Endurance Testing of HEMPT-based Ion Propulsion Modules for SmallGEO

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Thales Electron Devices GmbH (TEDG) is qualifying a novel type of ion propulsion system based on High Efficiency Multistage Plasma Thrusters (HEMPT). This so-called HEMPT Assembly (HTA) will be integrated on OHB-System AG's SmallGEO geo-stationary telecommunication satellite to perform attitude and orbit control manoeuvres. One of the leading requirements of the SmallGEO Electric Propulsion System is the lifetime; 4800 hours of integrated operation + 50% qualification margin. In order to demonstrate the lifetime capabilities of the HEMPT technology prior to the actual lifetime qualification with the QM unit, TEDG started a 4000h endurance test (called ET1) with a HEMPT Thruster Module (HTM) Engineering Model unit in August 2010. All HTM components were on Engineering Model level and were representative in form and function for the later QM and FM design. The endurance test was performed in the large LVTF-1 test facility at AEROSPAZIO Tecnologie s.r.l., Siena, Italy; the HTM was mainly operated in continuous mode @ SGEO working point (44 mN with a thruster power of 1380W). The test was successfully completed in March 2011, with excellent long-term behaviour and unique reliability; no single HTM-induced firing interruption has been observed. Though the HTM was mainly operated in continuous mode, 200 cycles with nominal start-up and shut-down operational sequences have been performed, with On-time durations ranging from 40 minutes to 2-3 days. A comprehensive post-test investigation has shown that the thruster discharge channel was covered by a conductive carbon layer induced by back-sputtered graphite from chamber walls; this facility-effect is an issue for stable thruster performance. Hence, ET1 has been restarted in the ULAN facility at TEDG, using a chamber wall material with sufficiently high vapour pressure (Aluminium). This allowed reaching the nominal SGEO lifetime (4800 hours) with very stable performance of all components of the HTM, which gives high confidence in the lifetime qualification still to be performed.

Nomenclature

BOL = Beginning Of Life
CDR = Critical Design Review
ET1 = Endurance Test 1

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FCU = Xenon propellant Flow Control Unit
GIT = Grid Ion Thruster
HEMPT = High Efficiency Multistage Plasma Thruster
HEMPTIS = HEMP Thruster In-orbit-verification on SmallGEO
HTM = HEMPT Thruster Module
MMS = Mechanical Mounting Structure
NHKS = Neutralizer Heater Keeper Supply
PSCU = Power Supply and Control Unit
SGEO = Small GEOstationary satellite
TEDG = Thales Electron Devices GmbH
THR = Thruster
NTR = Neutralizer

I. Introduction

THALES Electron Devices is presently qualifying an innovative ion propulsion subsystem based on High Efficiency Multistage Plasma Thrusters (HEMPT). The so-called HEMPT Assembly (HTA) is targeted to the needs of commercial communication satellites but also offering a qualified and flight-proven off-the-shelf product for scientific missions. HTA development activities have started in 2007, and in 2008 German Space Agency DLR has kicked-off the so-called HEMPTIS (HEMPT In-orbit-verification on SmallGEO) project which includes full development, qualification and flight hardware delivery for the SmallGEO platform of OHB Systems. SmallGEO is developed in the frame of European Space Agency ESA's Artes-11 program, and its first launch will be through the commercial Hispasat AG1 mission.

Despite being a small to middle-sized telecommunication satellite with an in-orbit mass of 1900kg and a payload mass and power of 400kg and 3.5kW, respectively, the use of the HEMPT Assembly allows mass savings of as much as 220kg compared to conventional chemical propulsion. In combination with Thales' highly cost-effective system approach, ion propulsion becomes an attractive commercial solution also for smaller spacecrafts.

One of the primary requirements of the SmallGEO Electric Propulsion System is the lifetime; 4800 hours of integrated operation + 50% qualification margin. In order to demonstrate the endurance capabilities of the HEMPT technology and identify possible lifetime-limiting effects prior to the actual lifetime qualification with the QM unit, TEDG started a 4000h endurance test (called ET1) with a HEMPT Thruster Module (HTM) Engineering Model unit in the large LVTF-1 test facility at AEROSPAZIO Tecnologie s.r.l., Siena, Italy, in August 2010. All HTM components were on Engineering Model level and were representative in form and function for the later QM and FM design.

This paper describes the test article, the test set-up and gives a summary of the test results, including the recent data of the ET1 extension ongoing at TEDG, and of the post-test investigation performed on the HTM unit.

II. Test Article

The test article is represented by a HTM engineering model, HTM-EM3 (for illustration see Figure 1). The HTM consists of a High Efficiency Multistage Plasma Thruster of type HEMPT 3050, of a hollow cathode neutraliser of type HCN 5000, of a Flow Control Unit (FCU) and a central Mechanical Mounting interface Structure (MMS), on which all components are mounted[1,2,3]. In addition, HTM-EM3 is mounted on a testing integration interface frame which represents the thermal and mechanical interface of the satellite and which serves to integrate the thruster module onto the thrust balance.

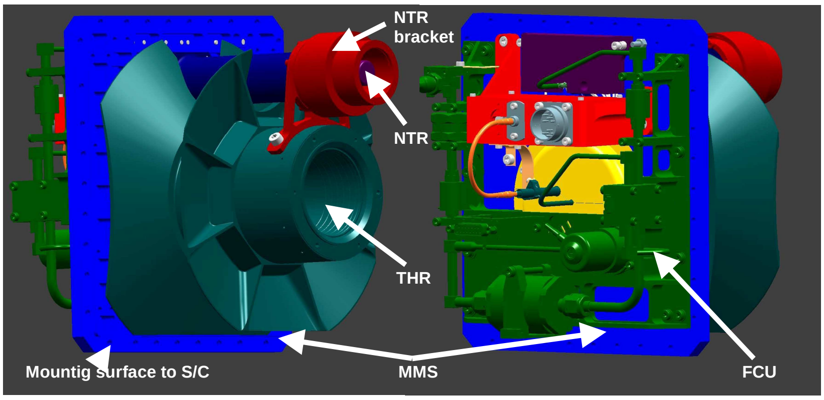

Figure 1. 3D-drawing of the HEMPT Module. ***Left: front side; right; rear side.***

All components are on Engineering Model level and are representative in form and function for the later QM and FM design. Both thruster and neutralizer designs are equal to the baseline designs which have verified all operational and performance requirements.

III. Endurance Test ET1

A. Test Set-up

The HTM-EM3 Endurance Test 1 has been performed in Large Vacuum Test Facility No.1 (LVTF-1) at AEROSPAZIO Tecnologie s.r.l., Siena, Italy. The LVTF-1 consists of a diamagnetic horizontal stainless steel chamber, which is 11.5 m long and has a diameter of 3.8 m for a total volume of ~120 m^3. The interior of the test facility is fully lined with pure graphite panels. The pumping system includes six panels cooled by cold heads and surrounded by liquid nitrogen baffles, specifically designed to pump Xenon (pumping speed > 120.000 l/s)[4]. The nominal chamber pressure during the HTM operation was ~2.5e-6 mbar (corrected for Xe).

The test facility is equipped with Thales developed thrust balance[4]. It has a sensitivity of <100 µN. The thruster is mounted on the top of the thrust balance. All sensors, actuators and girders are inside the holding frame structure, which is thermally stabilized, so that thermal drifts are significantly suppressed. During endurance testing with thermal stable operation an excellent drift stability of less than 1 mN per day has been achieved.

The LVTF-1 test facility is equipped with an ion beam diagnostics set which is mounted on a rotating semicircular arm; 32 Faraday Probes (FP) with guard ring are placed at different angular positions on the arm in order to determine the thrust vector position (via ion current measurements), and 1 Retarding Potential Analyzer (RPA) provided by TEDG for ion energy characterization and sputtering rate calculation. The probe arm is positioned such that the centre of the thruster exit section corresponds to the centre of the semicircular arm and the arm rotation axis coincides to the vertical axis crossing the centre of the thruster exit section (see Figure 2). Each probe is mounted on the arm so that the collector faces the centre of thruster exit section at a distance of 1 m. This configuration enables complete 1m-radius hemispherical profiles of the exhaust plume to be obtained.

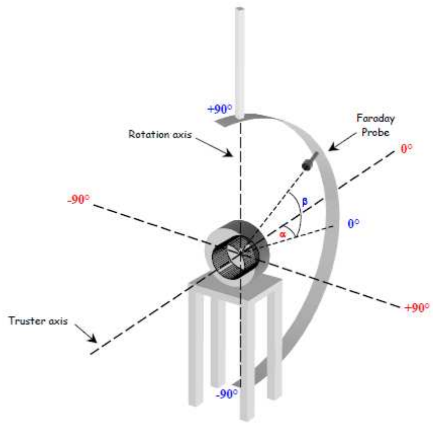

Figure 2. Schematics of the LVTF-1 beam diagnostic system

All power supplies, interlocks and measurement units are installed into a standard 19" rack, placed in a temperature-stabilized control room[4]. The thruster discharge is powered with a 6 kW, 1200V dc anode power supply. The neutralizer and FCU are powered with laboratory power supplies. The anode line is equipped with a current sensing circuit on high potential to measure the anode current. The voltage of the anode line is read back using a resistor bridge. The return (negative) line of the discharge power supply (negative pole) is connected to "electric propulsion ground" (EP_GND). The electric propulsion ground is insulated from the chamber ground to allow test in "floating" configuration, where the ion current must be compensated by the neutralizer current and no additional current loop via the chamber structure exists. The electrical set-up is hardware-protected from the too high negative bias of EP_GND relative the facility ground (-65V).

A Xenon supply system provides controlled gas flow to the HTM[4]. The gas flow is measured by a Bronkhorst gas-flow meter, the necessary for the FCU operational pressure is controlled by a Bronkhorst pressure controller. A pressure sensor is installed immediately before the HTM. All pipes inside the vacuum chamber as well as outside consist of stainless steel tubes with Swagelok 1/8" and VCR 1/4" connections.

B. Test Results

The HTM-EM3 Endurance Test 1 started on the 26th of August 2010 in the LVTF-1 test facility at Aerospazio, Siena, Italy (see Fig. 3).

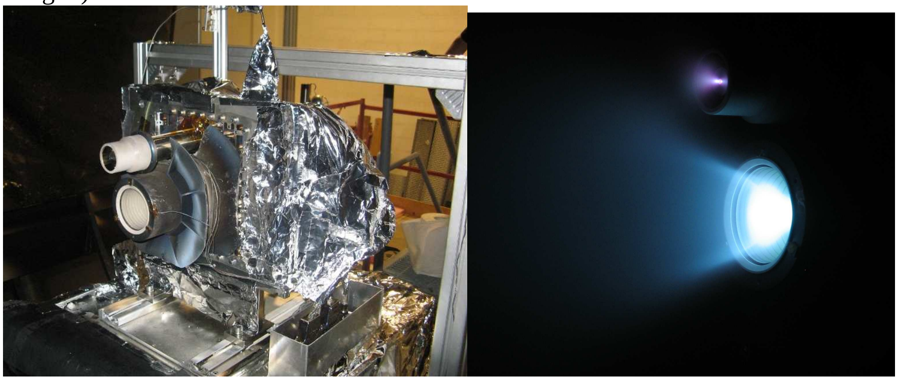

Figure 3. HTM-EM3 unit in the LVTF-1 facility at Aerospazio.
Left: mounted on thrust balance; right: in operation @ SGEO working point

HTM-EM3 was only once exposed to atmosphere during the Endurance test, at the intermediate inspection in January 2011. The HTM was mainly operated in continuous mode @ SGEO working point (44 mN with a thruster power of 1380W), with periodical shut-downs for thrust measurement purpose. The following flight-representative settings have been used:

1) anode voltage kept constant at 1000V;
2) anode current stabilized at 1.38A regulating the THR Xenon flow in closed loop;
3) Neutralizer Keeper current set to 1.5 A;
4) operation in floating mode;
5) S/C interface temperature = 16 ± 5°C.

Figure 4 shows the HTM thrust measured by the TEDG thrust balance after 100 hours of integrated firing from test start, demonstrating high thrust stability over many hours of continuous operation (standard deviation in 22h = 0.3%). Figure 5 shows the HTM thrust evolution during ET1; the thrust steadily decreased with running time from the BOL value of 44.5 mN to 40.1 mN after 2900 integrated hours. This decrease is induced by the successively built-up of a conductive graphite layer on the discharge channel due to re-deposition of vacuum chamber material eroded by thruster ion beam impingement. This conductive layer causes an increasing leak current that sums to the actual ion current up, progressively reducing the HTM mass flow commanded by the FCU controller to meet the anode current set-value of 1.38 A, as shown in Figure 6. In addition, the ionization zone is shifted from the inner main cusp towards the

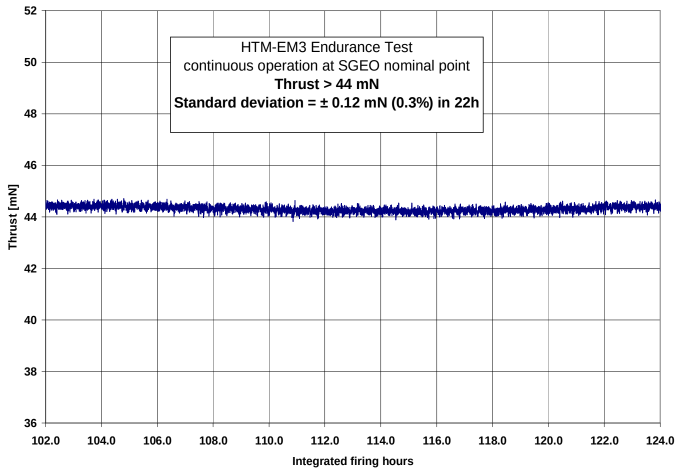

Figure 4. HTM continuous operation @ SGEO working point.

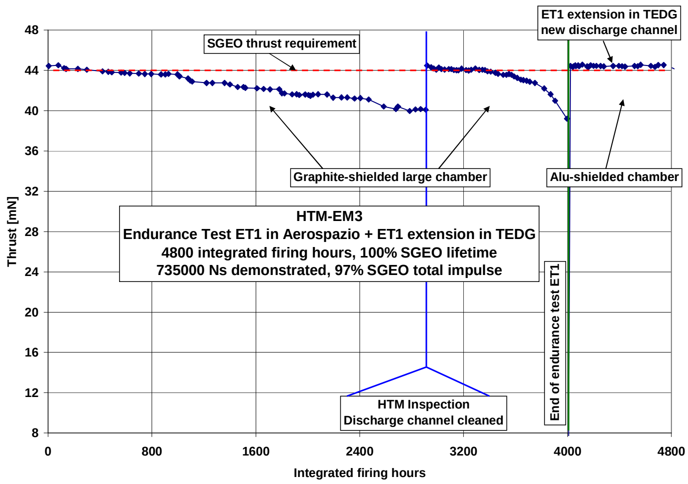

Figure 5. Thrust evolution with firing time in Endurance Test 1 and ET1 extension.

thruster exit such that more low energetic and less high energetic ions are expelled (see Figure 7). Both effects increase the thermal losses, which are responsible for the progressively increase of the thruster temperature, as shown in Figure 8. An intermediate inspection has been performed after 2900 firing hours breaking the vacuum and visually inspecting the HTM directly on the thrust balance; The discharge channel is covered entirely by a dark conductive carbon layer.

Before restarting the test, the discharge channel has been cleaned from the conductive layer with dry abrasive paper and the resulting particles removed with a vacuum cleaner, in an attempt to recover the HTM performance at BOL. Indeed, the data collected after the test restart demonstrate a full recovery of HTM performance, as shown in Figures 5, 6, and 8. This gives a strong indication that the HTM performance degradation in the first 2900 firing hours was caused by the operating time-depending facility effect of back-sputtered graphite deposition inside the discharge channel.

After test restart, HTM-EM3 showed similar performance evolution as during the first 2900 hours with a slightly faster degradation in the last part of the test, which was successfully completed in March 2011 showing unique reliability; no single HTM-induced firing interruption has been observed in 4004 integrated firing hours. The slightly faster degradation in the last part of the test is presumably due to a change of the surface morphology of the discharge channel after the dry abrasive cleaning process during the intermediate inspection after 2900 firing hours. Furthermore the standard cleaning procedure of the discharge channel during manufacturing at TEDG could not be conducted since the discharge channel was not removed from the thruster at the intermediate inspection. Both aspects may play an important role concerning the sticking of back-sputtered carbon from the test facility chamber walls.

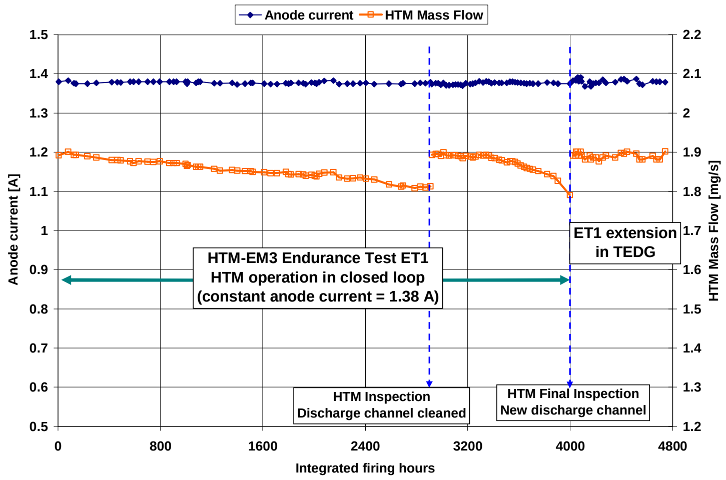

Figure 6. HTM mass flow evolution with firing time in Endurance Test 1 and ET1 extension.

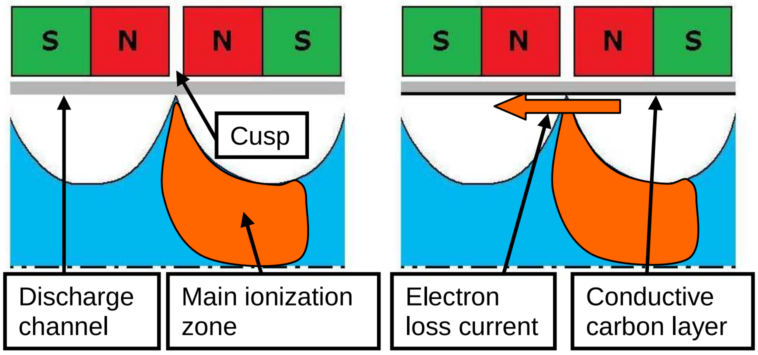

Figure 7. Schematic of thruster cusp region at BOL (left) and at the intermediate inspection (right).

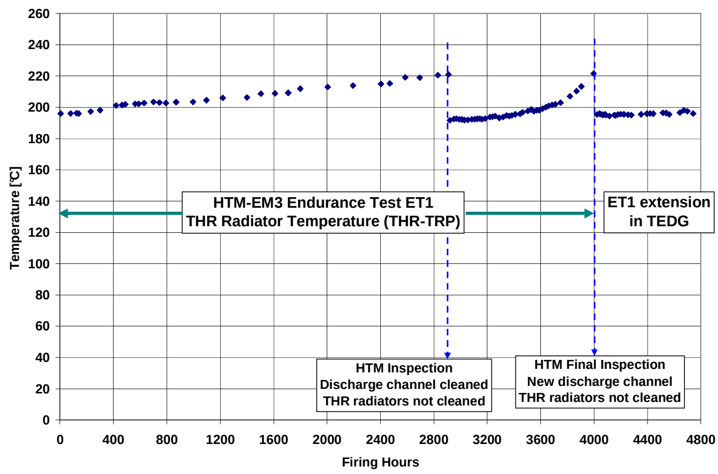

Figure 8. THR radiator temperature evolution with firing time in Endurance Test 1 and ET1 extension.

Though the HTM was mainly operated in continuous mode, 200 cycles with nominal start-up and shut-down operational sequences have been performed, with On-time durations ranging from 40 minutes to 2-3 days. Every ~500 hours the HTM was operated in pulsed mode; Figure 9 shows 6 firing pulses (40min On - 60min Off) @ SGEO working point performed immediately after the intermediate inspection at 2920 h. These SGEO nominal operational pulses demonstrate the HTM capability of pulsed operation with high performance repeatability; a total impulse variation of just 0.2% (3 sigma) has been calculated for these 6 consecutive pulses.

Stability of the ion current vector is considered to be an indicator of thrust vector stability. Characterization of ion current was performed by Aerospazio's personnel and with Aerospazio's diagnostics tools (Faraday Probes, see above). The current vector variation was within ±0.5° throughout the entire Endurance test.

Furthermore, the beam current vector stability was characterized during thruster warm-up (see Figure 10), under nominal chamber pressure, from the cooled state of the thruster (< 30°C). The current vector variation during thruster warm-up was within ±0.5° throughout the Endurance test. The current vector can migrate during the thruster warm-up until max 0.3° from the initial value, which is well within the requirement. One can also notice that the character of beam current variation during thruster warm-up changes over the Endurance test. This is believed to be due to the facility effects, when the graphite re-deposits onto the walls of thruster discharge channel. This graphite layer changes the properties of gas discharge. During the inspection the discharge channel was cleaned from the graphite layer, and after that the beam current comes to the initial values.

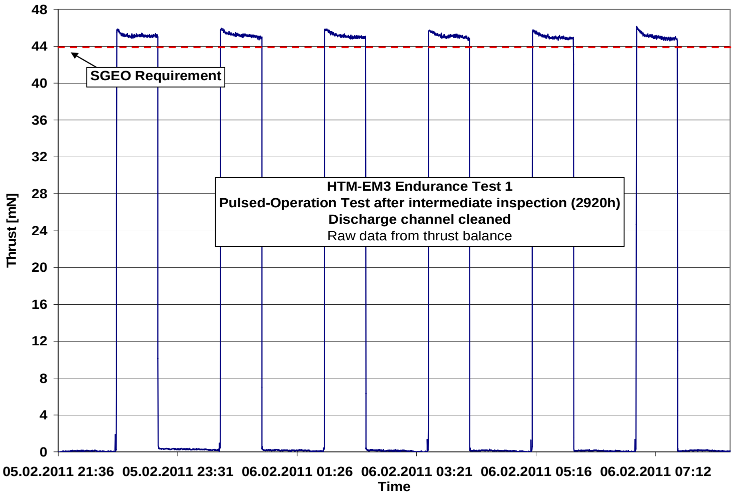

Figure 9. Pulsed-operation Test 7 after 2920 firing hours.

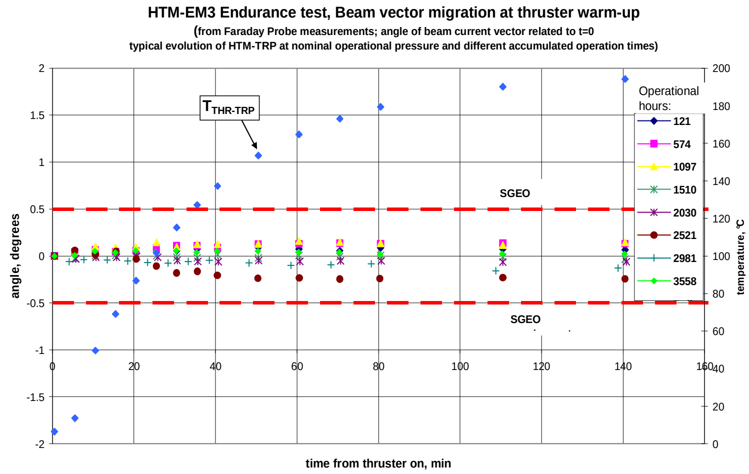

Figure 10. Beam current vector migration during thruster warm-up at different accumulated operation times during Endurance test

IV. Post-ET1 Investigation

A comprehensive post-test investigation has confirmed that the main reason for the performance degradation of the thruster during long-term operation in a graphite-lined test facility is the deposition of chamber wall material onto the surface of the discharge channel. In fact, a DPA analysis of the thruster discharge channel has revealed that carbon completely covers the surface of the discharge channel. A closer investigation of the main cusp region of the discharge channel (see Figure 7) showed that even this zone is entirely coated with carbon, as shown in Figure 11: The yellow coloring (cf. right panel of Figure 11) represents the carbon distribution of the cusp region measured by EDX. Although a less carbon coverage is found across the cusp zone it is still existent in a considerable concentration. Additionally, a resistivity of ~16 kOhm/cm was found across the cusp. This is a clear evidence for the formation of a conductive layer across the cusp region. Although this particular zone is the hottest spot of the discharge channel during thruster operation (~870 °C), carbon will not be re-evaporated as it sublimates at very high temperatures (~3600 °C). Furthermore, with increasing operational hours the layer thickness will also increase leading to further performance degradation. This behavior explains unambiguously the continuous deterioration of the thruster performance observed during ET1. The rationale given above is confirmed by showing that this effect can be ruled out by replacing the graphite coating of the vacuum chamber by another material exhibiting a melting (or sublimation) temperature below the maximum temperatures reached in the discharge channel. For this purpose, the ULAN test facility at TEDG has been coated with aluminum foil (the melting point of aluminum is at 660 °C). An additional thruster model has been operated in the aluminum-coated ULAN test facility. The design of this thruster is the same as for the thruster of HTM-EM3. During this test 770 firing hours were accumulated. The thruster performance remained stable as shown in Figure 13. The typical performance evolution of the same thruster operated in the carbon-coated ULAN test facility is also shown in the same graph for comparison; the massive

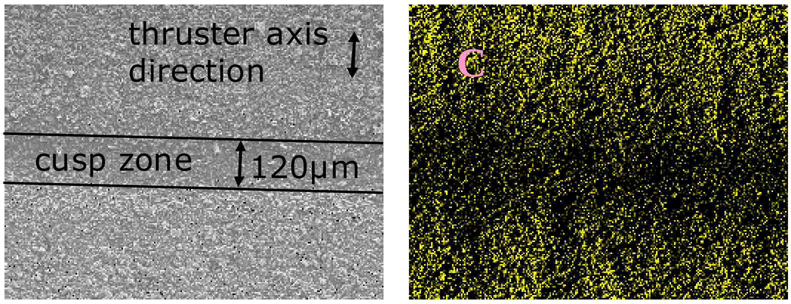

Figure 11. SEM image (left) and EDX mapping of carbon (right) in the cusp region of the thruster discharge channel after ET1.

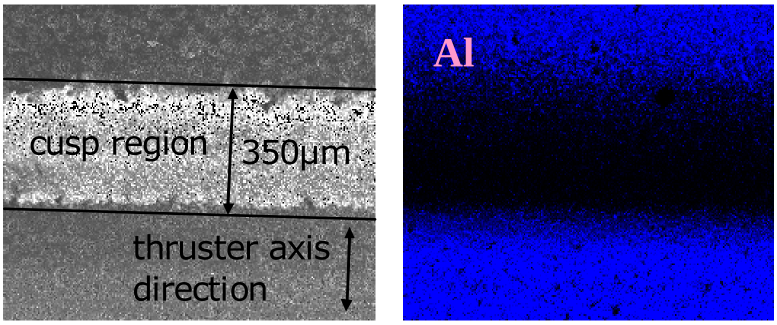

Figure 12. SEM image (left) and EDX mapping of aluminum (right) in the cusp region of the thruster discharge channel operated in the aluminum-coated ULAN test facility at TEDG

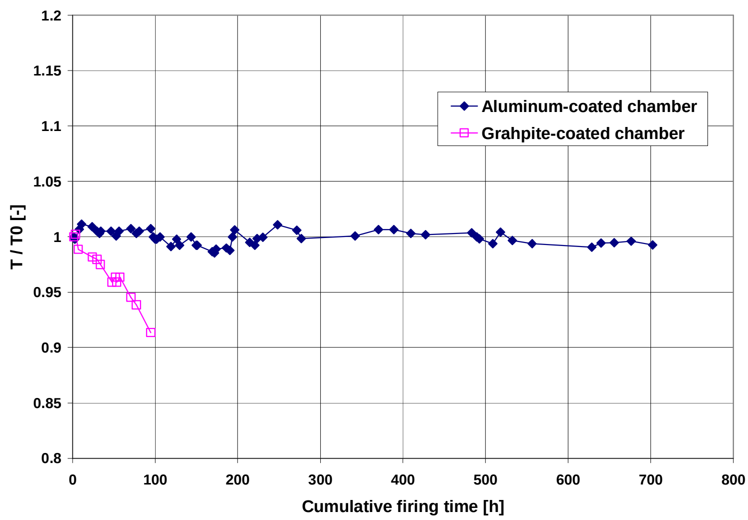

Figure 13. THR-EM5 thrust evolution with firing time as a function of chamber-wall material in the test facility ULAN at TEDG.

impact of the chamber wall coating on the thruster performance is clearly visible. In fact, the thrust degradation is much faster than in ET1 (see Figure 5) because the TEDG facility is much smaller than the Aerospazio facility, just 2.4 m diameter and 4.5 m length.

After testing the discharge channel of the thruster being operated in the aluminum coated ULAN test facility was also subjected to a DPA analysis (see Figure 12). An aluminum coating colored blue in the right panel of Figure 12 was found on nearly the whole discharge channel surface except in the cusp region. A more precise inspection of the cusp region showed that in this particular zone no aluminum was found whereas an aluminum coating was present on both sides of the cusp, as shown in Figure 12. Since this particular region represents the hottest zone of the discharge channel it is reasonable to conclude that aluminum vapor entering the cusp zone is re-evaporated immediately. Resistivity measurements delivered a value of >20GOhm/cm across the cusp; this gives additional evidence that no conductive layer across the cusp region is formed in a aluminum-coated test facility. The above findings clearly show that the chamber wall material significantly influences the thruster performance during long-term operation.

V. ET1 Extension at TEDG

After the post-ET1 inspection, the HTM-EM3 unit has been refurbished with a new discharge channel (same design used for ET1) and mounted in the ULAN Test Facility at TEDG, modified with the Aluminum coating. The goal of this ET1 extension was to add 800 hours of HTM operation to the ET1 integrated firing time, thus reaching the nominal SGEO lifetime requirement of 4800 hours with performance unaffected by the re-deposition of chamber material. Figures 5, 6 and 8 show that no significant degradation occurred in the additional 800 hours, thus confirming the findings of the post-ET1 investigation. Very stable performance of all components of the HTM has been observed, including the TEDG neutralizer (HCN 5000 Engineering Model). Figure 14 shows the cathode-to-ground coupling voltage, which gives an indication of the neutralizer capability to compensate the thruster ion current; this voltage showed "healthy" values between -14 and -12 V during the entire endurance test. Figure 15 shows the neutralizer keeper voltage peak value during the keeper discharge ignition transient. As expected, a small increase was observed after facility cryo-pumping system regeneration and facility venting, when the cathode is exposed to higher levels of Oxygen and water; however, the keeper ignition voltage always decreased to ~15 V after some operational hours, showing a "healthy" margin with respect to the PSCU Flight Model maximum voltage available for keeper ignition (37 V).

Table 1 lists the HTM-EM3 performance after 4800 integrated

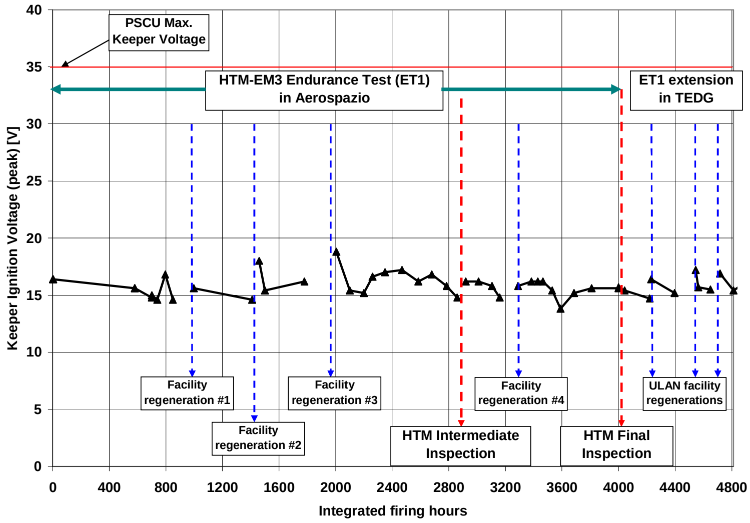

Figure 14. Cathode-to-ground coupling voltage evolution with firing time in Endurance Test 1 and ET1 extension.

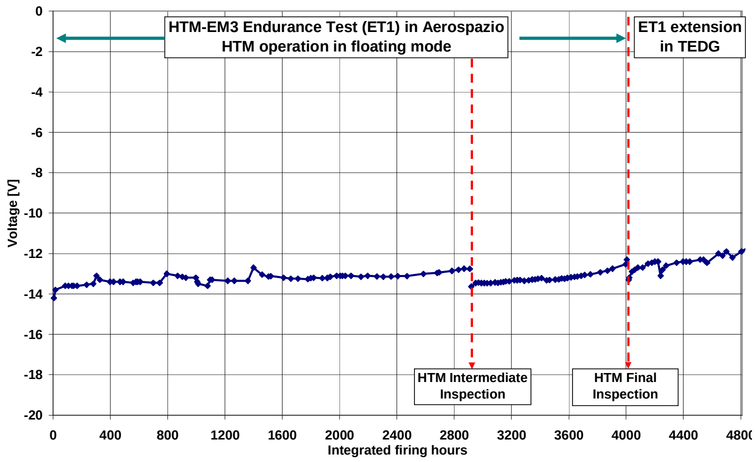

Figure 15. Keeper ignition voltage evolution with firing time in Endurance Test 1 and ET1 extension.

operational hours; the SGEO requirements on thrust level, specific impulse and power are verified, while the total impulse demonstrated (735 kNs) corresponds to 97% of the SGEO total impulse. This small discrepancy is due to the facility-induced thrust degradation observed in the Aerospazio graphite-coated facility; however, the ET1 extension will be soon continued, allowing HTM-EM3 to cumulate more total impulse.

Quantity/Unit	SGEO Req.	After 4800 firing hours (SGEO Lifetime)	Compl.
Thrust	**≥ 44 mN**	**44.5 mN**	**C**
Anode power	**≤ 1380 W**	**1380 W**	**C**
Keeper discharge nominal power	**≤ 42 W**	**16 W**	**C**
Keeper discharge ignition voltage	**≤ 35 V**	**15 V**	**C**
HTM specific impulse (including neutralizer)	**≥ 2300 s**	**2400 s**	**C**
Cathode-to-ground coupling voltage	**> -20 V**	**-12 V**	**C**
Total impulse demonstrated in ET1 + Extension	**760 kNs**	**735 kNs**	**C***

*test still ongoing

Table 1. Demonstrated performance after 4800 integrated firing hours

VI. Conclusion

Thales Electron Devices GmbH (TEDG) has performed an endurance test with an Engineering Model of the HEMPT Thruster Module (HTM) developed for the SmallGEO geo-stationary telecommunication satellite (SGEO). The test was started in the large LVTF-1 test facility at AEROSPAZIO Tecnologie s.r.l., Siena, Italy in August 2010; the HTM was mainly operated in continuous mode @ SGEO working point (44 mN with a thruster power of 1380W). The test was successfully completed in March 2011 cumulating 4000 operational hours with excellent long-term behavior and unique reliability; no single HTM-induced firing interruption has been observed. A thorough post-test investigation has shown that the thruster discharge channel was covered by a conductive carbon layer induced by back-sputtered graphite from chamber walls; this facility-effect is preventing flight-representative thruster performance in long-term testing. Hence, ET1 has been restarted in the ULAN test facility at TEDG, modified with a chamber wall material having sufficiently high vapor pressure (Aluminum) to re-evaporate from the main cusp region of the thruster discharge channel, thus preventing the formation of a continuous conductive layer. This allowed reaching the nominal SGEO lifetime (4800 hours) with very stable performance of all components of the HTM; the SGEO requirements on thrust level, specific impulse and power are verified, while the total impulse demonstrated (735 kNs) corresponds to 97% of the SGEO total impulse. These results give high confidence in the HEMPT Thruster Assembly (HTA) lifetime qualification still to be performed.

Next steps are the continuation of ET1 test in the Aluminum-coated TEDG facility in order to further confirm the high HTM performance stability with time, and the setting-up of the HTA lifetime test in the Aerospazio facility, which is presently under refurbishment with the installation of a suitable Aluminum coating.

Acknowledgments

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