Verification of a Flow Control Unit with Gas Purifier and Integration into the HEMP Thruster Module

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Abstract: Thales Electronic Systems GmbH has developed, manufactured and currently qualifies a novel electric propulsion system for the SmallGEO Hispasat AG1 mission. The key components of this system are the High Efficiency Multistage Plasma Thruster HEMPT 3050 and the Hollow Cathode Neutralizer HCN 5000. Both components require Xenon but with different needs. The thruster requires mainly a precise flow control since the provided thrust is directly proportional to the Xenon flow. On the other hand, the neutralizer is insensitive to a certain flow variance, but requires ultra-pure Xenon, with remaining impurities in the ppb-range, in order to operate in a healthy mode. These needs are satisfied by the Flow Control Unit (FCU) which comprises a proportional flow control valve in the thruster flow branch and a gas purifier combined with a flow restrictor in the neutralizer flow branch. It became clear that the successful verification of sufficient purifier getter capability, from first integration into FCU up to electric propulsion sub-system testing on spacecraft, is of vital importance to customers. Since the getter has no own indication about the capacity status, a purification performance measurement is performed. Argon tracer gas with 1.4 ppm oxygen volume content is fed to the system and impurities at the outlet are monitored. On FCU level, the low flow of the neutralizer branch complicates this measurement and on HEMP Thruster Module (HTM) level, the fact that no fluidic outlet interface except for thruster gas exit and hollow cathode exit exists poses additional challenge. This paper documents the FCU performance verification methods used at Thales and describes the integration process of the FCU into the HTM. The developed method for good health testing of the gas purifier on FCU and on HTM-level including equipment description, will be presented.

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Nomenclature

FCU = Flow Control Unit
FR = Flow Restrictor
GP = Gas Purifier
HCN = Hollow Cathode Neutralizer
HEMPT = High Efficiency Multistage Plasma Thruster
HFS = HEMP Functional Simulator for FCU
HTM = HEMP Thruster Module
IV = Isolation Valve
PFCV = Proportional Flow Control Valve
TES = Thales Electronic Systems GmbH

I. Introduction

Thales Electronic Systems GmbH has started the development of a new ion thruster concept, the so-called High Efficiency Multistage Plasma Thruster HEMPT since about a decade ago. In the following years, TES has successfully mastered the breadboard model phase for the HEMPT technology. The obtained operational and performance characteristics of both thruster and neutralizer and their compatibility with existing space power supply technology have shown the possibility to set up an ion propulsion system based on HEMPT 3050 and HCN 5000 which exhibits a high level of reliability and unique cost-efficiency[1]. In consequence, TES has initiated the development of a complete ion propulsion subsystem, the so-called HEMPT Assembly. The first assignment of the HEMPT Assembly is on OHB's SmallGeo platform for the commercial Hispasat AG1 mission.

This paper presents the basic architecture of the FCU for the HEMP Thruster Module as well as a short description of the Module and the PSCU in Chapter II. Chapter III is dedicated to the verification of the FCU and describes the sequence used for acceptance testing of these units. In Chapter IV the method for integration of the FCU into the Thruster Module is presented. The verification methodology for gas purifier health check on unit and module is given in Chapter V and Chapter VI, respectively. Finally in Chapter VII, the results are summarized.

II. HEMP Thruster Module 3050 & PSCU

Each of the four HEMP Thruster Modules (HTM) for the SmallGeo HAG1 electric propulsion system consist of a thruster of type HEMPT 3050, a neutralizer of type HCN 5000 and a Xenon propellant Flow Control Unit (FCU). All module components are integrated on a mechanical mounting structure which also represents the thermal and mechanical interface to the spacecraft. This compact modular design allows for a low handling complexity during test and verification and for easy integration into the satellite. Photography of a HEMPT Module is given in Figure 1. On the rear side of the HEMPT Module, the FCU and all electrical interfaces are mounted. This provides defined thermal conditions for heat sensitive components such as valve seals and coils and cable insulations.

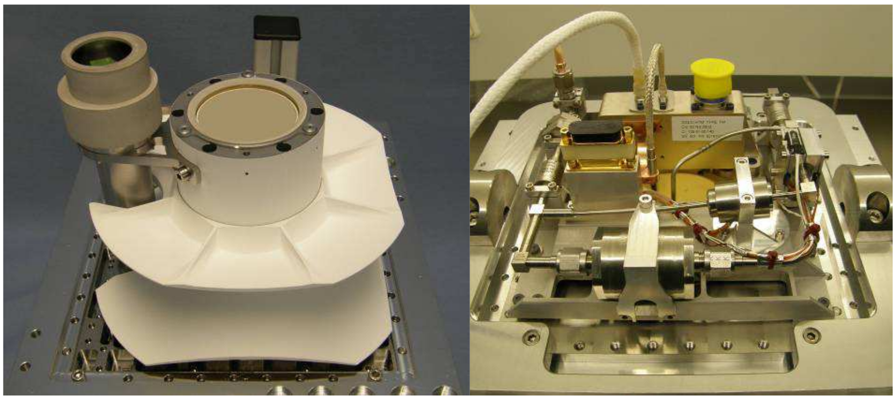


Figure 1. Photography HTM FM1.
Left: front side; right: rear side.

The power for the four HEMPT Modules is provided by the Power Supply and Control Unit (PSCU). Its input power to each HEMPT Module is about 1440W. This power is distributed mainly to the thruster but the neutralizer and the FCU are also supplied by it.

A. HEMPT 3050

The HEMPT 3050 has a nominal input power to the anode of 1500 W at 1000 V and provides a thrust of 50 mN at a specific impulse of 3000 s. For SmallGEO HAG1, the input power is limited to 1380 W resulting in a thrust level of up to 45 mN at an anode specific impulse in excess of 2800 s.[1] For stable thrust operation, the thruster requires mainly a precise flow control since the provided thrust is directly proportional to the Xenon flow. The typical thrust stability of 1% is achieved already one minute after thruster ignition.[3]

Details on the HEMPT concept and on general operational and performance characteristics are reviewed, e.g., in [4] and [5].

B. HCN 5000

The neutralizer prevents electrical charging of the satellite by compensation of the positive ion current with an equal negative electron current. The HCN 5000 is a hollow cathode dispenser neutralizer with maximum current capability of 5000 mA. For the emissive cathode material a barium impregnated tungsten-osmium sintered body with work function of 1.98 eV is used.[7] Nominal operation of the hollow cathode neutralizer in a healthy range is at EP-ground-to-facility-ground voltage (i.e. the so-called coupling voltage) of -14 V to -12 V.[3] As a matter of fact, the coupling voltage is dependent on Xenon flow rate and its purity. Typically, the coupling voltage increases with increasing Xenon flow rate.

Several measurement campaigns already concluded that the hollow cathode neutralizer can cope with certain mass flow variance as long as a minimum mass flow is kept. These measurements have been performed with ultra-pure Xenon, fed through a gas purifier with purification capability to the low ppb-levels for oxygen and moisture. It is for this reason that the neutralizer branch of each FCU is outfitted with a gas purifier in order to provide the required gas purity to the cathode.

Details on the HCN concept and on general operational and performance characteristics can be found in [3].

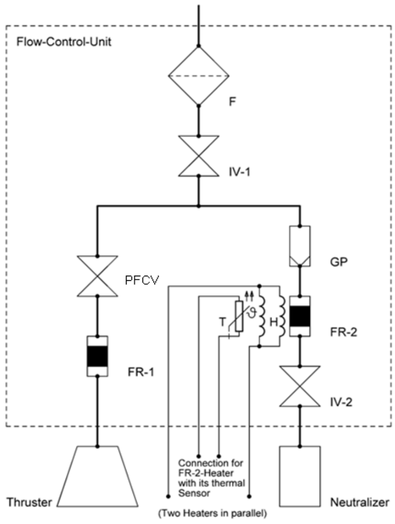
C. Flow Control Unit

The Flow Control Unit (FCU) of the HEMPT 3050 Module has been developed and manufactured by MOOG Bradford in the Netherlands. Each FCU supplies one HEMPT 3050 and one HCN 5000 Neutralizer with Xenon. The design and architecture of the FCU follows strictly the overall chosen concept of high cost efficiency which is achieved by usage of off-the-shelf components which are already space qualified. The tubing used for connecting the components is 1/4” or 1/8” stainless steel tubing.

The architecture of the FCU is shown on Figure 2.

The fluidic inlet of the FCU features a screwed fitting conform to AS-4395-4, which is a well-known space standard for connecting gas tubes. This flared fitting connection incorporates a single use copper gasket and has impressive flight heritage since the early 1960. This screwed connection has been preferred to welded joints since it fits better to the concept of an easily mountable and compact module.

The gas flow is filtered by a particle filter with 2 micrometer rating which protects the downstream components from pollution. The FCU can be completely isolated by the nominally-closed inlet isolation valve (IV1). The tubing splits then into thruster line and into neutralizer line. Both lines can be controlled independently by operation of proportional flow control valve (PFCV) in the thruster line and/or outlet isolation valve (IV2) in the neutralizer line.



F	**Filter**
PFCV	**Proportional Flow Control Valve (normally closed)**
FR	**Flow Restrictor**
GP	**Gas Purifier**
IV	**Isolation Valves (normally closed)**
T	**Temperature Sensor**
H	**Heater (consists of two heaters in parallel)**

Figure 2. Architecture of FCU.

Gas throughput to the thruster is mainly restricted by the flow restrictor (FR1). The usage of the FR1 downstream of PFCV optimizes the stability of the thruster line control loop. The required inlet pressure to FR1 is controlled by closing the control loop using the PFCV and the HEMP thruster anode current.

The neutralizer line is outfitted with a xenon gas purifier (GP). The gas purifier is able to remove the following impurities (to output levels below 1 part-per-billion volume content) from the gas flow: oxygen, water, carbonic oxides, non-methane hydrocarbons and hydrogen. A heater is included to maintain both flow restrictors (FR1 and FR2) within a defined temperature range (85 °C to 90 °C) in order to prevent mass flow variation to the neutralizer due to large FCU temperature differences. The temperature of the flow restrictor block is monitored by the PSCU by means of a dedicated Pt1000 temperature sensor.

The aluminum FCU support structure is mounted to the Module's mounting plate by 12 bolts of the type M4 TiAl6V4 coated with molybdenum disulfide. Special attention has been given to the thermal design of the FCU, since one side, beneath IV2 and the flow restrictors, is mounted with good thermal conductivity while the other side is thermally decoupled from the rest of the Module by means of PEEK spacers. As a result, the FCU benefits from the thermally well controlled side of the Modules interface which is located close to one of the spacecraft's radiator.

The 3D-Model of the FCU is shown on Figure 3.

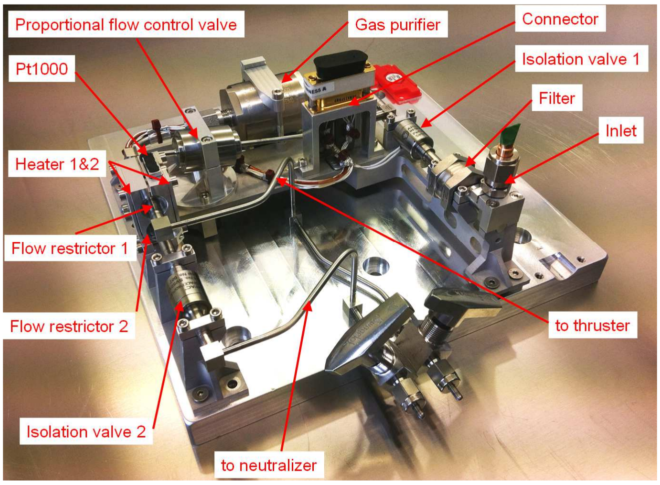


Figure 3. Photography of the FCU.

D. Power Supply and Control Unit

The anode current measurement unit as well as the closed loop regulator, which controls the FCU throughput to the thruster, is located within the PSCU. To eliminate ripple on the feedback signal it is low pass filtered prior to the actual measurement. The control loop for the FCU is closed in the PSCU by an analogue PID regulator whereas temperature control of the FCU's flow restrictor block is done by a simple proportional controller. FCU valves drivers are also located within the PSCU.

Details on the PSCU architecture as well as general operational and performance characteristics can be found in [6].

III. Verification of Flow Control Unit performance

Purpose of the verification is to confirm the conformity of the FCU with its functional performance specifications and requirements and identify discrepancies. Typically, the control loop for the required gas flow is an integral part of the propellant feed system. The feedback signal is then coming from a pressure or mass flow sensor. On the HEMP Thruster Assembly, the control loop for actuation of the FCU proportional valve is implemented in the PSCU. As feedback signal, the HTM thruster anode current, measured by the PSCU is used. On one hand, this reduces the complexity of the system since no additional sensing component within the FCU is required, but on the other hand, the management of the interfaces and the separation of responsibilities increases effort on system engineering side. As a result, the demonstration of functional performance and environmental compatibility on FCU level is difficult, since HTM and PSCU are required for the verification of the control loop. However, early risk mitigation by verification on FCU level would significantly reduce cost and schedule impacts in case of discrepancies related to the control loop and FCU performance. It is for this reason that great effort was placed on the development of adequate simulator hardware and procedures in an effort to perform a detailed acceptance test program already on FCU level at the supplier.

Consequently all relevant compatibility aspects of all 8 FCUs could be successfully verified at an early state.

E. Acceptance testing at the supplier

The acceptance test campaign at the FCU supplier consists of the following individual test steps at acceptance level and duration:

- Visual inspection and physical properties test
- Isolation and resistance test
- Leak test
- Proof pressure test
- Leak test
- Functional test
- Mechanical environmental test

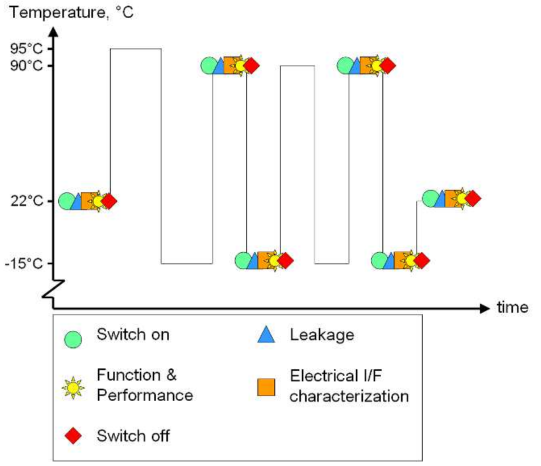


Figure 4. Thermal vaccum cycling temperature profile.

- Thermal vacuum test incl. functional tests and leak tests at 3 different temperatures
- Cleanliness test

The thermal vacuum cycling temperature profile at acceptance level is shown in Figure 4.

F. Incoming inspection at TES

Typically the first step after receipt of the FCU from the supplier is the incoming inspection. The purpose of this inspection is to verify that the unit has survived the transportation process without damage. This is done by repetition of the following critical tests which have been performed by the supplier before: visual inspection, isolation & resistance test, and functional test.

1. Visual inspection

The FCU is verified to comply with its approved configuration drawing. Then, the hardware is checked for visible damage.

2. Isolation & resistance test

The isolation resistance measurements are performed for all components at 250 V DC. In a second step, the resistance of all components is measured.

3. Functional test

In order to being able to easily verify the FCUs' environmental compatibility, the HEMP functional simulator for FCU (HFS) has been developed and its performance has been verified by TES. The HFS consists of an electrical part and a fluidic part.

The fluidic part of the HFS has two gas inlets and one common outlet. The two separate branches are for parallel checkout of FCU's Thruster and Neutralizer line. Each branch features the key components: a flow restrictor and a differential pressure sensor monitoring the pressure drop over the flow restrictor. The high pressure side upstream of the flow restrictors has a 1/8" tubing welded design. The low pressure part downstream of the flow restrictors (1/4" tubing with Swagelok couplings) is connected to a single outlet port which is connected to a vacuum pump during operation.

The electronic part of the HFS is accommodated in a 19" single slot for standard rack installation. The electronics is used to directly control the FCU with the integrated valve and heater driver stages while the HFS signals, e.g. pressure sensor voltage, are monitored and evaluated. The control features include a manual mode for operation of FCU valves and heaters, open loop operation of FCU, operation of HTA representative closed loop operation of the FCU with voltage signal from the fluidic part of the HFS as feedback signal. Data logging and operation of the HFS is performed by RS422 protocol via USB connection between the electronic part of the HFS and a standard PC.

The correlation between HFS voltage signal of pressure sensor and Xenon mass flow through the flow restrictors has been empirically determined by comparison to a mass flow measurement method with calibrated equipment. The resulting calibration curve of the HFS is given in Figure 6.

Figure 5. Photography of HEMP functional simulator for FCU.

Left: fluidic part; right: electronic part.

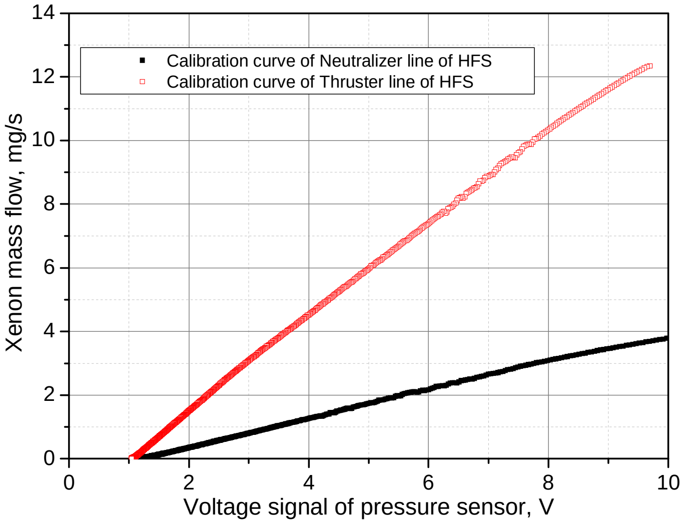


Figure 6. Calibration curve for HFS.

IV. Integration of FCU into HEMP Thruster Module

The integration of the FCU consists of the following activities:

1. Potting of FCU to HEMPT Module incl. mounting of interface bolts
2. Welding of Thruster line and Neutralizer line tubing
3. Installation of grounding strap

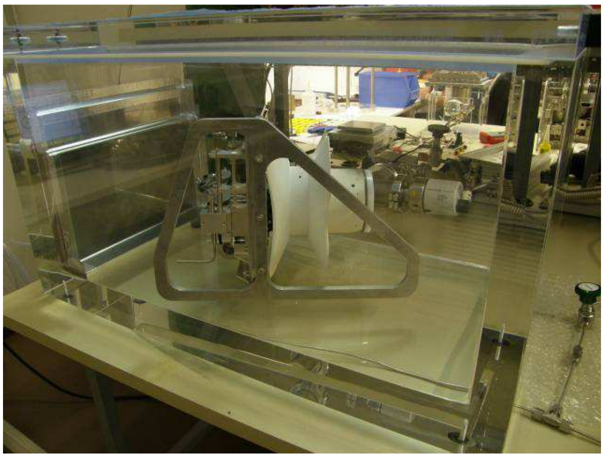


Figure 7. Photography of acrylic box for FCU integration welding process

The second activity posed a certain challenge which needed to be coped with. A standard tube welding process with an orbital TIG welding machine requires an inert gas atmosphere outside and inside of the tube's weld location. While the shielding gas outside of the tube is generated by the welding head itself, the inert atmosphere at the inside is typically ensured by applying the forming gas which flows through the tubing at a certain forming pressure. In our case, the FCU's flow restrictors restrict the gas flow too much to be able to apply sufficient forming gas for inertization. Furthermore, the forming gas would inflate the weld pool and could generate welds unacceptable against the applicable welding standard DIN 29595, indicating that the weld process or its parameters are not stable.

In order to circumvent this effect and simultaneously ensure process stability, TES has developed an alternative method to apply inert gas to the internal tubing. A vacuum-tight box made from acrylic glass, which accommodates the complete module, is used to provide the required inert atmosphere inside of the tubing. In a first step, the box is inertized and in a second step, the lid of the box is removed for the final welding step. Since the forming pressure equals atmospheric pressure in this case, a specific welding schedule has been developed for this qualified process.

V. Verification of gas purifier good health on FCU level

Since pure gas, with impurities less than Xenon grade 4.0 normally offers, is required to ensure HCN 5000 cathode lifetime, the gas purifier is a critical component of the HEMPT Module. As consequence, providing proof that the gas purifier is able to fulfill the specified lifetime requirements is inevitable. In order to satisfy this need, TES has developed a good health test for verification of sufficient remaining gas purifier capacity to fulfill HAG1 lifetime requirements. This test is performed by TES on each FCU after incoming inspection and prior to integration into HTM.

G. Measurement methodology

The FCU gas purifier good health test is based on the measurement of the oxygen concentration at the gas outlet of the FCU while a tracer gas, in this case Argon, with known oxygen contamination (1.38 ppm oxygen concentration) is fed through the FCU at 5 bar inlet pressure.

In a second test step, the background oxygen concentration is measured by feeding pure Argon gas to the FCU. This is achieved by an additional gas purifier in test set-up that removes the oxygen from the tracer gas such that only highly-purified gas is fed to the FCU. The background oxygen concentration is typically in the range of some ppm, dependent on the leak tightness of the tubing including FCU under test

The difference of both oxygen concentration measurements

$$\Delta\varphi = \varphi(O_2\, meas, tracer\ gas) - \varphi(O_2\, meas,\ purified\ gas) \tag{1}$$

allows to determine the good health of the gas purifier.

In case of a fully functional FCU gas purifier, the difference between both readings $\Delta\varphi$ is within measurement tolerance. On the other hand, a completely saturated FCU gas purifier without getter function can be identified by a $\Delta\varphi$ of about 1.38 ppm.

It is for this reason that the following pass criterion for the good health test has been defined: $\Delta\varphi \leq \pm 0.3$ ppm.

H. Oxygen concentration measurement device & operating principle

The device used for measurement of the oxygen concentration is a MICHELL XZR series oxygen analyzer (XZR-400-RM-220) which operates on the zirconium oxide principle. The zirconium oxide sensors are often referred as the 'high temperature' electrochemical sensors. The principle is based on the Nernst principle [W. H. Nernst (1864-1941)].

The measured gas is routed to the inlet port of the analyzer and flows through a 1/8" stainless steel tube into the oven where the zirconia oxygen sensor is located. The gas circulates in the oven, which is heated to temperatures above 600°C, in this case 634 °C, necessary for the zirconia oxygen sensor to operate properly. The sensor generates a signal that is proportional to the logarithm of the ratio of the oxygen concentration in the sample to the oxygen concentration contained on the sealed reference side of the sensor. This generated signal is also dependant on the sample flow rate. For different flow rates, the corresponding calibration factors need to be taken into account. Within the oven, the gas is heated to a temperature at which the zirconium oxide sensor is maintained. The sensor generates a voltage signal that is proportional to the natural logarithm of the oxygen concentration $\varphi(O_2)$.

$$U = \frac{RT}{4F} \ln \frac{\varphi(O_2 ref)}{\varphi(O_2 meas)} \tag{2}$$

R is the universal gas constant: $R = 8.314462\ J \cdot K^{-1} \cdot mol^{-1}$
F is the Faraday constant, the number of coulombs per mole of electrons: $F = 9.64853399 \cdot 10^4\ C \cdot mol^{-1}$
U is the voltage signal generated by the sensor in V

With a known reference electrode and a constant temperature it is possible to define the oxygen concentration using the Nernst-equation given in Equation (2).

I. Calibration factors for oxygen analyzer measurement

Since the generated signal at the sensor is dependant on sample flow rate, a calibration factor for the FCU gas flow (given in Table 1) has been determined empirically. According to Equation (2), the oxygen concentration is

$$\varphi(O_2 meas) = K_1 \cdot e^{K_2 \cdot U} \tag{3}$$

with the factors given in Table 1.

Calibration factor	Equipment / instrument	Value (determined empirically)
$K_1 = -\frac{4F}{RT}$	HTM neutralizer line gas flow calibration factor for Argon with 5 bar_a inlet pressure	65.0
$K_2 = \varphi(O_2 ref)$	MSRS reference concentration	11598

Table 1. Calibration factors for oxygen analyzer measurement.

VI. Verification of gas purifier good health on HTM level

The gas purifier good health verification test is performed on all HTM QMs and FMs. The methodology of the HTM level test is equal to the previously described method on FCU level. The main difference to the FCU level test is that the HTM has no typical fluidic interface like a coupling at the gas outlet. So the gas has to be taken directly from the Neutralizer's hollow cathode orifice bore for the gas purity analysis. As a consequence, the Neutralizer fluidic port adapter assembly has been designed to allow connecting with tubing directly to the cathode bore.

The adapter design comprises two interfaces to the Neutralizer. The first interface attaches to the hollow cathode front disk. An o-ring seal isolates the inner gas path (analysis path) from the surrounding volume. The achievable leak rate of this seal is in the order of $1 \cdot 10^{-5}$ mbar·l/s Helium. The second interface attaches to the Keeper electrode by a second o-ring that generates a toroidal volume around the first interface. This second volume is continuously flushed with grade 5.0 Nitrogen during the measurement in an effort to establish a further isolation barrier.

This method separates the inner gas path sufficiently from the surrounding ambient atmosphere such that the purity measurement – in the range of ppm – can be performed. The leak rate of this assembly is in the order of $1 \cdot 10^{-7}$ mbar·l/s Helium.

The complete adapter assembly is clamped from the rear side to the bottom of the HTM Neutralizer mounting flange, as shown in Figure 8.

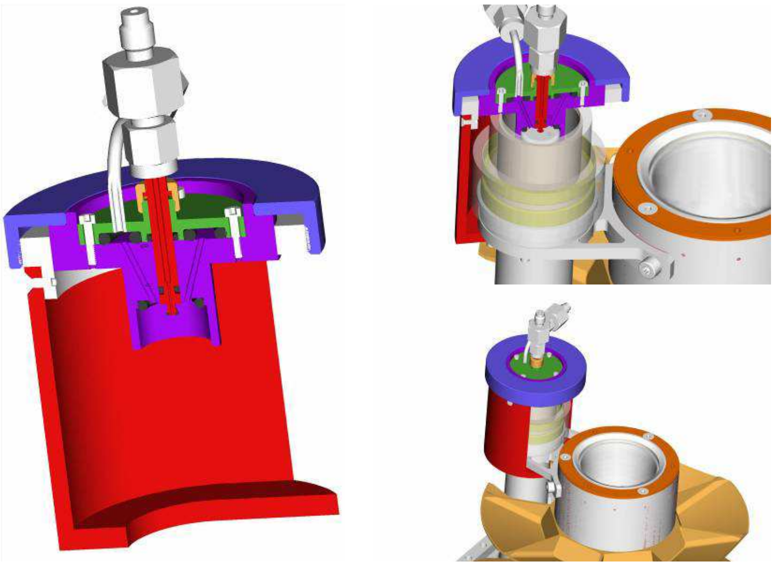


Figure 8. 3D-model of Neutralizer fluidic port adapter assembly. *Left: cross section of adapter; right: adapter mounted to HEMPT Module.*

During the performed tests, the background oxygen concentration was typically in the range of some ppm, dependent on the leak tightness of the tubing including HTM under test and Neutralizer fluidic port adapter assembly. This offset is sufficiently low such that the good health of the gas purifier can be determined on HTM level.

J. Results of gas purifier good health check on HTM level

The results of the gas purifier good health check as performed on HTM-QM1, HTM-FM1, and HTM-FM2 are summarized in Table 2.

GP good health test	φ_1(O_2meas, tracer gas) [ppm]	φ_2(O_2meas, purified gas) [ppm]	$\Delta\varphi_{measured}$ [ppm]	Requirement [ppm]	Compliance
HTM-QM1	6.75	6.52	0.23	< 0.3	**C**
HTM-FM1	9.66	9.60	0.06	< 0.3	**C**
HTM-FM2	8.14	8.14	0.00	< 0.3	**C**

Table 2. Summary of gas purifier good health test results of HTM-QM1, HTM-FM1 & HTM-FM2

Next to the simple assessment of the difference between the two measurement points φ1 and φ2, the evolution of the measured oxygen concentration during the test provides further information. Figure 9 shows the measured oxygen concentration while the gas input is switched between tracer gas and pre-purified gas.

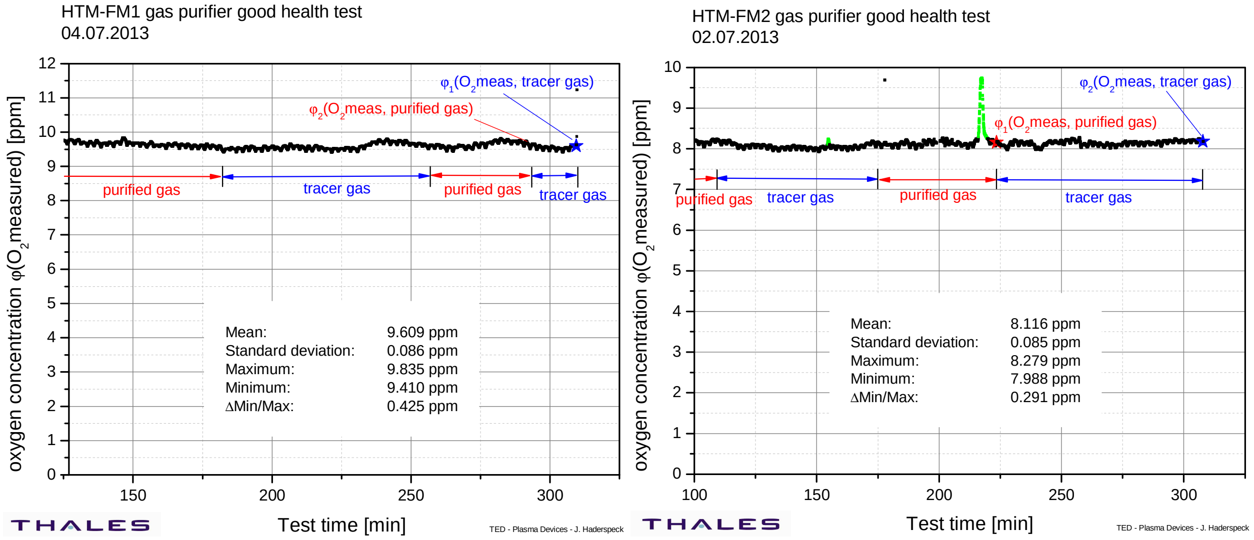


Figure 9. Evolution of the measured oxygen concentration at HTM outlet with tracer and pre-purified gas. *Left: HTM-FM1 results; right: HTM-FM2 results.*

The two green peaks at minutes 155 and 220, in the right side of Figure 9, are the result of insufficient nitrogen flushing of the neutralizer fluidic test adapter. A failed Teflon seal at the gas bottle made it necessary to deactivate the nitrogen supply for a short period of time. The original oxygen concentration reading could be brought back after the Teflon seal was exchanged and the nitrogen flushing restored. It is for this reason that these peaks are classified as minor anomalies caused by a facility effect. The abnormal data was not included in the statistics analysis.

In summary, there is virtually no difference, between impure and pure gas fed to the HEMPT Module, at the Modules' outlet measurable. Therefore, one can conclude that the gas purifier within the HTMs are sufficiently gettering the impurities from the tracer gas.

VII. Conclusion

TES has successfully verified the relevant compatibility aspects of all FCUs for the SmallGEO Hispasat AG1 mission. The developed methodology for the gas purifier good health test on FCU level and on HEMP Thruster level was successfully used on the complete FCU family and additionally on 3 Thruster Modules so far

Next steps are firstly to complete the conformity test of the remaining HEMP Thruster Modules with their functional performance specifications and requirements. Furthermore, the presented gas purifier good health check methodology will be developed further in an effort to produce a procedure for checking the remaining gas purifier capacity even with the HEMP Thruster Modules integrated to the spacecraft.

Acknowledgments

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References

[1] N. Koch et al.; Development, Qualification and Delivery Status of the HEMPT based Ion Propulsion System for SmallGEO; Proceedings of the 32nd International Electric Propulsion Conference, IEPC-2011-148.

[2] S. Weis et al.; Architecture, Functional Features and Operational Characteristics of the HEMPT based Ion Propulsion System for SmallGEO IEPC-2011-223.

[3] M. Schirra et al.; Mixed Metal based Hollow Cathode Neutralizer Technology for HEMPT based Ion Propulsion Systems; Proceedings of the 32nd International Electric Propulsion Conference, IEPC-2011-216.

[4] N. Koch, H.P. Harmann, G. Kornfeld; Status of the Thales High Efficiency Multi Stage Plasma Thruster Development for HEMP-T 3050 and HEMP-T 30250, Proceedings of the 30th International Electric Propulsion Conference, Florence 2007, IEPC-2007-110 (2007).

[5] N. Koch et al.; The HEMPT Concept – A survey on Theoretical Considerations and Experimental Evidences; Proceedings of the 32nd International Electric Propulsion Conference, IEPC-2011-236.

[6] R. Braeg, F. Herty, W.Lenz, N. Wagner; The Power Supply and Control Unit for the HEMP Thruster, IEPC-2013-134, 33rd International Electric Propulsion Conference, Washington D.C. 2013.

[7] B. van Reijen et al.; Environmental and Operational Qualification of the THALES Mixed Metal Hollow Cathode Neutralizer for the HEMP-T based Ion Propulsion System, IEPC-2013-282, 33rd International Electric Propulsion Conference, Washington D.C. 2013.