Progress in Lifetime Test of HEMP-T Electric Propulsion System

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Thales qualifies the HEMP-T electric propulsion system with two HTM qualification models, the HTM-QM1 and the HTM-QM2, and with one PSCU engineering-qualification model, the PSCU-EQM. The HEMP-T propulsion system is planned for accommodation on the Heinrich Hertz satellite (H2Sat). Thales performs now the Lifetime Test with these qualification models. The HEMP-T Lifetime Test is carried out at the Aerospazio test facility. The HTM-QM1, powered from the PSCU-EQM, performs a Lifetime Test scheme based on the cycling and firing hours requirements for the H2Sat mission. The objective is to perform more than 8500 firing hours and more than 10000 cycles. The HTM-QM2, powered from the laboratory power supplies, performs the typical H2Sat operational cycling, with 100% cold starts and will demonstrate 77% spacecraft application lifetime. Both HTMs and the PSCU perform stable. No intermediate vacuum chamber opening was required so far. The HTM-QM1 + PSCU-EQM have reached the required qualification factor 1.0, with more than 6600 accumulated operating hours and more than 7800 operating cycles.

Nomenclature

FCU	=	Flow Control Unit
GSE	=	Ground Support Equipment
HTA	=	HEMP Thruster Assembly
HTM	=	HEMP Thruster Module
I/F	=	Interface
QF	=	Qualification Factor
QM	=	Qualification Model
PSCU	=	Power Supply and Control Unit

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I. Introduction

THE Business Unit Electron Devices of Thales Deutschland has developed, in the frames of the HEMP-TIS project, an electric propulsion system based on the High Efficiency Multistage Plasma Thruster (HEMP-T)[1,2]. Now Thales performs a qualification of the HEMPT propulsion system. HEMP Thruster Module (HTM) consists of the HEMP-T, the cathode-neutralizer and the flow-control unit (FCU), all these components mounted onto the mounting structure (MMS)[3]. FCU distributes Xe between the cathode, at constant flow rate, and the thruster, through the proportional valve which operates in closed loop with the anode current measured at the Power Supply and Control Unit (PSCU). The HEMP-T assembly (HTA) is intended for integration on board of geostationary communication satellites to perform attitude and orbit control manoeuvres. Each HTA consists of two to four HTMs, electrical harness and one PSCU. Each HTM provides the total specific impulse of >2300s and the thrust of 44mN, under the operating voltage of 1000V and nominal anode current of 1.38A, which is a nominal operation point for SGEO and H2Sat missions.

HTA qualification is being carried out with two HTM qualification models, the HTM-QM1 (Figure 2) and the HTM-QM2 (Figure 3), and one PSCU engineering qualification model, the PSCU-EQM (see Figure 5).

The HTM-QM1, the HTM-QM2, and the PSCU-EQM have successfully completed the qualification testing according to SmallGEO (SGEO) mission requirements, up to the Lifetime Test. In particular, the HTMs were tested in the wide range of HTM interface temperatures: between -15°C and +65°C, and in the wide range of environmental temperature: between -160°C and +41°C. The HTMs have shown a very low performance variation during that qualification sequence[4].

Now, the HTM-QM1, the HTM-QM2 and the PSCU-EQM undergoing the HTA Lifetime test.

II. HEMPT Lifetime test plan

The HEMPT Lifetime Test plan corresponds to the SGEO and H2Sat qualification requirements. The test plan includes parallel testing of two HTMs, HTM-QM1 and HTM-QM2, in the same vacuum facility. Each HTM performs its own test sequence independently (see Figure 1). The HTA Lifetime Test configuration was already presented[6]. Here are the main points.

The HTM-QM1 and HTM-QM2 operate on the nominal operation point throughout the test: 1.38A anode current stabilized in closed loop with the HTM Xenon flow, and 1000V anode voltage.

The HTM-QM1, coupled with the PSCU-EQM by harness with flight-representative connections to PSCU and HTM, performs a Lifetime Test scheme based on the PSCU cycling and HTM operating hours requirement. This test will collect a number of PSCU cycles and HTM firing hours corresponding to the nominal H2Sat lifetime requirements (including a qualification margin 1.3), i.e. >10000 cycles and >8500 firing hours. HTM-QM1 will perform twice as much operational cycles as required for H2Sat mission, but will fulfil the SGEO cycling requirements. From these HTM cycles, >9800 are "hot" cycles and >300 are "cold starts". The "hot" cycles have a reduced thruster cooling time of approx. 40 min in order to meet the amount of required cycles; this results in the additional effect that the HTM is cycled towards temperatures close to the maximum operational temperatures foreseen. This is considered by Thales on H2Sat as worst-case cycling scenario (very high operational temperatures, fast temperature slopes) for the magnets, the most critical thruster component. The "cold" cycles from a thruster temperature reference point (TRP) below -55°C, with 60 min firing time are the worst-case cold starts and will verify the HTA capability to ignite at the lowest expected in-flight thruster temperature. Furthermore, this HTM-QM1 is mounted on the thrust balance and fully characterized with periodic thrust measurements and ion beam scans. The following operational procedure is applied at each cycle:

- PSCU on;
- HTM start-up procedure (pre-heat HTM);
- Neutralizer ignition;
- Thruster ignition;
- Operation at nominal point for predefined time;
- HTM off;

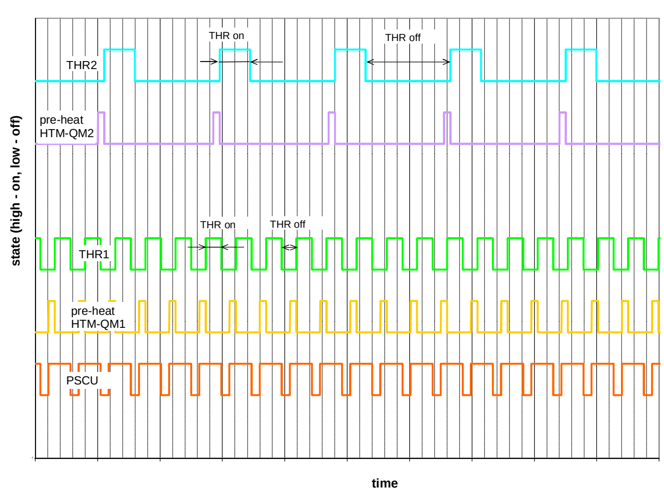

Figure 1. Lifetime test firing scheme

- PSCU off;

The duration of the full HTM-QM1+PSCU-EQM vacuum firing sequence is estimated to be more than two years. HTM-QM1 and HTM-QM2 will be operated with a FCU minimum inlet pressure, as this is considered worst case for cathode operation.

The HTM-QM2 will perform the cold operational cycling; due to the very long OFF-time needed to cool down the thruster to the starting temperature of approx. -40°C, 3000 cold cycles with total >4900 firing hours will be carried out in more than two years of vacuum firing sequence.

III. Lifetime test set-up

The HEMPT Lifetime test is performed at the Aerospazio vacuum test facility LVTF1[5,7]. The LVTF1 consists of a diamagnetic horizontal stainless steel chamber, 11.5 m long and 3.8 m in diameter, with a total volume of ~120 m3.

The minimum attainable basis pressure on the order of 2e10-8 mbar, typical Xe pressure during HTM testing is 2.2e10-6 mbar.

LVTF-1 has a chamber conditioning system in order to properly outgas the inner surfaces of the chamber during the pump-down phase. It consists of a high power fixed mounted heater.

The in-vacuum test set-up was designed for accommodation of two HEMP thruster modules. As already mentioned, the HTM-QM1 and the HTM-QM2 are tested simultaneously in the LVTF1 vacuum chamber.

The HTM-QM1 is installed on top of the thrust balance (Figure 2). The thrust balance was developed by Thales[4]. The thrust balance has sensitivity below 0.05mN. The thruster axis of HTM-QM1 coincides with the geometrical axis of the vacuum chamber. The thruster and the neutralizer are surrounded by the thermal shroud (see Figure 4) for a definite radiation environment: shroud can be cooled down by liquid nitrogen, maintained at ambient temperature or heated up. The HTMs are mounted onto the testing interface frame, which allows for thermal control of the HTM mounting interface (I/F) to simulate the operational conditions on the satellite. The FCU is covered with MLI foil during the testing.

The ion beam diagnostics is aligned to the HTM-QM1 thruster. The ion beam diagnostics set is mounted on a rotating semicircular arm inside the chamber and consists of:

- 32 Faraday Probes (FP) with guard ring placed at different angular positions on the arm which is used to determine the thrust vector (via ion current measurements);
- 2 RPAs provided by Thales.

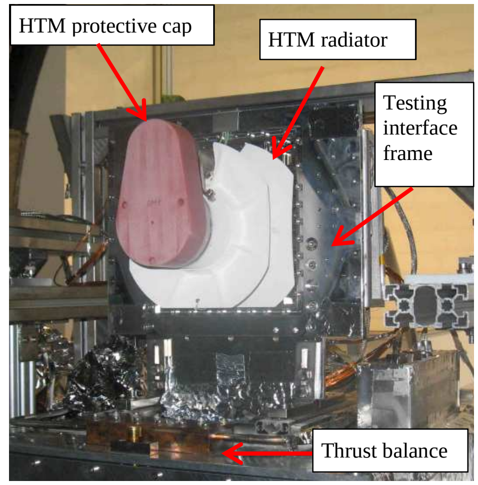

Figure 2. HTM-QM1 on the thrust balance in the Lifetime test vacuum chamber (thermal shroud is not yet installed).

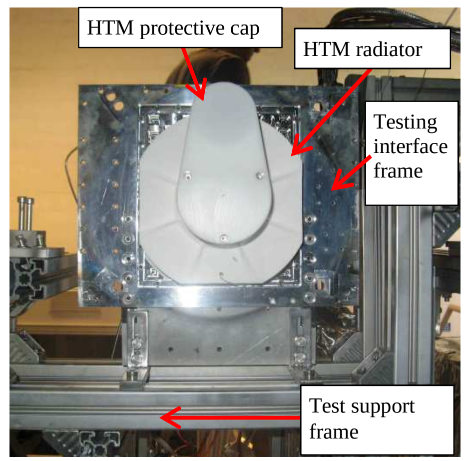

Figure 3. HTM-QM2 on the test support frame in the Lifetime test vacuum chamber (thermal shroud is not yet installed).

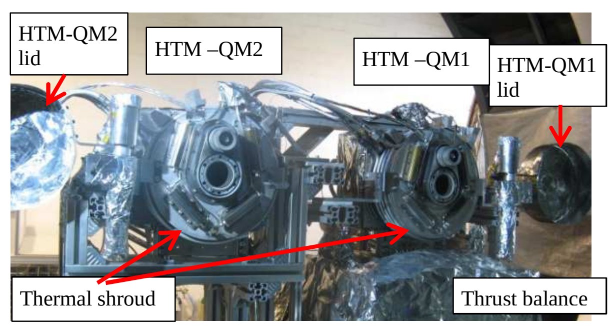

Figure 4. HTM-QM1 and HTM-QM2 in the Lifetime test vacuum chamber, with the installed thermal shrouds; final test set-up before chamber closure.

Each probe is mounted on the arm so that the collector faces the centre of thruster exit section at a distance of 1 m. The arm is moved by a stepper motor with a step angle of 0.45 deg and can perform a 180 deg rotation (-90 deg to +90 deg off axis).

The beam diagnostics arm is additionally equipped with the in-vacuum foto camera, which allows for in-situ visual observation of the HTM-QM1.

The HTM-QM2, on its testing frame, is mounted onto a dedicated test support inside the vacuum chamber approx. 60 cm off the chamber axis (Figure 3). The thruster and the neutralizer are surrounded by the thermal shroud as well (see Figure 4), for a definite radiation environment. The testing frame allows for thermal control of FCU. The FCU is covered with MLI foil during the testing.

Each HTM is equipped with its own HTM lid (Figure 3). The purpose of the lid is to protect the thruster from contamination with the vacuum chamber wall sputtered products during the time, when this thruster is off and the second thruster is operating. The HTM lids are independently remotely controlled.

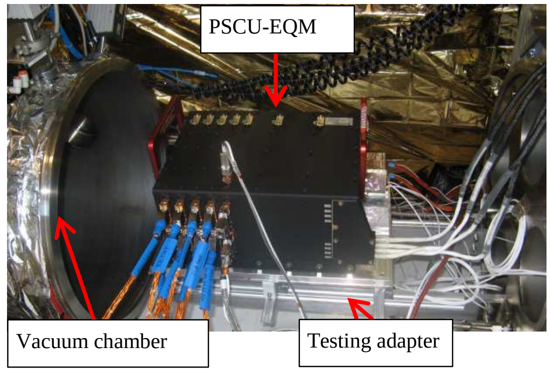

Figure 5. PSCU-EQM on the testing adapter in the dedicated PSCU vacuum chamber.

The vacuum chamber is provided with the view port, enabling observation of the HTM-QM1 and the HTM-QM2.

The PSCU-EQM is installed into the dedicated vacuum chamber, which is situated close to the LVTF1 chamber. This enables improved access to electrical signal measurements. The PSCU vacuum chamber is equipped with its own pumping system with minimum attainable basis pressure on the order of 5e10-6 mbar.

The PSCU-EQM is installed onto the testing adapter inside the dedicated vacuum chamber (Figure 5). The testing adapter allows for the thermal control of the PSCU mounting I/F to simulate the operational conditions on the satellite.

HTM-QM1 is fully powered and controlled from the PSCU-EQM. HTM-QM2 is powered from the laboratory power supplies and controlled by ground support equipment (GSE) (Thales). PSCU-EQM is powered from the bus simulator and controlled with MIL-1553-STD GSE (Thales). The overview of electrical set-up is presented in Figure 6.

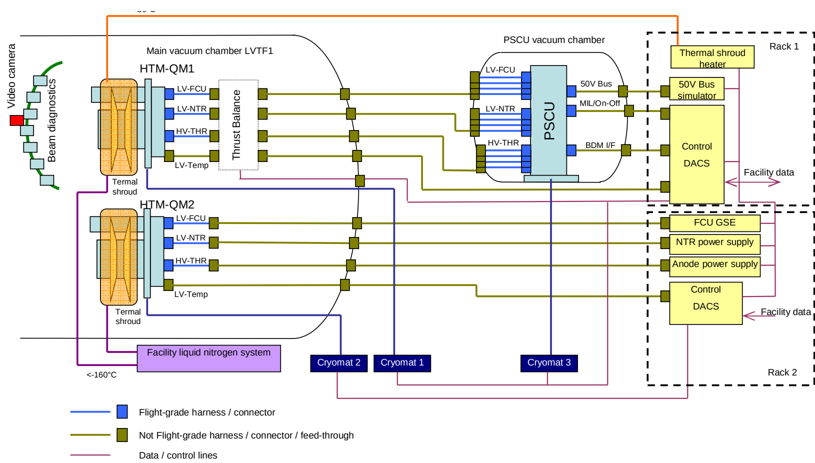

Figure 6. Overview of Lifetime test electrical and thermal set-up.

The end electrical connections to the HTMs and to the PSCU are made from the flight-grade cables, representative of the satellite harness. The intermediate cables are laboratory grade.

The bus simulator provides the PSCU-EQM with the power and simulates the 50V satellite bus. It is connected to the PSCU through the line impedance stabilization network (LISN).The PSCU-EQM is controlled from the GSE via the MIL-STD-1553 communication standard.

The PSCU-EQM controls the start-up, operation and shut-down of HTM-QM1. The PSCU integrates a number of measurement and protection functions. It provides the system master unit (SMU) with telemetry (TM), including thruster, neutralizer and FCU currents and voltages, PSCU and HTM critical temperatures. All the PSCU TM is acquired by the GSE during the Lifetime test.

The HTM-QM2 is powered with laboratory power supplies: the anode high-voltage (1000V) power supply, the neutralizer keeper power supply (0..50V dc) and the neutralizer heater power supply (0..15V ac). The HTM FCU is controlled by the FCU Driver, which simulates the FCU controlling function of the PSCU. A dedicated current and voltage measurement unit is placed in the supply rack for the HTM-QM2.

The HTMs are operated in the floating cathode configuration throughout the tests. The “minus” poles of high-voltage power supplies for both thrusters are not electrically connected.

The HTMs are equipped with a number of temperature sensors. Several temperature sensors are part of test hardware (flight HTMs will be also equipped with such temperature sensors). For the HTM-QM1 these temperature sensors are evaluated by the PSCU. Other temperature sensors, which are not a part of test hardware, are evaluated with the GSE. For the HTM-QM2, all temperature sensors are evaluated with the GSE.

Both HTMs are feed independently from the laboratory gas system. The laboratory gas system consists of the bank of Xe bottles, filters, pressure reducers, pressure controllers, pressure sensors, gas flow meters, valves and corresponding tubing. The operating gas pressure at the entrance of the HTM-FCU is representative of the satellite gas pressure and is constant through the Lifetime test.

The end gas connection to the HTM-FCUs is flight-grade and will be also qualified during this test.

IV. Results till the Qualification Factor 1.0

Activities according to the HTA Lifetime Test plan were started at the end of May 2015 upon the successful completion of test readiness review (TRR). The HTM-QM1 and the HTM-QM2 were installed on their positions inside the vacuum chamber, as shown in Figure 2, Figure 3 and Figure 4. The PSCU-EQM was installed into the dedicated PSCU vacuum chamber, as shown in Figure 5. After the electrical checks, both vacuum chambers were closed and the pump-down started.

The HTM-QM1 and the HTM-QM2 were first switched on according to the Lifetime Test plan at the end of August 2015.

The HTM-QM1 has reached the Qualification Factor QF=1.0 in September 2017. The HTM-QM1 + PSCU-EQM have accumulated more than 6600 operating hours and more than 7800 operating cycles. The HTM-QM2 has accumulated more than 3500 operating hours and more than 2200 operating cycles. These results were achieved

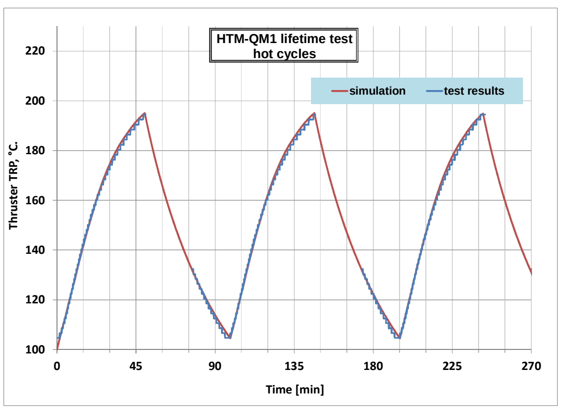

Figure 7. HTM-QM1 thruster TRP profile during the "hot" cycles, comparison with the previous numerical simulation. *test data from the PSCU-EQM (during the cool-down the PSCU is off – no data).*

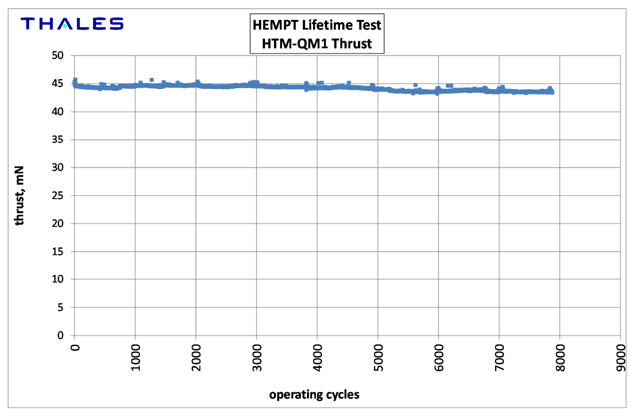

Figure 8. HTM-QM1 thrust.

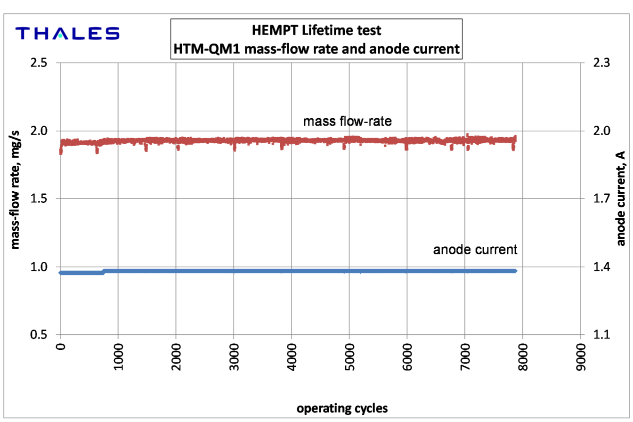

Figure 9. HTM-QM1 mass flow-rate and anode current (anode current – PSCU telemetry). *lower values of the mass flow-rate correspond to cold cycles.*

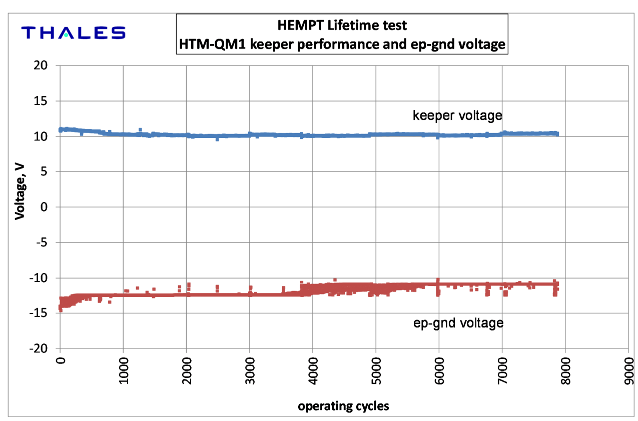

Figure 10. HTM-QM1 keeper voltage and ep-gnd voltage (PSCU telemetry).

without intermediate opening of the vacuum chamber.

Predicted by the numerical simulation the temperature profile of the thruster TRP coincides very well with the test results for the HTM-QM1 (Figure 7) and for the HTM-QM2 (Figure 11).

Performance of both HTMs and of the PSCU-EQM remains stable over the accumulated cycles.

HTM-QM1 thrust remains stable over the first 4500 operating cycles (Figure 8). Then, it shows a tendency to slightly decrease, and then it remains stable over the 2000 operating cycles. The decrease is about 1.2mN from the begin-of-test values.

Mass-flow rate remains constant at constant anode current (Figure 9). Lower values of the mass-flow rate throughout the test correspond to the "cold" cycles.

The HTM-QM1 keeper voltage and the cathode-to-ground (EP-gnd) voltage show a healthy behavior (Figure 10), with small fluctuations at the first several 100 operating hours after pump-down from atmosphere (initial "conditioning" phase). Keeper ignitions are reproducible and stable.

Mass-flow rate of the HTM-QM2 is constant at constant anode current (Figure 12).

The HTM-QM2 keeper keeper and ep-gnd voltages show a healthy behavior as well (Figure 13).

The vacuum chamber and the test set-up assure simultaneous operation of two HTMs (Figure 14) without anomalies.

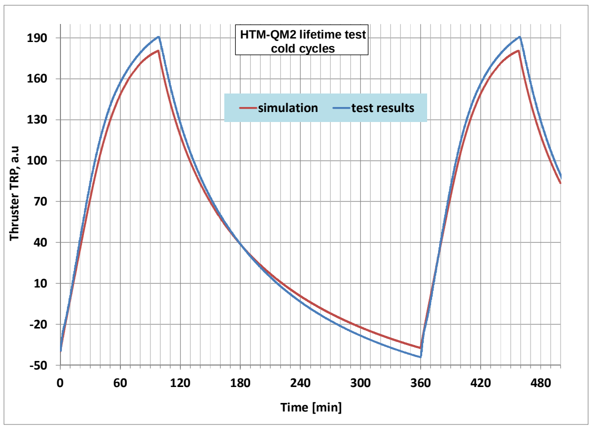

Figure 11. HTM-QM2 thruster TRP profile during the "cold" cycles, comparison with the previous numerical simulation. *test data from the GSE.*

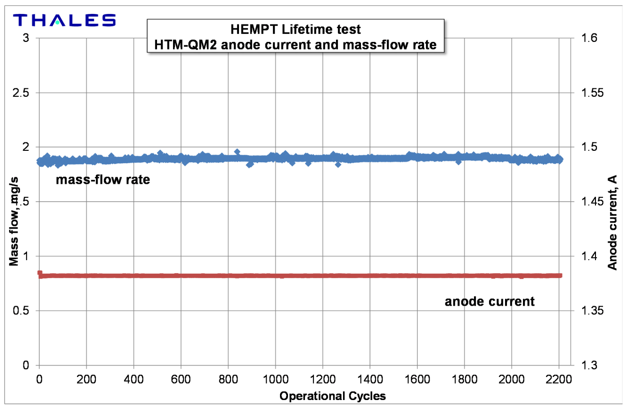

Figure 12. HTM-QM2 mass flow-rate and anode current.

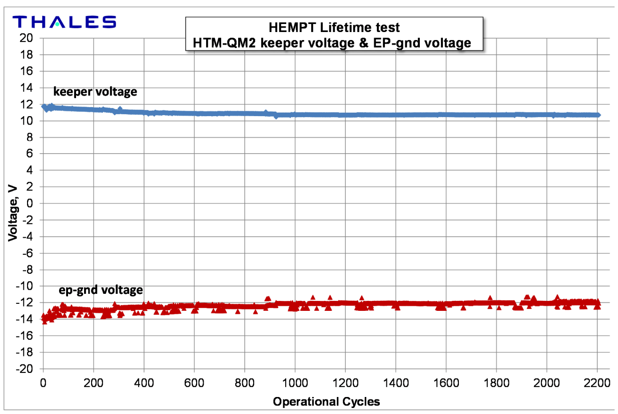

Figure 13. HTM-QM2 keeper voltage and ep-gnd voltage.

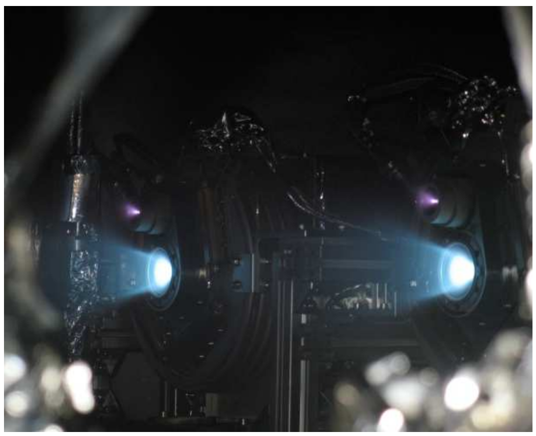

Figure 14. HTM-QM2 (left) and HTM-QM1 (right) operating simultaneously.

V. Conclusion

Thales carries out the Lifetime Test with two qualification HEMP Thruster Modules, HTM-QM1 and HTM-QM2, and with one qualification power supply and control unit, PSCU-EQM. This Lifetime Test is one of the most complex ones in the field of electrical propulsion: it includes simultaneous and fully independent operation of two thrusters in the same vacuum chamber. The qualification factor QF=1.0 is reached on HTM-QM1+PSCU-EQM. The HTMs and the PSCU do not show significant performance changes. The HTM-QM1+PSCU-EQM have accumulated >6600 operating hours and >7800 operating cycles, the HTM-QM2 has accumulated >3500 operating hours and >2200 operating cycles. The HTMs demonstrate a stable simultaneous operation in the same vacuum chamber throughout the test. The Lifetime Test is continued.

Acknowledgments

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