, as described in more details in Ref. 5.

Table 1. Hardware test matrix.

	QUALIFICATION					QUAL. ACCOMPANIMENT					
HARDWARE MODELS	Performance, functional	Vibration	Shock	Thermal vac.	Lifetime	Detailed plume charact.	EMI	ESD susceptibility	Coupled, E2E, system tests	Cluster firing	Facility commissioning
STM A1		✓	✓	✓					✓	✗	✗
QM4 (cathode only)	✓				✓						
EQM1	✓	✓	✓	✓	✓			✓	✓		
EQM2	✓	✓	✓	✓					✓	✗	✓
EQM3	✓	✓	✓	✓		✓	✓		✗	✗	✓
QAM	✓	✓	✓	✓	*Part.*				✗	✗	

✓ **Test performed or on-going;** ✗ **Test planned or possible.**

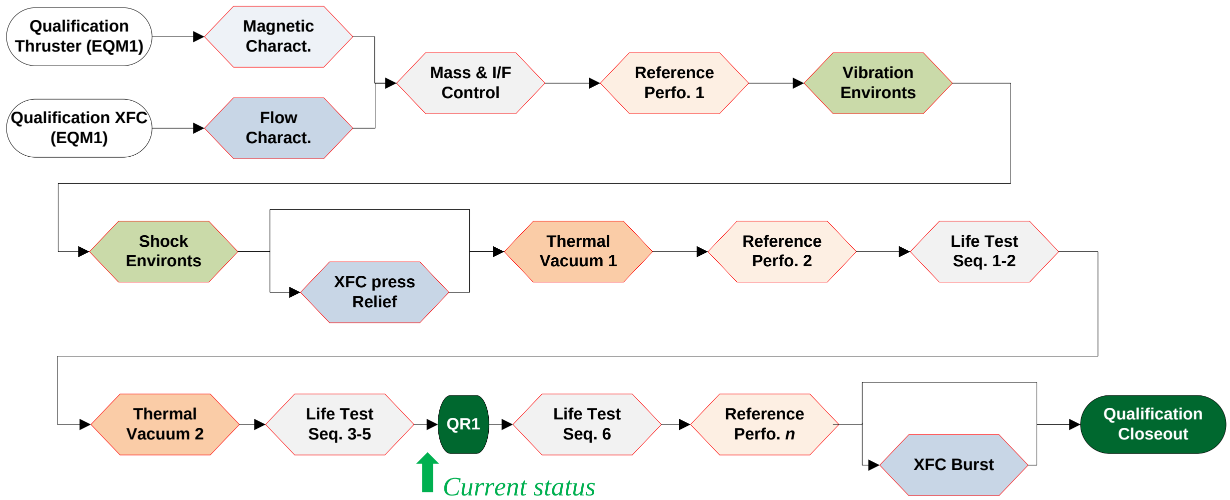

Figure 8. Thruster Unit qualification test sequence summary.

Several life test sequences (1 to 6) are referred to in Figure 8. This corresponds to different steps in terms of mission coverage (total impulse capability, number of ON/OFF cycles) as well as operating points. All along the life test, performance characterizations as per the acceptance test sequence are performed at regular intervals. This is referred to as “Reference Performance” testing.

The XFC pressure relief test was a verification of the capability of the XFC valves to open; then remain open for a specified duration; and then close, at the Maximum Expected Operating Pressure (MEOP). This test also included verification of the valves cycled actuation capability at MEOP. Finally, the XFC burst test is a demonstration of the XFC ability to withstand an upstream pressure of 4 times the MEOP.

The key test campaigns were distributed over the hardware models as per the hardware test matrix of Table 1. The primary qualification unit, EQM1, is outlined in red. The other units shown are all high-fidelity units built to the flight design. Other, lower-fidelity models such as Breadboard Models, Structural & Thermal Models, or Engineering Models were tested in the earlier phases of the development to progressively retire the main technical risks, as discussed in further details in Ref. 4.

The main results of the key test campaigns were discussed in Ref. 5. The progress in the qualification program is now driven by the progress of the life test, which is the focus of Section IV. At the time of writing, life test sequence 5 is nearing completion. This corresponds to a planned change in operating conditions, where most of the thruster operation will be performed at 375 V and 4.5 kW throughout the remaining Sequence 6, whereas operation has mostly been cumulated at 300 V and 5 kW to date. This is a significant milestone and the data package for a first Qualification Review (QR1) to be held in the last quarter of 2019 is under preparation.

IV. Life Test Progress

The thruster operating domain is represented in Figure 9 and covers a range in discharge power of 2.5–5.0 kW. This domain is driven in part by limitations associated with the available PPU options. Operating time is essentially split between the 5 kW/300 V (OP5), and the

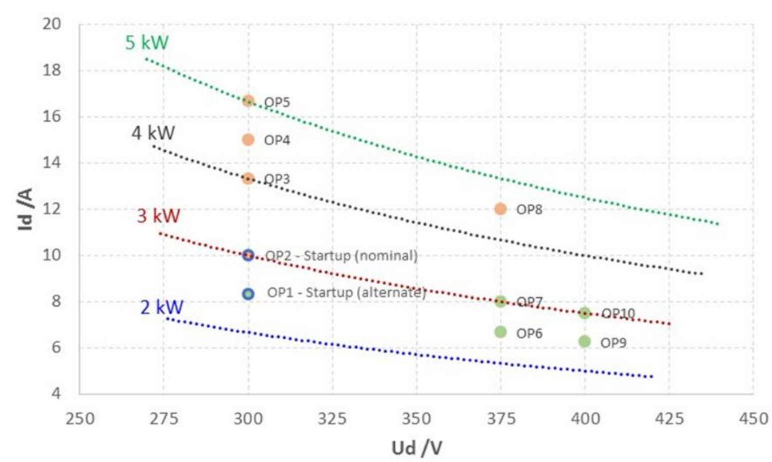

Figure 9. PPS®5000 operating domain.

4.5 kW/375 V (OP8) operating points. Yet, all ten operating points shown in Figure 9 are visited and characterized at regular intervals all along the life test, typically every 500 hrs. Nominal startup is performed at 3 kW/300 V (OP2) for repeatability, but low-power ignition capability to 2.5 kW/300 V (OP1) is verified at regular intervals. Upon discharge ignition, the thruster is immediately throttled to its target operating point with no need for stabilization delay. The thruster is shown during operation over its performance characterization domain in Figure 10, with photographs taken at each one of these ten reference points.

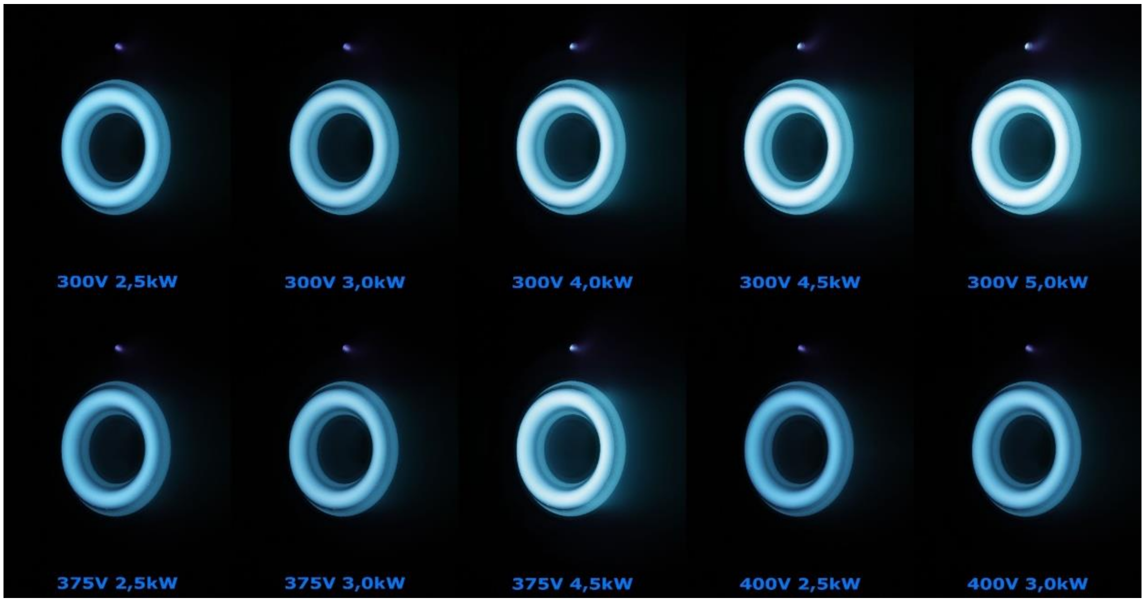

Figure 10. EQM1 thruster after an accumulated run time of about 1,070 hrs at 5 kW, during operation at the 10 reference performance points inside the operating domain.

As per the qualification test plan, the objective of the extended life test is to 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 268 MJ. Following the currently projected throttle profile, this will be done over a total operating time of 16,415 hours and 9,415 ON/OFF cycles. For reference, the qualified total impulse capability of the lower-power PPS®1350 is 3.39 MN.s at 1.5 kW over a cumulated lifetime of 10,532 hrs.[14] This was already a high standard for a Hall thruster in this power range.

At the time of writing at the end of August 2019, the PPS®5000 EQM1 thruster has accumulated a total impulse of 8.8 MN.s and operated over a total of 9,000 hrs, reaching the set milestone for QR1 (Figure 8). The number of thruster ignition cycles is currently 1,838, a moderate number corresponding to the end of an EOR mission profile. The current distributions of operating time and total impulse are shown in Figure 11. As can be seen, the thruster is operated at or near full-power during almost all of the life test, so that the total impulse is demonstrated at the highest

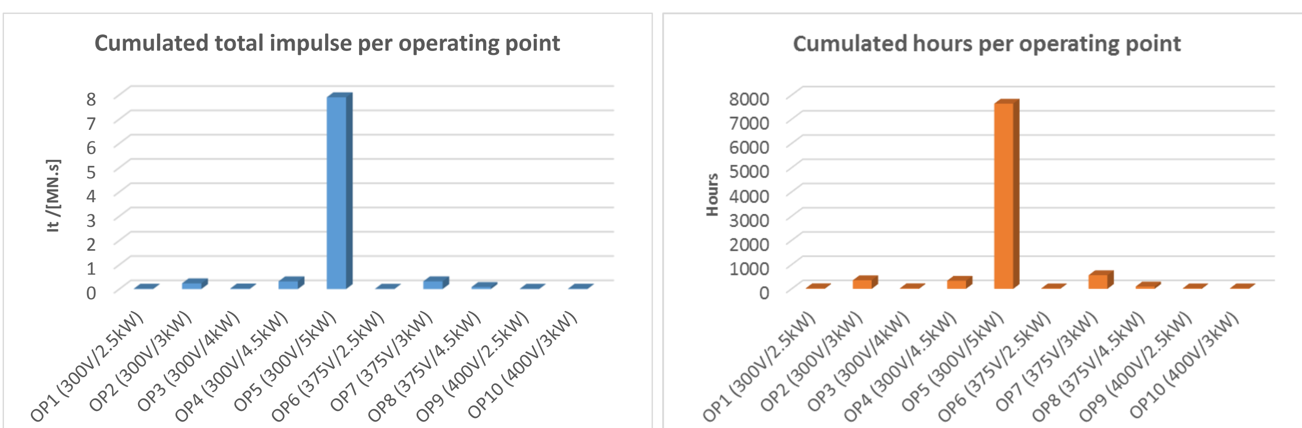

Figure 11. Cumulated total impulse and operating hours per Operating Point on EQM1 unit.

thruster temperatures and cathode emission current. For the remainder of the life test (Sequence 6), the thruster will now switch to operating at OP8 (375V/4.5kW).

Thruster performance is mapped all along the life test, roughly every 500 hrs, over the 10 operating points represented in Figure 9 and Figure 10. The measured thrust and specific impulse (*Isp*) are shown in Figure 12 for the ten reference performance points at 300 V; 375 V, and 400 V of discharge voltage, respectively (top to bottom). The two successive data sets at about 2,030 hrs and 2,100 hrs correspond to performance characterizations pre- and post-thermal vacuum cycling test, respectively.

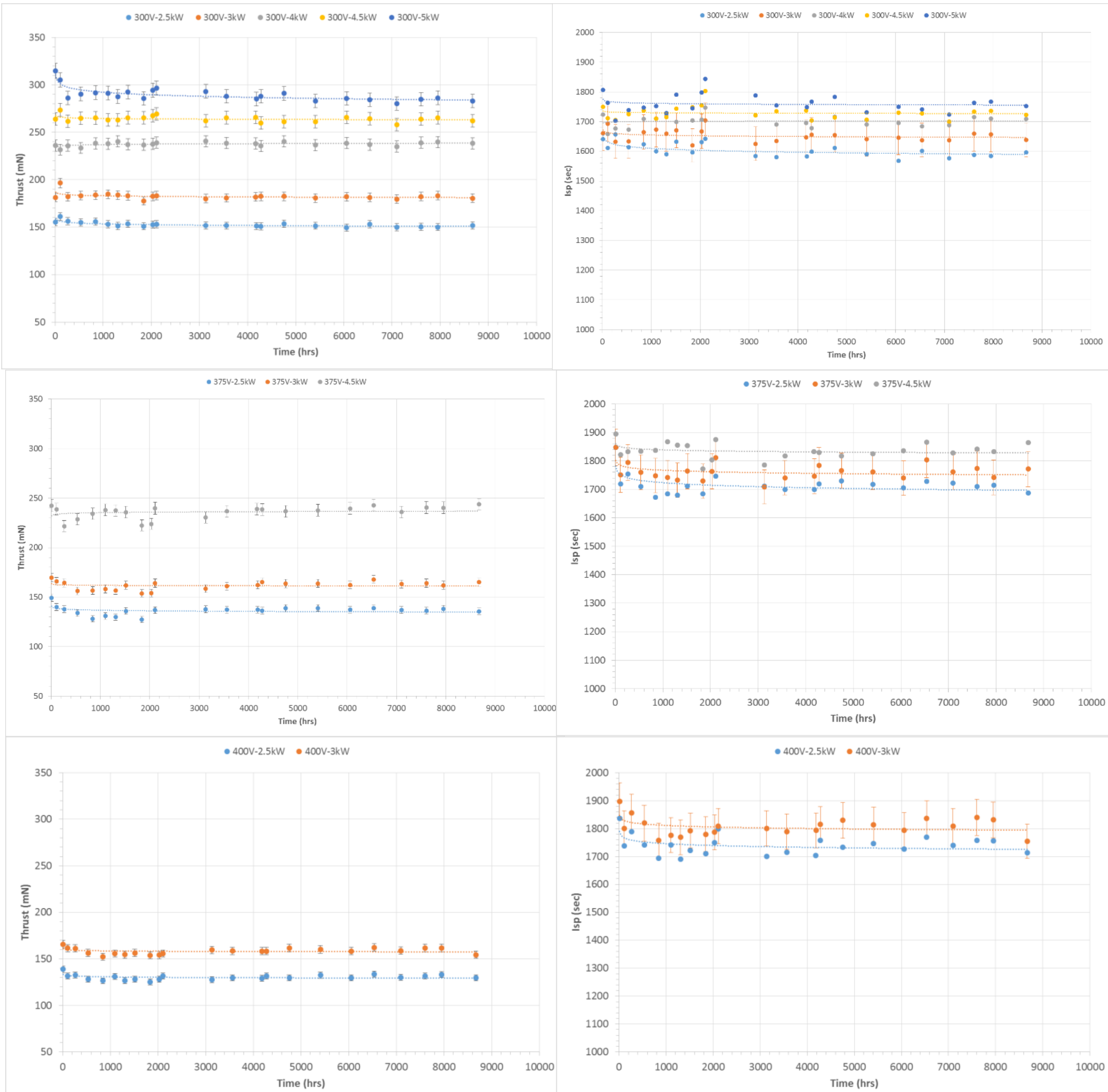

Figure 12. EQM1 performance characterization measurements during the life test. *Left: thrust; right: Isp. From top to bottom: data at 300 V; 375 V and 400 V of discharge voltage.*

V. Qualification Accompaniment Model

As discussed in Section III.B, a Qualification Accompaniment Model (or QAM) thruster was produced in 2018 at the initiation of the production ramp-up for flight units. This was to demonstrate manufacturing reproducibility at entry of production, two years after the manufacture of the primary qualification unit supporting the life test.

The QA Model was submitted to a test sequence identical to that of the primary qualification sequence of Figure 8, albeit with additional thermal vacuum cycles before the mechanical environment tests. Also life testing was replaced by a partial wear test limited to 1,000 hrs.

The thermal vacuum cycles consisted in a cold start, hot firing, and then a hot start, as shown in Figure 13. This succession was repeated for a total of 20 times. The qualification temperature requirements are presented in Table 2. In Figure 13, TC_7 is the thermocouple attached to the back of the cathode, and the other thermocouples are attached to different thruster locations. In particular, TC_1 is the Temperature Reference Point for the thruster.

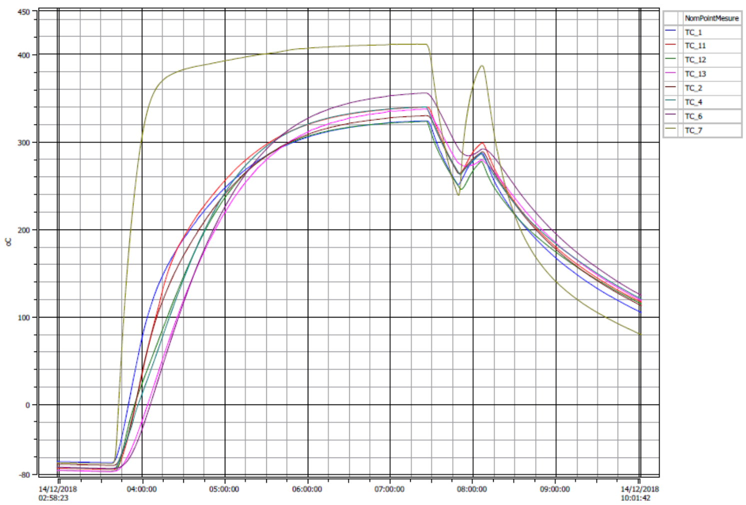

Figure 13. Qualification thermal vacuum cycle.

Table 2. Thruster and XFC temperature 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

Performance repeatability was found to be excellent with the EQM1 unit. Over all 10 Operating points, the average difference was 1.5% for thrust, and 1.2% for Isp. The detailed statistic over all operating points during acceptance testing of the first 14 units will be provided in Section VI.

The QAM unit was submitted to the qualification-level and duration vibrations as presented in Ref. 5. It was also submitted to the same shock test campaign, cumulating three shock events per axis. No significant dispersions with respect to EQM1 were observed. The QAM thruster cumulated a total of 203 hrs and 174 cycles going into the 1,000-hr wear test, so that the totals at completion of the planned test campaign are 1,210 hrs and 279 cycles. Again, essentially all the operating time was accumulated at OP5 (300V/5kW). While the qualification lie test of EQM1 is being carried out in the LIC test facility at Safran, Vernon, France, the QAM partial life test was conducted in the LVTF1 test facility at Aerospazio, Italy.[15,16] The performance evolution over the 1,000-hr wear test is shown in Figure 14.

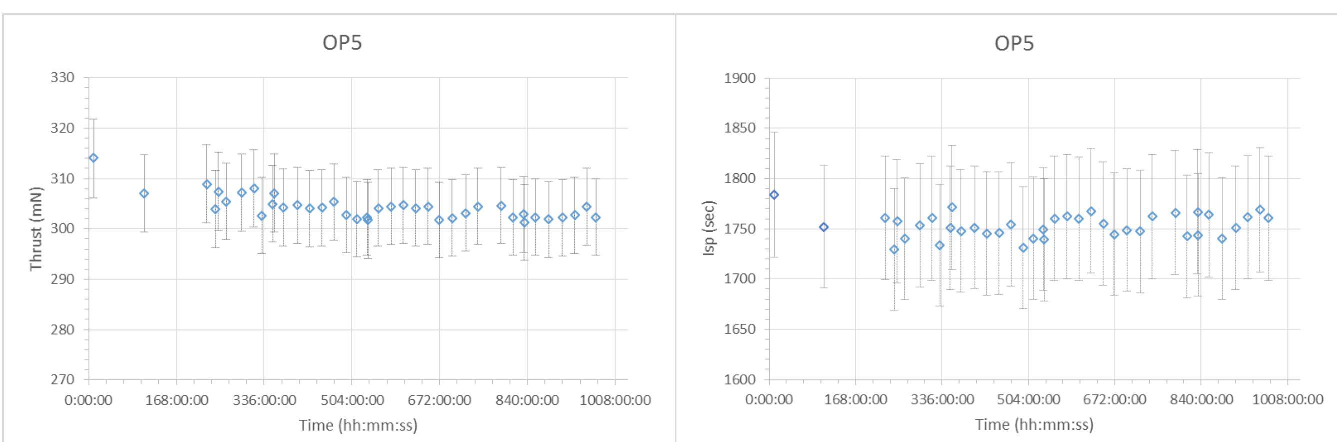

Figure 14. Evolution of thrust and total Isp during partial wear test of the QAM unit.

Overall, the QAM thruster produced along with the first recurring units in the new production facility described in Section VI was found to behave in every way consistently with the qualification hardware, and the production could be ramped up with confidence.

VI. Recurring Production

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 platform. 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.[17]

In order to meet the demands of the rapidly-increasing market, Safran inaugurated in early 2018 a new facility building to support the necessary production ramp-up. This facility in particular features a 185-m² clean room with work stations to allow for integration of up to four thrusters in parallel. The new facility is shown in Figure 15.

Figure 15. Safran building dedicated to EP and inaugurated in 2018 (left); and 185-m² clean room (right).

Another key driver of manufacturing rate capability is the capability to acceptance-test the thrusters produced, all the while conducting the life qualification test of the EQM1 unit in the LIC test facility. The strong partnership established by Safran with test provider Aerospazio[15,16] is part of the solution to ensure manufacturing rate capability. Two test facilities have been commissioned at Aerospazio for acceptance testing of production units. In parallel, the LIB test facility at Safran, previously limited to acceptance testing of the lower-power PPS®1350, was upgraded and commissioned to also support acceptance testing of the PPS®5000. The thermal vacuum cycling performed on the QAM was in fact conducted in LIB.

To date, 14 units have been acceptance-tested and complete flight sets of PPS®5000 thruster units have already been delivered to Customers, with more scheduled in the coming weeks. The production is tighly controlled and dispersion parameters are observed to be remarkably reduced on this first family, especially since they include data from thrusters tested in three different test facilities: LIC and LIB at Safran, and MVTF2 at Aerospazio. This is shown in Table 3, where thrust and total Isp during acceptance reference performance #1 is shown for all 10 reference performance points. Pictures of production hardware ready for shipment are shown in Figure 16.

Table 3. Reference performance during acceptance tests for 14 PPS®5000 units.

	OP1		OP2		OP3		OP4		OP5		OP6		OP7		OP8		OP9		OP10	
	F (mN)	*Isp* (s)	*F* (mN)	*Isp* (s)	*F* (mN)	*Isp* (s)	*F* (mN)	*Isp* (s)	*F* (mN)	*Isp* (s)	*F* (mN)	*Isp* (s)	*F* (mN)	*Isp* (s)	*F* (mN)	*Isp* (s)	*F* (mN)	*Isp* (s)	*F* (mN)	*Isp* (s)
Average	160	1634	193	1678	238	1694	286	1753	315	1771	143	1785	167	1805	242	1862	141	1853	163	1859
Std. dev.	0.6	21.5	1.1	31.1	1.4	20.4	1.9	28.7	2.4	23.1	1.9	31.1	0.9	23.9	1.4	22.4	1.0	28.6	0.9	25.1
Std. dev. (%)	0.4	1.3	0.6	1.9	0.6	1.2	0.7	1.6	0.8	1.3	1.3	1.7	0.5	1.3	0.6	1.2	0.7	1.5	0.6	1.4

VII. Conclusion

The PPS®5000 Hall Thruster Unit is approaching the first Qualification Review, corresponding to a milestone in the life test covering with margins an envelope of Electric Orbit Raising (EOR) missions. This followed an accelerated development program that mandated significant adaptations to standard development logics. 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.

A total of three qualification-standard thruster units, EQM1, EQM2 and EQM3 were manufactured and tested. EQM1 is the primary qualification unit and has undergone the complete suite of acceptance and environment qualification tests. It is at the time of writing 9,000 hours into its 16,400-hr life life-qualification test. The EQM2 and EQM3 units are being used to support qualification accompaniment tests, mostly for system compatibility aspects. In parallel with the production ramp-up for flight hardware in 2018, a Qualification Accompaniment Model (QAM) was built and tested following the qualification test sequence (except for the full life test). This was done to support the success oriented, largely parallel development approach taken for the PPS®5000 and the entry intro series production.

Necessary investments have also been made to support the production ramp-up necessary to satisfy the PPS®5000 customers. In particular, a new facility building was inaugurated in Vernon, Normandy, France in 2018, and three vacuum test chambers compatible with PPS®5000 acceptance testing have been commissioned for production, on top of the LIC facility supporting the on-going life test.

Figure 16. PPS®5000 flight hardware ready for shipment: Thruster (left) and XFCs (right).

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