ENDURANCE TEST OF PROEL NEUTRALIZER FOR THE RIT 10: REVIEW OF THE ACTIVITIES AT ESTEC LABORATORIES

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Abstract

The use of ion propulsion system on board of commercial satellites for orbital control manoeuvres offers a concrete opportunity to obtain a series of benefits that, in turn, result in an increased cost effectiveness of the mission.

Within the European scenario of ion propulsion, the reference space mission for operational test of an ion propulsion package is represented by the ESA ARTEMIS communication satellite. Within this programme PROEL TECNOLOGIE is involved in the development and qualification of the neutralizer for the RIT 10 German thruster which, together with the British UK 10, will be employed on board of ARTEMIS for north-south station keeping operation.

A key point of the neutralizer qualification activities is represented by the endurance test whose fulfilment will provide a great deal of the confidence for the in-flight neutralizer operation.

This paper presents a review of test activities and relevant results carried out at ESA European Research and Technology Center (ESTEC) to characterize the lifetime operation of PROEL neutralizer collecting thus significant data on its performance throughout time in view of the flight mission.

Furthermore the possibility to compare these data with the ones coming from the tests at PROEL laboratories offers other significant opportunities of verification of neutralizer performances.

The endurance test is still running having, at present, accumulated an operation time of more than 5000 hours with approximately 2500 restart procedures.

In the paper a description of the test facilities employed for the endurance test of the neutralizer is also presented.

Introduction

The development of a neutralizer suitable to operate with the RIT 10 ion thruster started at PROEL in 1989, with the breadboarding phase under ESA contract. Within this programme PROEL acted as sub-contractor of MBB with the task of developing a new neutralizer that could be used as alternative, possibly with better performances, to the already existing one previously developed.

The neutralizer development has been carried out in a very compressed time schedule (thanks to the existing experience in PROEL in the field of vacuum/gas electron tubes) in order to provide ESTEC with an item that could be integrated in the test set up for extensive lifetime test, to acquire confidence of the device operation in view of the already scheduled flight mission.

The results of this test, as well as the test procedures and facilities, are the main objectives of this paper.

Within a radiofrequency ion propulsion system, such as RIT 10, the neutralizer device is used as a plasma source from which low energy electron can be extracted for the following purposes:

1) neutralization of the positive charge in the ejected ion beam through an equivalent negative charge to preserve the spacecraft neutrality;

2) compensation of the positive space charge of the ion beam and then improvement of collimation, which results in a higher thrust efficiency;

3) generation of primary electrons for RF thruster discharge ignition.

The active element of the neutralizer is the hollow cathode plasma source, within which the ionization discharge is produced by field-enhanced thermionic emission.

The neutralizer realization technology (see Fig. 1 and Fig. 2) is based on the following main components:

- hollow cathode with low work function emitting insert heated to thermionic emission temperature by a heating filament;
- keeper electrode with ceramic insulation interface to the hollow cathode assembly;
- ceramic insulator which separates electrically the hollow cathode assembly from the neutralizer body;
mounting interface to the thruster case;
- fitting to the propellant feedline;
- electrical interface with cabling and connector.

The neutralizer is one of the critical components of an ion propulsion system and its operation capability in terms of thermonic emission current, steady-state operation, restart from cold temperature, ignition time, operation throughout a large number of on-off cycles, affects in a dramatic way the successful working of an ion thruster.

It is therefore mandatory for such a component, to acquire on ground evidence and confidence of extensive device operation in a simulated space environment, in order to minimize the risks of unsuccessful completion of the space mission.

The lifetime operation, called also endurance test, still running at ESTEC laboratories, has already provided significant data and results on PROEL neutralizer long term performances.

The general layout of the test facility is schematically shown in Fig. 3. The facility comprises:

- vacuum system;
- propellant gas feedline and flow control unit;
- electrical power supply and control unit;
- data acquisition system.

![Schematic of the testing facility](image)

The photo of the whole test set-up is shown in Fig. 4.

![Picture of the test set-up](image)

**Vacuum system**

The vacuum system consists of a vacuum chamber and a high vacuum pumping system.
The vacuum chamber is a stainless steel vertical cylinder with an inner diameter of 1 m. and a height of 1.2 m. The hardware to be tested is accommodated into a horizontal cylindrical hatch having a diameter of 0.32 m. and a length of 0.36 m. A sliding mechanism allows the hardware extraction/introduction from/to the cylindrical hatch (see Fig. 5).

The Xenon pump (type RPK 10000), which is a second stage of a cryopump, is connected to a condensing plate of about 1300 cm$^3$ of surface. The temperature of the plate at the beginning of the test is about 25$^\circ$K whilst after about 2000 hours of test increases up to some 40$^\circ$K due to the thickness of the Xenon layer.

The pumping speed of the Xenon pump is about 6000 l/s. A vacuum level of the order 8.0E-9 mbar can be reached when the Xenon is not injected into the chamber.

In case of test operation with a single neutralizer, a vacuum level of 1.5 10^{-6} mbar is achieved in the chamber. When two neutralizers are operated simultaneously, the cryopump and the Xenon pump are capable to maintain a vacuum level of about 3.0E-6 mbar, the mass flow rate of the gas injected being equal to 0.04 mg/s for each neutralizer.

The vacuum level is monitored by means of an ionization gauge and a dedicated alarm system interrupts the test in case of malfunctioning.

**Propellant feeding system**

The propellant feedline system has been designed and realized to provide the gas supply contemporary to two neutralizers, so that they can be tested in parallel.

Fig. 6 shows the propellant feeding system, mounted on the outer part of the flange which accommodates the neutralizers. The system is composed of two identical and independent feeding lines, each one supplying a single neutralizer, consisting of:

- a gas bottle containing Xenon;
- pressure reducing valves;
- a mass flow controller;
- an electropneumatic valve connected to the neutralizer power supply (main power supply);
- two manually operated valves.

With the operation of the turbomolecular pump, together with the forepump and the root, a background pressure of 10^{-6} mbar can be reached. At this pressure level these pumps are switched off and the cryopumps are activated.

The cryopump (type RPK 3600), which had originally a pumping speed of 3500 l/s, has been modified in such a way that only the second stage is acting as a cryopump with a temperature of 14$^\circ$K. The minimum temperature of the radiation shield is maintained at about 100$^\circ$K by an electrical heater in order to avoid Xenon condensation and evaporation. In this way only the second stage will pump the gas with a pumping speed of about 1600 l/s.
Photo of Fig. 7 outlines the Xenon feedline piping configuration.

Fig. 7: Picture of the Xenon feedline

At the interface with the flange, one gas feedthrough goes to an Oxygen absorber, which is placed inside the chamber and supplies the Xenon to the neutralizer, whilst another gas feedthrough is used to evacuate the piping.

A metal-sealed valve is placed between the Oxygen absorber and the neutralizer. This valve is automatically controlled by the control unit which operates an electro-motor placed outside the chamber.

The reason for having an Oxygen absorber in the Xenon supply line is that the residual oxygen content of some vpm, which is present in the gas, can produce malfunction of the neutralizers as it has been found during the testing activity of the past years.

The use of an Oxygen absorber is also foreseen in the flight configuration to avoid any risk of neutralizer cathode contamination, due to residual oxygen in the gas feedline.

For the purpose of the test, the Oxygen absorber has been mounted inside the vacuum chamber. Thus even a small leakage in the feeding line outside the chamber cannot influence the purity of the Xenon.

The mass flow control system comprises two mass flow controllers (neutralizer) and a dedicated power supply. The nominal operating range of the mass flow meter, is $0.1 \pm 0.5$ scc/min. Since the mass flow rate needed to operate the neutralizer is in the range $0.01-0.5$ scc/min, the two controllers have been modified and a special calibration for the use with Xenon has been made for this test.

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**Power supply and control unit**

The power supply unit manages the operation of both neutralizers (start-up, steady state operation, shutdown) together with the propellant distribution system, providing all the required control functions.

The power supply is composed of two identical sections, each one controlling a single neutralizer together with the dedicated valves.

Figure 8 shows the block diagram of one section of the power supply. The power supply logic, besides controlling the correct operation of the neutralizer, commands the various phases according to a sequence which can be modified by the user to simulate different mission profile.

![Diagram of power supply and control unit](image)

**Fig. 8:** Neutralizer power supply and electrical set-up

The voltages required for the neutralizer operation are:

- **keeper voltage:**
  
  to regulate the discharge between cathode and keeper:
  
  - nominal operating voltage $12 \pm 25$ V,
  - igniting voltage $200$ V,

  at constant power operation;

- **neutralizer cathode heater voltage:**
  
  - nominally $10 \pm 13$ Vms

  to heat the cathode up to $1000 \pm 1300^\circ$C for ignition;

- **neutralizer bias voltage** (only for the test without the thruster):
to regulate electron current according to beam current:

* voltage range 0÷35 V (max. 200 mA).

A particular of the rack containing the electrical equipment is shown in Fig. 9.

![Fig. 9: Picture of the electrical equipment rack](image)

In photograph of Fig. 10 is shown the collecting target mechanical structure with two neutralizer contemporary under test.

![Fig. 10: Functional test of two neutralizers](image)

### Data acquisition system

A computer controlled data acquisition system has been set up for this test. The system is based on commercially available data acquisition and control hardware.

The data are transmitted from the power supply to a Hp 3852 data acquisition unit, equipped with a 5 1/2 Digit Integrating Voltmeter and Relay Multiplexers, and transferred over a HPIB data link to a Hp series 9000 computer.

A computer code has been written to store and display data during the test. In particular it allows the user to have:

- real time display of the process on the computer screen;
- automatic storage of data on hard disk and 3 1/2" floppy;
- automatic printout of real time stripcharts showing all the measured parameters;
- soft key driven menu which allows to backup data during the test for an off-line analysis and to display on the screen different parameters of both neutralizers.

An off-line computer system, based on a Hp Vectra, is available to perform data reduction and analysis during the life test.

Since the power supply logic provides all the necessary control functions, the software does not have any control capability over the experiment.

The neutralizer operating data which are measured at a rate of one set of readings per minute and stored on the Hp 9000 are:

- heater voltage (H Volt);
- keeper voltage (K Volt);
- keeper current (K Curr);
- bias current (B Curr);
- mass flow rate (M Flow);
- background pressure (P Back).

As a backup in case of hardware or software failure, two strip-chart recorders have been added to the data acquisition system.

### Operating procedure

Because of the low thrust delivered by Ion Systems (typically in the range 10 to 25 mN) and the desire to minimize the thrusting time in order to maximize the efficiency of the manoeuvre, the amount of correction...
performed at the orbital nodes is small. Moreover, in the case of station keeping of medium large satellites, having beginning of life mass ranging from 1200 to 2500 kg, the correction manoeuvres must be executed daily. Typical average values for the nodal firing time of an Ion thruster used for NSSK operation, are in the range 2 to 3 hours per day with a total operating time of more than 7000 hours for a 10-years mission.

For the purpose of lifetime test, an accelerated on/off cycle of 2.0 hrs on / 0.5 hrs off (about 9 cycle/day) has been selected. The total cumulative operating time of the neutralizer is expected to be in the range of 4000 to 6000 hrs.

Once the neutralizer has been mounted inside the chamber and the required vacuum level is reached, it is necessary to perform the activation of the cathode active material (insert) according to the following procedure:

1. the heater current is switched on and left at a value of 0.5 A for 12 hours;
2. the heater current is then increased up to a value of 1.6 A in steps of 0.1 A/s;
3. the keeper voltage is switched on (200 V) during step 2 in order to allow the collection of the thermionic emitted electrons;
4. the heater current is kept at 1.6 A for 2 hrs;
5. when an electron current of at least 2 mA is obtained all the voltages are switched off and the neutralizer is ready for ignition.

The neutralizer discharge is switched on with the following steps controlled by the main power supply:

1. the cathode heater is switched on for five minutes (1.6 A reached in steps of 0.1 A/s);
2. the electropneumatic valve is opened (Xenon flow opened);
3. the neutralizer valve inside the chamber is opened;
4. after 6 seconds the mass flow controller is switched on;
5. the keeper voltage is switched on;
6. the neutralizer discharge is ignited;
7. the cathode heater is switched off just after the discharge ignition;
8. after 1 min the bias voltage is switched on.

The neutralizer is fired for two hours and then switched off for 1/2 hour. This forms a complete cycle which is then repeated until the required total operating time is reached.

Should the neutralizer fail to ignite after 3 minutes, the power supply waits 1/2 hour and then steps 1 to 8 are repeated until discharge is obtained.

**Test results**

The neutralizer performances versus time are fully characterized through the monitoring of the main operation parameters.

The operation parameter under control are the following:

- **heater voltage** $V_H$ (which allows the monitoring of the heating filament hot resistance versus time, being the heater power supply current controlled);
- **keeper voltage** $V_K$ and **keeper current** $I_K$: being $V_K I_K$ constant due to the constant power operation of the keeper power supply, the variation of $V_K I_K$ versus time provides an information on the possible variation of the discharge regime during life time operation (this is valid when if the bias is switched off);
- **bias voltage** $V_B$ and **bias current** $I_B$: being the bias power supply current controlled, the setting of a value of $I_B$ allows a correspondent positioning of $V_B$ in order to reach equilibrium. This voltage is related to the electric field necessary to extract the electron current $I_g$ from the neutralizer;
- **mass flow rate** $m$: the constance of this parameter when the neutralizer is switched on should be verified throughout the lifetime operation. Fluctuations of this parameter are directly related to malfunctionings in the Xenon flowline;
- **background pressure** $P$: the monitoring of this parameter is important to verify the correct operation of the vacuum system during the lifetime test.

Before starting the lifetime test of the neutralizer, a series of tests was performed using a dummy neutralizer (electric simulator) driven by the main power supply logic with the same duty cycle foreseen for the subsequent endurance test.
Calibrated quantities of Xenon were injected into the chamber through the propellant feeding line and the vacuum level monitored to verify the capability of the pumping system to maintain the required value of the background pressure.

The lifetime test on the neutralizer, still running, has been performed for a time in excess of 5000 hours (about 5500 hours). The stability of neutralizer operation parameters can be demonstrated through the comparison of the recording tracks from the chart recorder.

The tracks of Fig. 11, 12 and 13 are referred to a record of the main parameters at different moments during the test.

Fig. 11 was produced after about 100 hours of operation, Fig. 12 after some 3000 hours whilst Fig. 13 refers to one of the more recent cycles of the test when approximately 5500 hours of cumulative firing time were achieved.
The explanation data to interpretate the tracks of Fig. 11, 12 and 13 are the following:

<table>
<thead>
<tr>
<th>Track n.</th>
<th>Parameter</th>
<th>Line Type</th>
<th>Scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(V_K) (V)</td>
<td>continuous thick</td>
<td>1V/div</td>
</tr>
<tr>
<td>2</td>
<td>(I_K) (mA)</td>
<td>dashed</td>
<td>10 mA/div</td>
</tr>
<tr>
<td>3</td>
<td>(V_H) (V)</td>
<td>continuous thin</td>
<td>0.2V/div</td>
</tr>
<tr>
<td>4</td>
<td>(\dot{n}) (sccm)</td>
<td>dotted</td>
<td>0.01 sccm/div</td>
</tr>
</tbody>
</table>

(1) The zero line of \(\dot{n}\) is shifted of 20 divisions, consequently the mass flow rate during operation is about 0.4 sccm (corresponding to 0.04 mg/sec).

Note: due to mechanical reasons (analog chart recorder) the time bases of the 4 tracks are mutually shifted.

The tracks of the figures where recorded when the target was biased with a current of 70 mA.

It is quite clear from the comparison of the above mentioned figures the good repeatability of all the working parameters which did not show any significant sign of degradation over the entire test. The change in the shape of the tracks relevant to \(\dot{n}\) parameter (Fig. 12 and 13) is due a non perfect operation of the flow controller during the off period. In any case the neutralizer switch-off is not affected, being the absolute stop of Xenon flow guaranteed by the automatic closure of the shut-off valve inside the vacuum chamber.

In Fig. 12 the slight fluctuations of the keeper current are due to the noise produced by the keeper power supply that in the continuation of the test has been substituted by a twin model.

It could be curious to point out that part of the GSE (mass flow controller, keeper power supply) did not really survive in full efficiency the lifetime test of the neutralizer and that on the contrary the latter did not show any remarkable degradation in performances even if its operation has been occasionally interrupted for the recovery of malfunctioning equipments.

The lifetime test has been performed with a bias current of the target, simulating the presence of the ion beam from the thruster, of about 70 mA.

A very significant indication of the neutralizer performance is represented by the voltage-current characteristic.

During one of the last cycles of the neutralizer lifetime test the target bias current was varied between 50 and 90 mA and the correspondent values of the bias voltage were recorded.

The variation of \(V_{\text{bias}}\) versus \(I_{\text{bias}}\) is shown in Fig. 14 in the case that the keeper power supply is working at the constant power of about 8.5 W.

The upper limit of 90 mA, was due to the bias power supply (power limited).

It is important to point out that the electron current that can be extracted from the neutralizer, when a collecting target positively biased is used, depends on the power of the target power supply. The expected emission current when a real ion beam is present is reasonably higher.

This is mainly due to the compensation of the negative space charge produced by the positive ions in the beam.

This curve is only to demonstrate that electrons can be really extracted. It is valid only for the given test setup, geometry, discharge power, background pressure, etc. In connection with the ion beam of a thruster a bias voltage has not to be used.

As said, the lifetime test is in progress and another 2000-3000 hours of testing are planned before opening the chamber for the inspection of the neutralizer (a detailed analysis is foreseen in PROEL also through scanning electron microscope and micro-analysis).

\[ V_{\text{bias}} \text{ vs } I_{\text{bias}} \text{ - measured data} \]  

Fig. 14: \(V_{\text{bias}}\) versus \(I_{\text{bias}}\) with the keeper power supply operating at a constant power of about 8.5 W
Conclusion

A facility to test Xenon neutralizers for ion thrusters has been set-up at ESA Electric Propulsion Laboratory.

The facility includes a vacuum chamber of about 1 m$^3$ volume, a cryopanel for condensation of Xenon gas, a cryopump and a Xenon pump (vacuum level of 8x10^-9, without gas flow). The mechanical ground support equipment includes also a Xenon gas feedline with a mass flow controller and service valves. The electrical ground support equipment is mainly constituted by the electrical power supply and control unit for neutralizer operation and by the data acquisition system for the recording/processing of the results from the test.

The facility has been successfully used to test a neutralizer manufactured by PROEL TECNOLOGIE for the RIT-10 ion engine within the ARTEMIS programme.

The test was dedicated to the lifetime performance evaluation (endurance test) of a neutralizer fed with Xenon gas at the nominal flow rate of 0.04 mg/sec.

The accumulated operation time in excess of 5000 hrs, without any appreciable degradation of the working parameters, has provided encouraging data and then the confidence of the successful device operation, in a simulated space environment, in view of the real space mission.

The continuation of the lifetime test at ESTEC, the extensive qualification programme, at present running at PROEL TECNOLOGIE, and the test of the neutralizer together with the thruster will complete the test programme necessary to qualify the device for the flight mission of 1994.

References


