Results of the 15000 hours lifetime test for the RITA Ion Propulsion on ESA's ARTEMIS satellite

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The Ion Propulsion Package IPP onboard ARTEMIS is the first European application of electric propulsion on geosynchronous communication satellites for North South Station Keeping. The IPP is employing two different technologies: The Electronbombardement Ion Thruster Assembly (EITA) of Astrium Ltd. - Portsmouth - and the Radiofrequency Ion Thruster Assembly (RITA) of Astrium GmbH - Ottobrunn. In order to prepare for the mission the EIT has performed a 2000 hour durability test that will be concluded by testing a grid manufactured with EOL holes. The RIT has completed a 15,000 hour full system life test. Launched on July 21, 2001 the IPP was successfully activated and is awaiting its use for NSSK and orbit rising. After a brief description of the IPP and its components the paper will focus on the RITA life test and give early results of the first in-orbit activities.

I. Introduction

Artemis is a geosynchronous Telecommunication satellite developed by the European Space Agency ESA to demonstrate future technologies. The IPP is used to provide the Δv required for North-South-Station-Keeping (NSSK).

On July 21, 2001 ESA's ARTEMIS satellite was launched on an ARIANE 5 from Kourou. After the satellite had reached a circular interim orbit at 31,000 km height the Ion Propulsion Package (IPP) was activated and commissioning tests were performed. The IPP was successfully performance checked and initial tests to support the orbit rising were performed.

In support of the mission since June 1998 the two thruster technologies are undergoing life tests. The EIT (Electronbombardement Ion Thruster) manufactured by Astrium Ltd (UK) has completed a 2000 hour test and will be equipped with grid manufactured with EOL size holes. The RIT10 (Radiofrequency Ion Thruster) has successfully finished its 15,000 hours system life test that was started since June 1998.

Although the test, is dedicated to the thruster only, Astrium, in order to test the thruster as flight like as possible and to investigate potential interactions with the electronics or the feed system, decided to test the complete subsystem. The RITA subsystem, besides the thruster, consists of the Radiofrequency Generator (RFG), the Power Supply and Control Unit (PSCU), and the Flow Control Unit (FCU). During the life test the EQMs to date have demonstrated more than 120% of the life required for the 10 year mission.

In Mai 2001 after 13,000 hours of operation the RIT10 was inspected to determine the grid erosion. Based on the erosion data the expected life time of the RIT10 is substantially larger than the 15,000 hours required for the ARTEMIS Ion Propulsion Package (IPP) qualification. In addition it could be demonstrated that even an

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excessive accumulation of sputter material does not cause a shot in the grid system.

Main purpose of this paper is to give a concluding report about the RITA10 lifetime test. After a brief introduction, describing the IPP, with special emphasis on the RITA (a more detailed description of RITA on ARTEMIS is given in [1]), this paper will describe the results of the life test, give an update of the life time assessment, and describe the effect of sputter debris in the grid system. Finally the IPP activation process and on the IPP in- flight activation process and the recent status will be described.

II. ARTEMIS Mission Goals

ARTEMIS is a geo-stationary telecommunication satellite developed by Alenia Spazio as prime contractor for the European Space Agency, as part of the Data Relay Technology Mission (DRTM). ARTEMIS is a three axis stabilized satellite and has a mass of 3100 kg. The main purpose of ARTEMIS is to promote advanced telecommunication technology. ARTEMIS, after a number of delays, was launched on June 12, 2001 on an ARIANE 5 together with the PAS2B satellite. The planned mission duration is 10 years.

In addition the ARTEMIS satellite was selected to demonstrate the advantages of ion propulsion for station keeping of geo-synchronous satellites during a real mission. This will be the second use of ion propulsion in Europe, after its first flight demonstration of RITA on-board of EURECA in 1992.

III. The Ion Propulsion Package (IPP) on ARTEMIS

The Ion Propulsion Package (IPP) on ARTEMIS, developed under the leadership of Astrium GmbH, was customized to provide the Δv required for North-South-Station-Keeping. For this purpose one thruster on the north panel will be operated for 3 hours when the satellite passes the ascending node and a second one on the south panel when the descending node is passed. According to the baseline mission planning one RITA and one EITA system will be used alternately. The IPP consists of the following assemblies:

- 1 Propellant Storage and Distribution Assembly (PSDA) [Astrium Ltd] including the Xenon Storage Tank (XST) [MAN-Dowty] and the Electric Pressure Regulator Mechanism (PSME), an electronic Xenon pressure regulator.
- 2 Electron Bombardment Ion Thruster Assemblies (EITA - Kaufman type), which include the Electric Pressure Regulator Electronics EPRE of the PSDA [Astrium Ltd.]. The EITA subassemblies are the thruster EIT, the Propulsion Control and Electronics PCCE, and the Propellant Supply and Monitoring Equipment (PSME)
- 2 Radiofrequency Ion Thruster Assemblies (RITA) [Astrium GmbH]. The detailed description of the RITA is given below.
- 1 Ion Thruster Alignment Assembly, consisting of
  - 2 Ion Thruster Alignment Mechanisms (ITAM) [Austrian Aerospace] and
  - 1 Ion Thruster Alignment Electronics (ITAE) [Astrium GmbH]

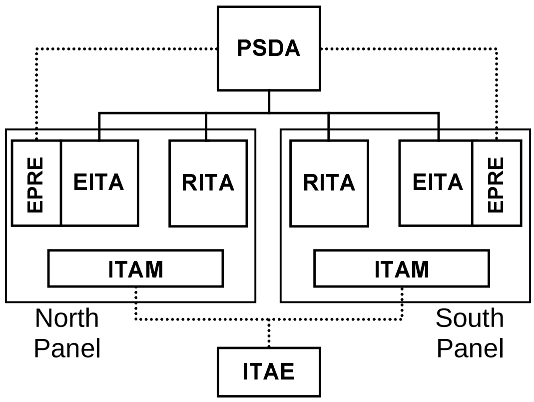

Fig. 3-1 ARTEMIS IPP block diagram

Figure 3-1 shows the block diagram of the IPP assemblies. The solid lines demonstrate the Xenon feed line tubes, while the dotted lines represent electrical connections.

The allocation of the IPP components on the satellite is shown in fig. 3-2. Two thrusters one EIT and one RIT10 are mounted on one ITAM on north- and south panel respectively.

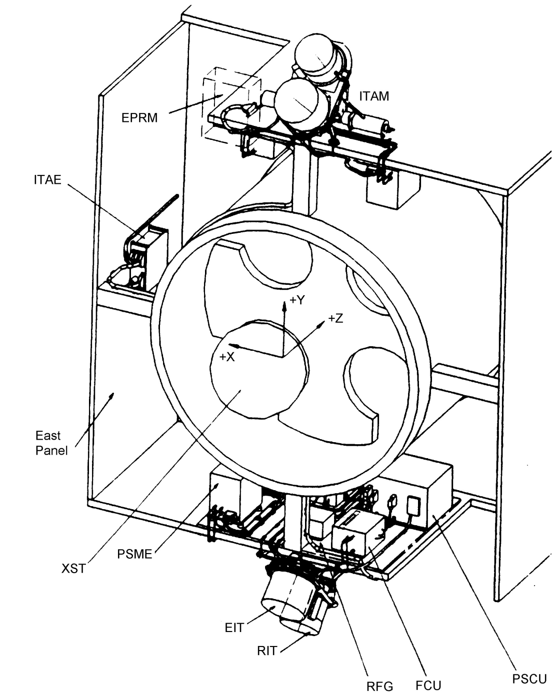

Fig. 3-2 Allocation of IPP on ARTEMIS

IV. RITA and its components

The Radiofrequency Ion Thruster Assembly (RITA) for ARTEMIS consists of the thruster (RIT10), the Flow Control Unit (FCU), and the Radio Frequency Generator (RFG), developed by astrium. The thruster electronic box, the Power Supply and Control Unit (PSCU) was developed by Officine Galileo. A block- and function-diagram is shown in Fig. 4-1. The RITA total mass is 15.4 kg including tubing, harnesses, and mechanical interface material. A more complete description of The RITA can be found in [1], [3] and [6]

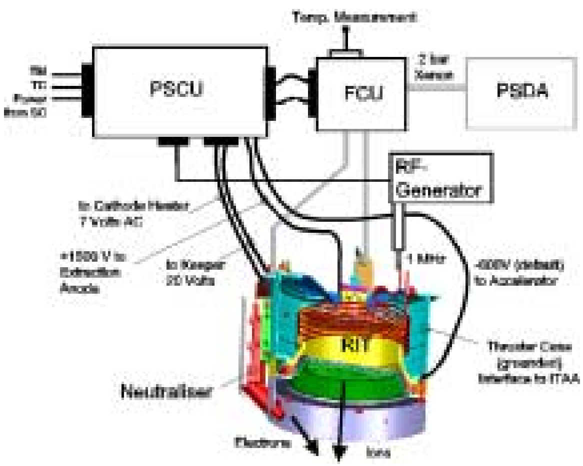

Figure 4-1: RITA Block Diagram

Figure 4-2 shows the thruster with the neutralizer in the vacuum test chamber prior to the start of the qualification testing. The white color is applied to reduce the heating of the thruster caused by solar radiation.

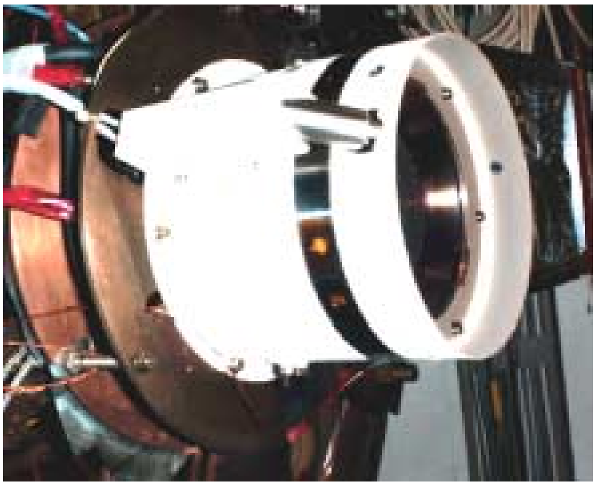

Figure 4-2: ARTEMIS Qualification Thruster

The Xenon flow to the thruster and the neutralizer is controlled by the Flow Control Unit (FCU). The FCU is capable to actively control the Xenon mass flow to thruster and neutralizer by varying the Xenon pressure in a plenum volume. This plenum pressure is kept between an upper and a lower threshold value, by opening an inlet valve if the lower limit is fallen short. Due to this the plenum pressure is oscillating ±5% of the nominal value and consequently the Xenon flow rate to the thruster is varying as well. In order to keep the thrust constant the beam current controller in the PSCU is regulating the power delivered to the radio frequency generator, which for the RITA is easily feasible as the beam current and consequently the thrust is directly proportional to the rf-power. The results of the life test prove that the RIT's life is not affected by non-optimized flow rates.

The RITA customized for ARTEMIS was successfully qualified and acceptance tested on equipment and assembly level in 1997. The major performance characteristics are as follows:

Nominal Trust:	15 mN
Total Thrust Range:	<1 to 18 mN
Thrust Repeatability	< ± 1°
Beam Diameter	87 mm

Beam Divergence (90% value)	≤ 11.5° half angle
Beam Voltage:	+ 1500 V
Thruster Power Consumption at 15 mN (incl. Neutralizer)	< 459 W
Specific Impulse (incl. Neutralizer at 0.46 mg/s Xenon)	> 3400 s
Total Impulse Capability (Spec.)	600,000 Ns
Dimensional Envelope	212 * 190 * 180mm
Cold Start	-85°C
Hot Start	> 150°C
Heat Dissipation (nominally)	< 95W

Tab. 4-1 RIT10 Design Data

The verification of the thruster's capability to provide the required total impulse is subject to a lifetime test that was started in June 1998. During this test 15,000 operating hours were to be performed in cycles of 3 hours on and 1 hour off. To verify the cumulative impulse per thruster of 810,000 Ns including a qualification factor of about 1.35. The test is described in the following paragraphs.

The beam neutralization is provided by a Laben-Proel hollow cathode neutralizer. The neutralizer's life capability was qualified on component level, prior to the system life test.

The electric equipment, RFG and PSCU, were qualified and acceptance tested on unit level. Later these equipment were used during the RITA qualification and acceptance for end-to-end testing. The RFG-EQM is used to operate the RFG during the entire life test. The same is valid for the PSCU, except during phases where the thruster was to be tested exceeding the operation range of the flight electronics.

V. RIT10 Lifetime Verification History

The life verification for the RIT thruster family using graphite acceleration grids was performed in 4 steps:

a During the early development of the RIT10 for ARTEMIS a durability test was performed on a performance representative engineering model (EM2). The thruster was operated for 3450 h using the typical NSSK (North-South-Station-Keeping) cycles of 3 hours on / 1 hour off. After an initial inspection the thruster was disassembled and inspected in greater detail. No erosion but that of the acceleration grid was found. Finally the extraction grid hole erosion was measured to verify an analytical model that describes the hole erosion growth.

b Based on the analytical model a new set of grids with end of life hole dimensions was manufactured and mounted to EM2. This "EOL thruster" in August 1997 was tested for 390h and the thruster provided a specific impulse clearly above the specified value.

c After the final design of the RIT10 for ARTEMIS was frozen, the first thruster of the flight lot (S/N01) was tested for 1140 hours. After the test the extraction grid hole erosion was measured again and was found comparable to that of EM2.

d The full system life test of the RIT10 EQM (S/N03) was started in August 1998. The 15,000 hour requirement was achieved on September 13, 2001.

VI. Life Test Objective

Except the verification of the subsystem function over the whole life, the following performance aspects were to be demonstrated:

- Thrust vector stability as a function of operation time and temperature
- Thrust vector stability as a function of life
- Specific impulse as a function of mission time. The mass flow to the thruster and to the neutralizer are measured in common by a commercial mass flow meter which is installed upstream of the FCU. This allows to determine the specific impulse. The thrust will be calculated as a function of the beam voltage and beam current.
- Total system power consumption., i.e. input power to the PSCU over life.

VII. Test Set-Up

Test object is the RIT 10 EQM (Engineering Qualification Model). In order to make this test as flight like as possible it was operated by the RFG-EQM, the PSCU-EQM, and the FCU-EQM.

The test is performed in the Gigant test facility at ESTEC in Noordwijk – The Netherlands -, see Fig 5-1. Thruster and neutralizer are mounted on a flange, inside the hatch of the vacuum chamber, which provides a flight like thermal environment. In addition the RFG and the FCU are installed inside the hatch. The RFG for proper thermal control is cooled similar to its accommodation on ARTEMIS. The PSCU, due to the limited space in the vacuum chamber, is accommodated outside the vacuum chamber on a cooled platform. Thus during the life test the electrical equipment were used similar to flight.

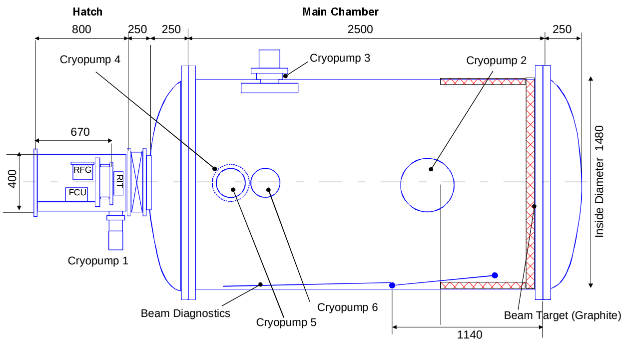

Fig. 6-1: Schematic of the ESTEC test chamber

Commanding, power supply and data acquisition of the PSCU are provided by a S/C simulator. Additional test data like temperatures, vacuum chamber pressures, and feed system pressures are monitored by a separate system called Test Power Supply (TPS). The TPS in addition can be used to operate the thruster in case special tests, exceeding the PSCU capabilities, are to be performed. S/C simulator and TPS are computer controlled and can be controlled either locally at ESTEC (The Netherlands) or remotely from Munich (Germany). In addition the ESA test chamber is equipped with a beam diagnostic and sputter measurement tools like QCM (Quartz Crystal Microbalance) and witness plates.

The ARTEMIS mission requires one 3 hr operation period per day for one thruster on both panels. This results in 3650 cycles during an operational life of 10 years. In order to abbreviate the test duration, the lifetime test thruster performs 6 segments (3 hours ON - identical to flight on-time per day - and 1 hour OFF – to guarantee a cooling down phase to typical mission start temperatures before the system is restarted. This allows to test flight representative thermal cycles. The test set-up is prepared such, that the commanding of the 6 cycles per day is pre-programmed and data are stored automatically. Due to this the thruster can be operated unattended, allowing a 24 hour a day, 7 days a week operation.

VIII. Grid Erosion Results

During the lifetime test at 1578, 3250, and 13000 hours of operation the thruster was removed from the test chamber and the hole erosion was measured:.

A: The deceleration grid especially close to the rim is subject to erosion, as shown in figure 8.1. Close to the center of the thruster no erosion was found. This is confirmed by the fact that the inside of the holes (channel) was covered with sputter material, which would not be there if the deceleration grid would be hit by ions. In this case the decel channel would have been metallic clean.

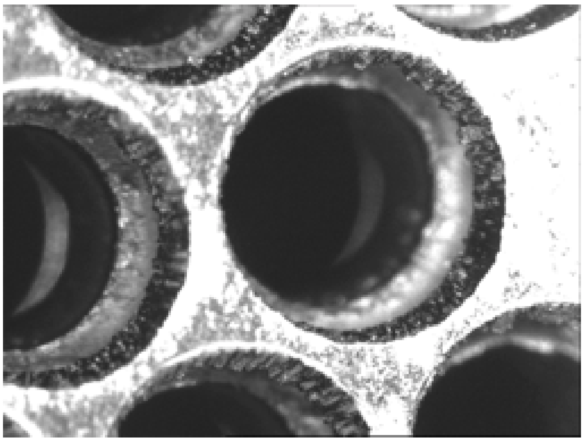

Fig. 8-1: Deceleration grid erosion close to the thruster rim

B. For the acceleration grid the erosion was measured as following:

- The acceleration grid holes show a homogeneous erosion up to about half of the grid diameter. When moving to the rim of the grid the hole erosion is reduced to about 50% of the center value. Figure 8-2 shows the average hole diameters at different distance from the grid's center.

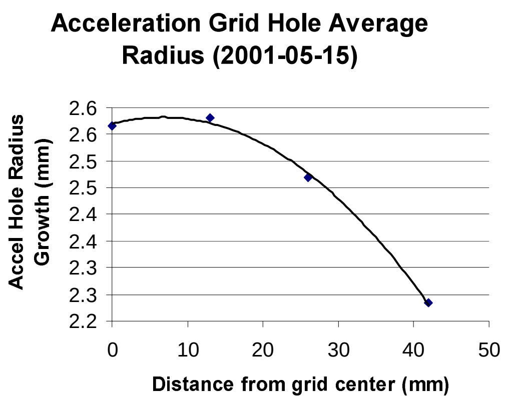

Fig. 8-2: Acceleration grid hole diameter as a function of the thruster radius

- The grid erosion as a function of the life time is shown in figure 8-3. As expected the erosion at begin of life is the highest. The erosion rate is significantly reduced after about 3000 hours. After about 5000 hours is quasi constant. These results on the other hand show that an extrapolation of a grid's life time based on a test of less than 4000 to 5000 hours is quite problematic.

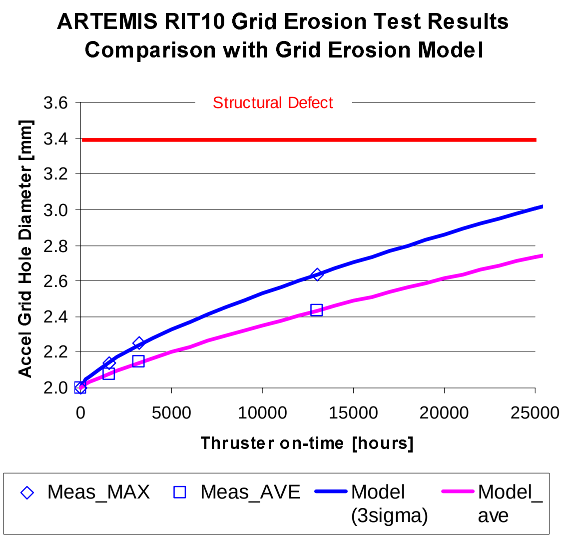

Fig. 8-3: Grid erosion data and prediction

This hole erosion measurements establish the confidence that the RIT10 grid has ample margin in respect to the life time of 15.000 hours required for the ARTEMIS program qualification. Indeed the data allow to predict a life time exceeding 20,000 hours.

The RIT operation principle shows a linear correlation between acceleration grid erosion on one hand and the consumption of rf-power, acceleration drain current and Xenon flow rate on the other hand (see figure . These three values are measured permanently during the test and prove a homogeneous growth of the accel grid holes.

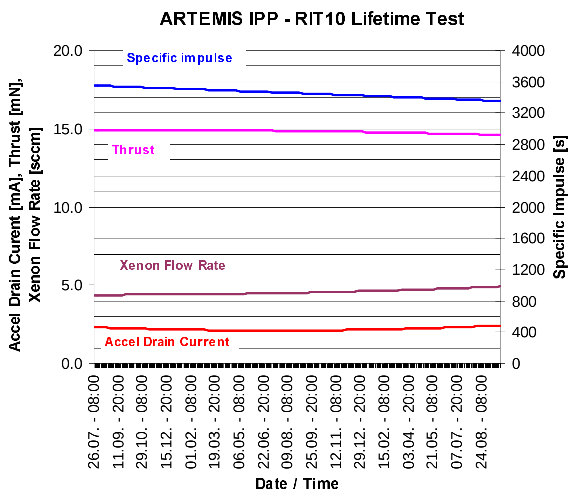

Fig. 8-4 RIT10 key performance trends during life test

Figure 8.4 shows the variation of accel drain current, Thrust, Flow rate and specific impulse versus life. Figure 8-5 below shows the RF-power increase as a function of the on-time and its correlation with acceleration grid hole diameter.

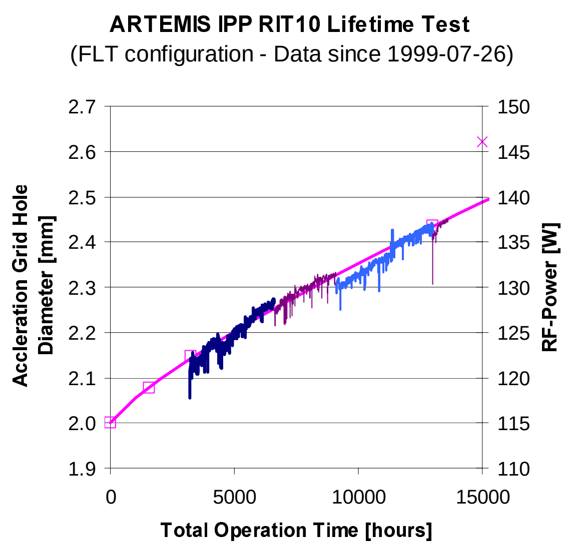

Fig. 8-5: RF-power as a function of life time

The pink line is the average acceleration grid hole growth. The blue lines are the measured RF-power. The steps at about 5000, 7000, 9000, and 11000 hours are effects of changed flow rates. The scatter in the line is caused by the fact that the integrated Xenon flow rate measured by a commercial flow meter for single operation cycles depends from the FCU plenum pressure at the begin of the cycle and the resulting number of fill cycles. The slope is 2 W of RF-power, which corresponds to 1.6%, for 1000 hours of operation. Considering the total power in put to RITA of 568 W this is a power increase of less than 0.5%.

The hole erosion of the acceleration grid is circular, as can be seen in the close up photography of the grid in figure 8-6. The holes were inspected visually by a CCD camera using an objective with fixed magnification, to measure the hole dimensions. In order to verify this the diameter of 19 holes were checked mechanically.

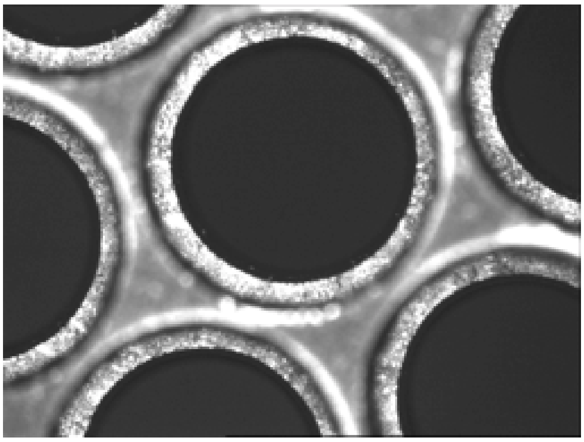

Fig. 8-6: Decel and Accel holes in the grid center

In the rim area of the grid the holes show a "rough" contour. These holes have only 4 neighboring holes and consequently don't have the hexagonal symmetry. An example is shown in figure 8-7.

C. Screen Grid Erosion: As the thruster was not disassembled the screen grid could not be inspected, but due to the RIT operation principle the screen grid is not subject to erosion. If due to operational failures the screen grid would be eroded, this would have been detected by the performance changes.

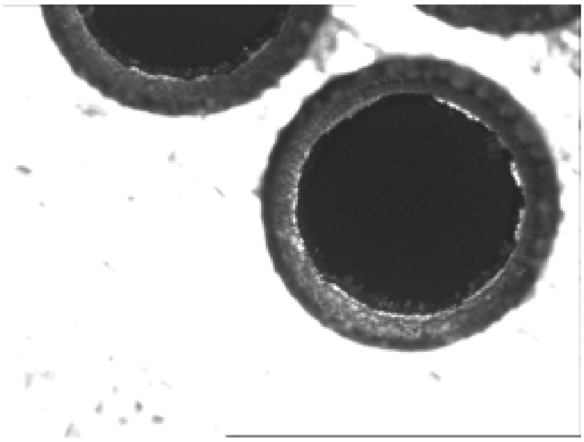

Fig. 8-7: Decel and Accel holes at the grid rim

A final inspection will be performed after the thruster is being removed from the test chamber. Currently the system is kept in standby, with the thruster remaining in the vacuum chamber to be able to support the mission

IX. Effects of Sputter Material Deposition

The another very interesting result of the 13,000 hour inspection is that even an excessive accumulation of graphite sputter material between the grids does not cause a performance loss or a short of the thruster.

The graphite that was found on the thruster, see figure 8-1, is to nearly 100% produced by material sputtered back from the graphite beam target, as was shown in [5].

Fig. 9-1: RIT10-EQM after 13000 hours

During the test graphite material sputtered back from the vacuum chamber's target, as can be seen in figure 9-1, was deposited on the thruster as well as on the grids. For comparison with the

BOL thruster see figure 4-2. Similarly one part of the graphite sputtered off the acceleration grid is deposited on the inner side of the deceleration grid and on the acceleration grid. Due to the vibration caused by the vacuum chamber's cryo pumps and thermal cycles this material can get loose. The loosened particles due to the vibrations of the cryo pump were accumulated in the lowest point of the thruster. Not only in the sun shade (see figure 9-2), but between the grids as well.

Fig. 9-2 Accumulation of graphite material in the thruster's sunshade

This material caused a temperature dependent increase of the acceleration drain current, while earlier in the test the acceleration drain current was independent form the temperature. The pink line with squares in figure 9-3 shows the measured "apparent" accel. drain current at 13000 hours as a function of the temperature.

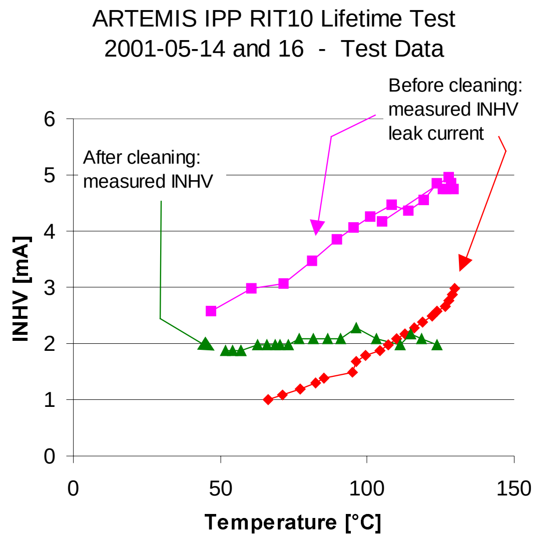

Fig. 9-3 Accel Drain Current Data

In order to check whether this drain current is real or not, the nominal high voltage was applied to the grids, but without gas flow. In case the pink line would be caused by a "real" accel drain current, no current would be measured in the absence of the gas flow. But a current represented by the red line (diamonds) was measured. This only could result from material accumulated between the grids that expanses as a function of temperature and by this improved the conductivity.

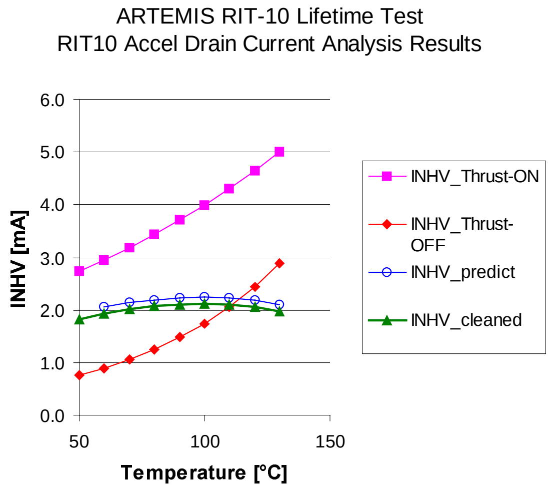

Fig. 9-4 Accel Drain Current Models

Figure 9-4 shows a best curve fit of the measurements using the same line code. The blue line (circles) represents the predicted "real" accel drain current (pink minus red). In order to verify this, the volume between the grids was cleaned with a vacuum cleaner without disassembling the thruster. After the cleaning the predicted temperature independent accel drain current, as shown by the green line (triangles) in figure 8-3 was measured. This value is identical to the prediction.

These results prove that the "apparent" accel drain current was caused by loose graphite sputter material accumulated between the grids. Due to the "bad" conductivity of the graphite the thruster performance was not compromised. In the case of a metal grid like Molybdenum, due to the better conductivity, this material most probably would have caused a permanent short.

Based on this it can be concluded the increase of the accel drain current that was observed after about 8000 hours of operation accel drain current has be attributed to the leak current produced by the sputter material. Figure 9-5 shows the accel drain current (INHV) as measured between 3000 and today (open diamonds). The black solid line indicates the apparent drain current that vanished (*) after the loose sputter material, accumulated in the lowest point of the thruster, was removed. By using this analytical description of the apparent drain current the real accel drain current, as it is shown in figure 8.4, can be determined.

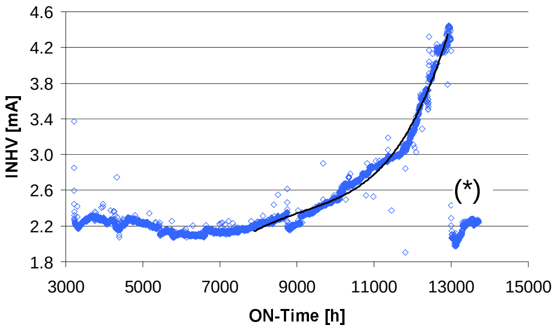

Fig. 9-5 Determination of the apparent accel drain current (black line)

X. Beam Divergence

As show above, the acceleration grid is subject to erosion, consequently it is expected that the growth of the holes has an influence on the shape of the beam and possibly on the beam vector. Consequently beam divergence and beam vector stability are objectives of the life test.

Three requirements are addressing the beam vector:

1 Beam vector migration < 1° over the life time

2 Beam vector migration < 1° from start to thermal equilibrium

3 The beam divergence (90% value) has to stay below 30° full angle

The comparison of the beam divergence measurements taken after 4000 and 12000 hours show that the beam divergence angle has not changed significant as a function of life time. Consequently the total beam intensity measured at 4000 hours and at 12000 hours is not changed.

Year	Angle / °	Percentage of Beam
1999	24.64 26.8	90.0% 95.0%
2001	24.6 26.2	90.0% 95.0%

Tab. 10-1 Beam Divergence Comparison 4,000 hours to 12,000 hours (full angle)

XI. Life Test Summary

During 13,000 hours of operation in total about 2.1 g of the graphite material was sputtered off the acceleration grid which corresponds to an average erosion rate of 0.16 g/1000 hours.

The System successfully has completed the 15,000 hours life test (qual. value). The number of thermal cycles was 5000. Besides the operation time the number of beam on commands has a significant influence on the grid erosion. The EQM thruster as of today was subjected to more than 37600 of these transition phases. This is more than 10 times the number needed for the mission..

The operational data are shown table 11-1 below:

Technical Data	**Requirement**	**Achieved after 15,000h**
Cumulative on time	15000 hours	15013 hours
Operation cycles	5000	5000
Thrust level	15mN +/-5%	15mN +/-0.9%
Specific Impulse	> 3000sec	> 3460sec
Main Bus Power	≤ 585W	< 570W
Total Xenon mass flow (thruster and neutralizer)	0.51mg/sec	< 0.45 mg/s

Tab. 11-1 RITA performance during life test

XII. IPP First In-Flight Results

ARTEMIS, launched from Kourou by an Ariane 5 on 12 July, had been put into the wrong orbit due to a malfunction on the launcher's upper stage. The injection orbit had a perigee of 590 km, an apogee of 17487 km and an inclination of 2.94°, compared to expected values of 858 km, 35853 km and 2° respectively. ESA rapidly developed a recovery strategy that aimed to take the satellite to a nominal geostationary position of approximately 36000 km, maximising the lifetime of the spacecraft originally planned to last ten years. The strategy consists of four steps, the first two of which have been successfully completed. As an initial step the 400 N apogee boost motor (Astrium GmbH) was fired during five perigee passes to increase the apogee to about 31000 km. Secondly the elliptical orbit was circularised by three consecutive motor burns. This resulted in a circular parking orbit with the satellite at approximately 31000 km, an orbit duration of about 20 hours and an inclination of 0.8°. After this parking orbit was achieved the solar arrays were fully deployed and the activation of the IPP was started.

The first step to activate the IPP was to deploy the gimbal mechanism (ITAM), i.e. the mechanical structure that supports the thruster platform of the ITAM during launch was retracted. In a r2nd step the feed lines downstream of the PSDA, the low pressure part of the tubing, was evacuated in order to clean if form potential contamination like Oxygen. Finally all four systems were powered on and checked out. Initial operation tests and performance checks were successfully performed.

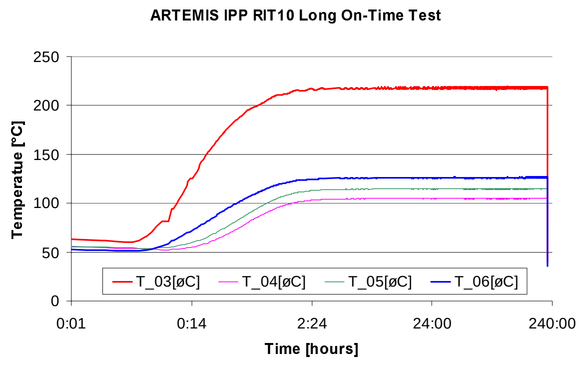

Fig. 12-1 RIT10 long duration test (219 hours) - logarithmic time scale -

In order to support the planning for the orbit rising, the RIT10 cycle tests were interrupted an two long duration firings of 68 and 219 hours were performed, confirming that the thruster after 2 hours of operation has reached its thermal equilibrium.

Currently a software patch of the AOCS to support the orbit rising with the ion thrusters is being prepared and the maneuver strategy for orbit rising with the ion propulsion is being developed. Finally it is planned to spiral from parking to nominal geostationary orbit using the ion-propulsion system.

XIII. Conclusions

The RITA ion thruster assembly on ARTEMIS has successfully completed the 15000 hours life verification. An inspection taken place at 13000 hours indicate a substantially higher life capability. These results give confidence that the larger RIT thruster that currently is under development will achieve a high life time as well. The RITA system performance was significantly better than the requirements

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