Environmental and Operational Qualification of the THALES Mixed Metal Hollow Cathode Neutralizer for the HEMP-T based Ion Propulsion System

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Abstract: The Thales HCN5000 neutralizer for ion propulsion systems has a Barium impregnated hollow dispenser cathode, which are known to be sensitive to poisoning effects. During the manufacturing, assembly, integration and testing phase the unprotected cathode is exposed to humidity in laboratory/clean room conditions, as well as during long delays within the launcher fairing on the launch pad. In order to show that the Thales hollow cathode can cope and recover from such extensive exposure a storage qualification test was performed on four HCN5000. Although an additional initial facility induced poisoning effect caused degradation of these neutralizers, all of them recovered after an upgrade of the gas feed line system. All four neutralizers passed the storage qualification on showed healthy operating parameters at very low cathode temperatures. A consecutive 1300 cycle test showed stable neutralization operation with healthy keeper and coupling voltages and low cathode temperatures under absolute worst-case conditions, covering the 3-year in-orbit verification phase for the SGEO HAG1 mission. Parallel accelerated life time testing is possible due to the nature of the mixed metal matrix of the Thales hollow cathode and has already proven 70khours of operation.

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I. Introduction

Thales is the world leader for space bound travelling wave tubes (TWT). Flight experience of over 500 million accumulated operational hours in space creates unique know-how regarding space qualified processes and TWT components, specifically of the applied cathode technology.

As a spin-off of the TWT technology Thales began the development of the HEMP-T ion thruster based upon the mirror-cusp magnetic field topology. A key component of any electric propulsion system (EPS) is the neutralizer. The purpose of a neutralizer is to start the plasma discharge within the electric thruster and provide a neutralizing current to the ion beam in order to prevent the satellite from charging itself negatively. In course of the HEMP-T development and in-orbit verification program HEMP-TIS it was chosen to develop and qualify such a neutralizer based upon the TWT cathodes.

The Thales hollow cathode neutralizer HCN5000 contains a cathode made of a Barium-Calcium-Aluminate impregnated mixed metal matrix. Barium impregnated dispenser cathodes are known to be sensitive to oxygen, during operation, and water during atmospheric conditions when left unprotected due to the reaction where Barium reacts with water to form different types of Barium hydroxides.

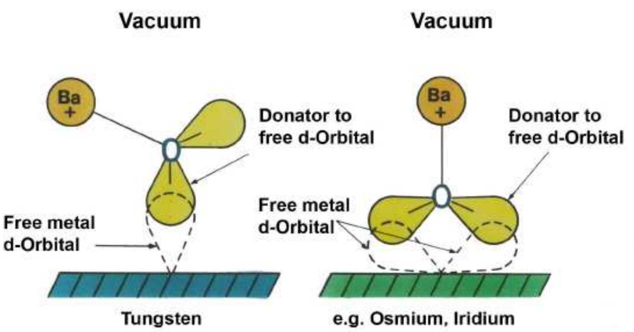
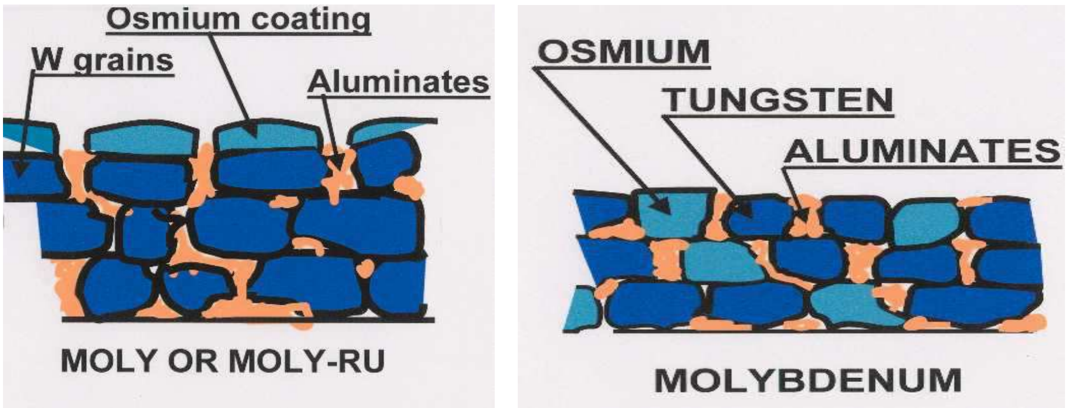


Figure 1. Orientation of a BaO molecule on a cathode surface

Nominally Barium evaporation during the heating phase of the neutralizer causes a monolayer of Barium to form on the surface of the cathode, which in turn forms a Barium-Oxide molecule, oriented such to minimize the work function, see Fig. 1. The introduction of water contaminants results in the reaction towards Barium hydroxide; this greatly affects the surface properties and prevents migrating Barium from wetting the complete surface, thus increasing the work function. This increase leads, by constant current emission, to an increase in the cathode temperature and thus to a reduction of the cathode life.

During the manufacturing, assembly, integration and testing (MAIT) phase it is unavoidable that the cathode will be exposed to air and therefore the cathode/neutralizer design must be robust enough to withstand the humidity exposures expected during this phase. This paper describes the qualification method and results of the work that was performed in course of the HEMP-TIS program to verify that the HCN5000 is able to cope with and recover from extended humidity exposure during worst-case conditions, such as a delayed sea launch and still retain the required functionality and expected life. During the storage qualification a facility induced poisoning effect was discovered, causing neutralizer degradation. Corrective action on the gas feed system proved the recoverability of the Thales cathode.



a) **b)**

Figure 2. a) M-Type cathode with Osmium coating b) MM-Type cathode with Osmium mixed into the metal matrix

II. Layout of the HCN5000

The HCN5000 consists of a barium impregnated hollow dispenser cathode where the Barium-,Calcium, -Aluminate is impregnated into a porous Tungsten-Osmium mixed metal matrix: the MM-type cathode with a work function of 1.98eV. The difference of such an MM-type cathode with respect to an M-type cathode is in the Osmium layer, which in case of the M-type cathode covers only the outer layer of the cathode, whereas in the MM-type cathode the Osmium is part of the porous matrix, see Fig. 2. The Osmium addition compared to a pure Tungsten cathode is a reduction of the work function by 0.1eV, or an effective temperature decrease of 50K and a lifetime extension by a factor of 3.3[1].

Key geometric feature of the cathode is the emissive front disc with an orifice bore, which lowers the keeper ignition voltage and the coupling voltage between cathode and ground, see Fig. 3. The cathode hollow cylinder and front disc are manufactured from a single pellet and form a combined Barium reservoir. A heater wire, embedded in a ceramic, is brazed to the rear side of the cathode and is able to heat the cathode up to the required temperature where the keeper discharge can be ignited. Precise thermal insulation of heater and cathode assembly reduces thermally losses and lowers the thermal gradient over the neutralizer components. The Xenon gas for the keeper plasma discharge, which is ignited and sustained between the keeper electrode and the cathode emissive insert, is fed from the rear side of the cathode through a thermal and electrically isolating feed line assembly. The complete neutralizer assembly is highly compact and weighs only 82 grams.

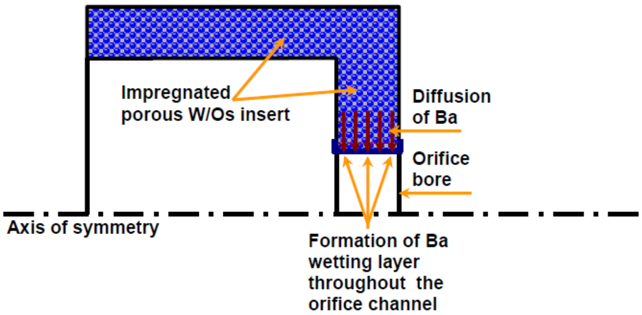


Figure 3. Layout of the Thales cathode with a Barium wetted orifice bore

III. Qualification Target

The HCN5000 qualification in course of the HEMP-TIS program is a twofold process. The first qualification has the purpose of proving the cathode resistance to the humidity it is exposed to during the MAIT phase, this qualification includes the neutralizer exposure to air while the satellite is mounted inside the launcher fairing and awaiting launch without the open cathode's protective covers. The worst case conditions are experienced during a sea-launch campaign; therefore the qualification for such a launch covers those of any other launcher. During the MAIT phase at Thales the HEMP-Thruster Module (HTM) is exposed several times to plasma operation, interchanged with exposure to air. Nominal handling procedures and storage conditions are targeted to reduce cathode expose to air as much as possible. Still the exposure cannot be completely avoided, therefore the qualification includes four cycles where the cathode is operated for 24 hours (representative operation time during performance or thermo-vacuum tests) in between which the cathode is exposed a minimum of 24 hours to a humidity rich atmosphere at elevated temperature, see Fig. 4. The launcher fairing exposure period is a maximum of 60 days, previous to which a 3 day exposure period needs to account for integration work during assembly and testing on spacecraft level. This qualification is successfully passed when the cathode can be reignited and nominal performance is recovered during a cycling test of at least 100 cycles.

It is expected that neutralizer exposure to air lowers the initial current emission performance, due to the accumulation of Barium hydroxide on the cathode surface. Once a plasma discharge is successfully started the cathode is heated due to electronic contribution[2] rather than ionic bombardment. Although the ion bombardment of the Xenon gas is a secondary effect in the heating of the cathode it acts as a cleaning process in which the top layer of the cathode, for instance Barium hydroxide is removed. The remaining MM-type cathode surface

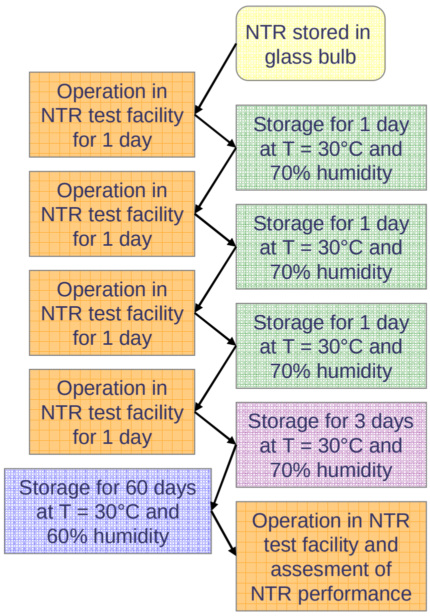


Figure 4. Storage qualification scheme for the HCN5000

is insensitive to ion bombardment due to its composition with Osmium as part of the metal matrix; therefore removal of the top layer by sputtering has no impact on the work function. The newly formed top layer of Barium wetted Tungsten-Osmium reacts to create Barium oxide and thus recovers the initial cathode properties.

The second qualification process is a cycle and lifetime qualification, which takes place after the storage qualification. This test simulates the first three years of the SGEO HAG1 mission during which the in-orbit verification time of the HEMP-T EPS is covered by performing 1300 SGEO representative cycles. The cycles are a nominal 40 minutes ON time and a 20 minute OFF time to allow for cathode cool-down. In parallel to the cycle qualification an accelerated lifetime test takes place on sub-assembly level, focusing on the cathode workmanship verification for batch release. The cycles are performed with nominal keeper and neutralization current, meaning 1.5A and 1.38A respectively. These are the exact same conditions for operation of the neutralizer when coupled to a thruster.

IV. Accelerated Cathode Life Test

Ion bombardment, evaporation and consecutive electrostatic transport mechanisms[3] constantly remove Barium from the wetting monolayer on the cathode surface. During manufacturing Barium is impregnated into the porous metal matrix and forms a reservoir which sustains the surface monolayer through migration to the surface. The life of the Thales neutralizer is limited by the cathode Barium reservoir, this follows from an operational temperature above 900°Cb and both a keeper discharge and coupling voltage below 15V[4] in nominal operation when coupled to a thruster.

Since the operational lifetime of the cathode is set to be dependant upon the cathode temperature it can be concluded that an accelerated life time testing can be performed by operating the cathode at elevated temperatures. This is valid for the Thales cathode since the Osmium is part of the metal matrix and not only a coating, therefore diffusion of the Osmium into the bulk body does not cause performance degradation while increasing the cathode temperature. The life acceleration factor has been determined by testing on tetrodes, see Fig. 5, where an acceleration factor of 60 can be reached by increasing the operational temperature from 980°Cb to 1170°Cb.

So far the accelerated life test on two cathodes for the HCN5000 have already shown 70.000 operational hours, far exceeding the required 4800 hours for the SGEO HAG1 mission.

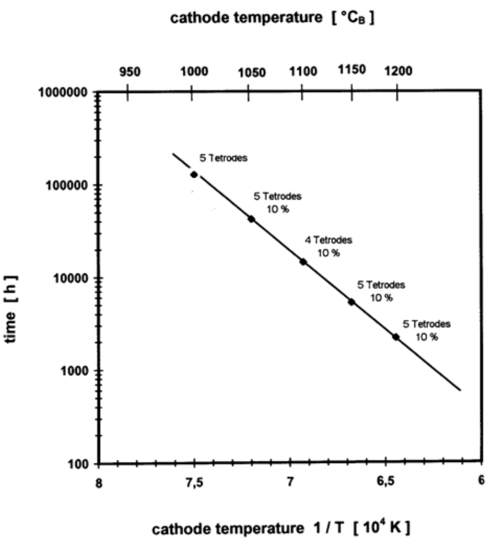


Figure 5. Cathode life versus cathode temperature

V. Facility Induced Cathode Poisoning

In course of the storage qualification a cathode poisoning effect was observed by the first neutralizer, used for pre-qualification and test-setup verification. The neutralizer had successfully passed the storage test and was performing representative SGEO cycles at the end of the qualification when a steady degradation set in, first the cathode temperature, coupling and keeper voltage increased, eventually the cathode failed to ignite after the nominal ignition sequence. The test setup was such that all feed-line components were located externally from the vacuum chamber to increase changeability of the setup. One of the components is a mass flow controller, causing a high pressure of more than 2 bar on the upstream end and a pressure of around 10 mbar on the downstream end. The cause for the cathode degradation was oxygen ingress into the feed line system at the low pressure side of the mass flow controller, causing oxygen to be transported with the xenon flow into the hot cathode. Standard leak-testing methods proved unsuccessful in detecting any leaks, this is in line with findings from the DERA cathode qualification test for the UK-10 for the ESA Artemis mission[5]. The subsequent solution to the problem was a redesign of the gas feed system such that no low-pressure tubing is present outside of the vacuum facility and all external tubing is welded instead of screwed whenever possible. After these measures cycled retest of the neutralizer was performed and full recovery and successful completion of the cycled test is shown without deterioration.

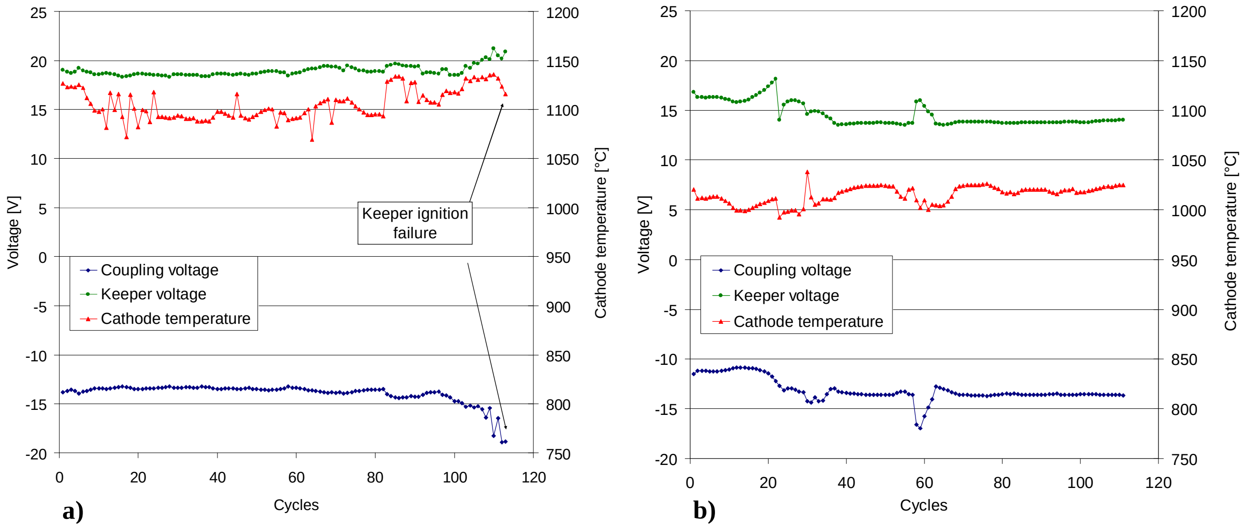


Figure 6. Mean values over 40 minute cyclic operation of the HCN5000 after the storage qualification program. a) failure due to facility induced cathode poisoning. b) healthy cathode operation after gas feed line upgrade.

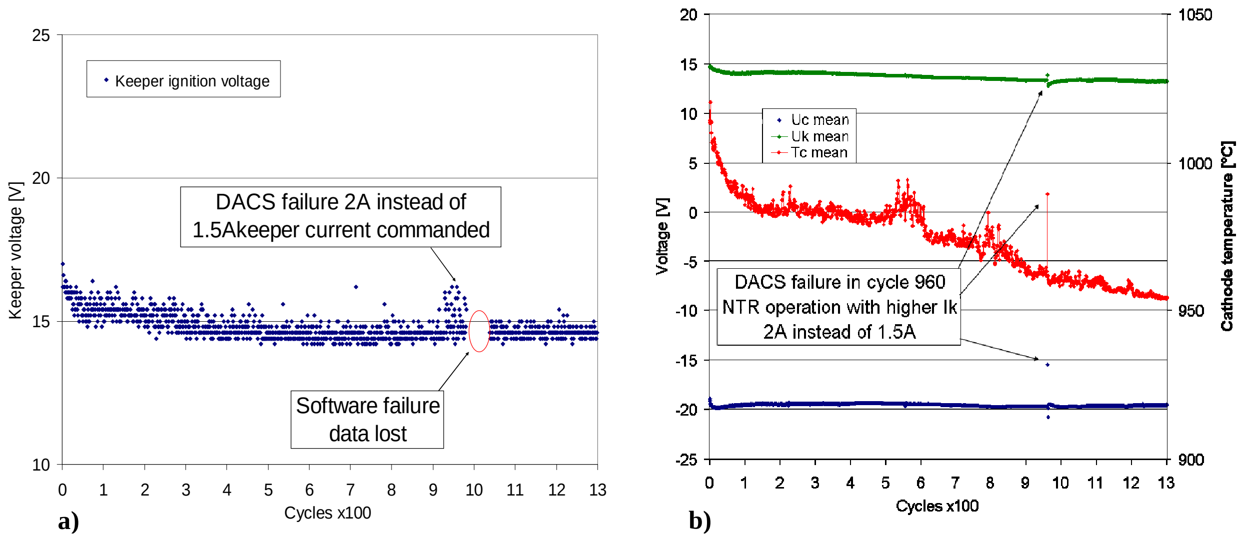


Figure 7. a) Keeper ignition voltage over 1300 cycles b) healthy cathode operational values under worst-case conditions operation after gas feed line upgrade.

VI. Qualification Test Results

The operation parameters of the HCN5000 for the SHEO HAG1 mission at keeper ignition are at a keeper current of 2A, when the thruster is started a neutralization current of 1.38A is added and the keeper current reduced to 1.5A. Initial separate testing of a neutralizer in a vacuum chamber without a thruster showed an elevated cathode temperature with respect to those measured when the neutralizer is coupled to a thruster, where the cathode temperature can be linearly deduced during tests from the heater resistance. The increased cathode temperature was thought to be caused by an increased resistance in the neutralization current due to the absence of the thruster plasma. In order for representative testing the neutralization current was reduced to 0.5A (keeper remains at 1.5A) to keep the cathode temperature between 1000°C and 1125°C as well as the coupling voltage around 15V. Testing after the gas feed line refurbishment however showed healthy cathode temperatures when operating at a keeper current of

1.5A and a neutralization current of 1.38A during the 1300 cycle test. From this it is clear that the facility induced poisoning was responsible for the increased cathode temperatures and the neutralizer can be fully representatively tested in the neutralizer test facility without being coupled to a thruster.

Phase one of the qualification involved the storage qualification during the HEMP-T EPS MAIT phase, during which the facility induced poisoning effect was detected while testing the pre-qualification neutralizer. The three qualification models had all already undergone partial storage qualification testing before the oxygen ingression into the feed line was found and were thus exposed to cathode poisoning. The cathode temperature of the pre-qualification neutralizer before the gas feed line upgrade increased up to 1130°C during cycling operation, whereas after the upgrade the retesting of the cathode showed a healthy operating temperature of around 1020°C. This recovery of the cathode after the feed line upgrade is also measured by the ignition voltage of the keeper, starting at 22V at the beginning of the repeated cycles and reducing to 15V after 110 SGEO HAG1 representative cycles. This is in line with the general observation of the qualification neutralizer tests, which were performed after the feed line upgrade, that the keeper voltage and cathode temperature reduces to lower values in the 24 hours of steady plasma operation after each exposure of an unprotected neutralizer to the high-humidity environment. It was however found necessary to alter the standard activation procedure after the 60 days of exposure, such that activation takes 24 to 48 hours at 50°C elevated temperature. This is a one-time procedure to be performed before the first firing of each neutralizer in space and will not influence the cathode life. Despite the initial facility induced cathode poisoning the pre-qualification and all three qualification neutralizers passed the storage qualification test and showed complete recovery from the initial poisoning.

Phase two of the qualification and part of the neutralizer batch release is the extended cycling test over 1300 representative SGEO HAG1 cycles. This test was performed with one of the qualification neutralizers after it successfully passed the storage qualification test. During these cycles a steady decrease of the cathode operating temperature was observed, most pronounced in the first 100 cycles and also visible in the operational keeper and coupling voltage. This leads to the conclusion that the cathode, performing at very low cathode temperatures, is highly resilient to poisoning and will recover over time. The cathode's very low operating temperature under these conditions leads to very high expected life time of more than 100khours and the shown 1300 cycles already covers the in-orbit verification time of three years without indication of any life or cycle limiting effect.

VII. Conclusions

The Thales developed HCN5000 is a low-weight neutralizer based upon a hollow dispenser cathode made of a Tungsten-Osmium metal matrix impregnated with Barium-, Calcium-Aluminates. These cathodes are known to be sensitive to humidity and are poisoned when exposed to oxygen during operation.

The Qualification of the HCN5000 involves a storage qualification, where the exposure of the open cathode to humidity during the MAIT phase including waiting time within the launcher fairing on the launch pad, and a life qualification. Operation of the neutralizers on the qualification chamber without being coupled to a thruster is a worst-case condition due to the absence of the thruster plasma environment. The storage qualification consists of cycled plasma operation with exposure to a high humidity environment in-between. During this storage qualification a facility induced poisoning effect was discovered, requiring an upgrade of the gas feed line to remove low pressure tubing outside of the vacuum chamber. All neutralizers that showed slow degradation due to oxygen poisoning during plasma operation were found to be recovering after the facility upgrade, performing at the final performance test with healthy cathode temperatures and keeper and coupling voltages. In conclusion all neutralizers successfully passed the atmospheric storage qualification program.

The Lifetime qualification consists of an accelerated life test by operating the cathode at an elevated temperature of 1170°C, this causes an acceleration factor of 60 with respect to the life time at the nominal 980°C. So far these tests have shown an available lifetime of at least 70khours. Additionally a cycling test was performed on one of the storage qualification test neutralizers. A total of 1300 representative SGEO HAG1 cycles was performed, covering the 3 years of the in-orbit verification, and no sign of neutralizer degradation was detected. Rather a steady lowering of the cathode temperature showed a recovering and healthy cathode operating approaching 950°C which is well below its defined maximum temperature. Also a steady and low keeper ignition voltage of around 15V supports the analysis of a healthy operating cathode, which is capable of operating well beyond the required life for the SGEO HAG1 mission.

Acknowledgments

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