Neutralizer/plasma contactor technologies: review of development activities at Proel Tecnologie

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Abstract

This paper presents the latest activities and the relevant achievements relevant to the neutralizer/plasma contactor technology, whose development has been undertaken by Proel Tecnologie since the end of the 80's. Many neutralizer/plasma contactor devices have been studied, manufactured, and tested by PROEL to cover different space applications. The neutralizer for the RIT10 ion thruster (300 mA current, 7W power) has now reached the stage of flight hardware. A bigger neutralizer (3A current, 50 W power) is now being developed at elegant BB/EM level for the ESA XX thruster. A family of plasma contactor devices, for emission currents up to 10 A, have been developed at EM level and successfully tested in view of applications on Tethered Space Systems. To assess the suitability of the plasma contactor technology, as applied to overcome the problem of spacecraft charging neutralization, analysis/test activities have been successfully carried out and a modular in-flight experiment has been configured for a demonstration of the technology effectiveness in the real space environment.

Introduction

Neutralizers/plasma contactors based on the hollow cathode technology, thanks to their capability to provide a low energy and a relatively high density plasma cloud can be profitably exploited, in space missions, for a number of operational and scientific applications. These devices, properly mounted and connected to the space vehicle, can establish a very low impedance electrical contact between the space vehicle itself and the surrounding plasma environment.

The main applications of neutralizers/plasma contactors are related to:

- neutralization of positive ions produced by an ion/plasma thruster;
- control/prevention of electrostatic charging of spacecrafts/space platforms;
- closure of the electrical circuit between the two ends of a Tethered Space System and the ionosphere to allow electric power, or alternatively, thrust generation;
- scientific experiments where the interactions between an artificially produced high density plasma cloud and the tenuous ionospheric plasma are investigated/characterized.

Proel Tecnologie has undertaken and is currently involved in a number of activities in the neutralizer/plasma contactor field, both under ESA and ASI contracts such as:

- Flight-Model (FM) Neutralizer for the RIT 10 ion thruster, due to be flown on board ARTEMIS satellite (ESA/DASA Contract) [1], [2], [3], [4];
- Engineering Model (EM) Neutralizer for the European primary propulsion ion thruster named ESA-XX (ESA/DASA Contract) [5];
- High current EM plasma contactors for Tethered System applications (ASI Contract) [5], [6];

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on ground test activities and preliminary assessment for an in-flight experiment on the plasma contactor technology used for spacecraft charging prevention (ESA Contract for on ground test activity).

The neutralizer for RIT 10 on ARTEMIS satellite

Status of activities for neutralizer FM design validation

In the frame of ARTEMIS program, PROEL TECNOLOGIE is currently manufacturing the neutralizer Flight Models (FM's) that will be delivered as components of the Ion Propulsion package (IPP), for what concerns the RIT 10 (DASA) Radiofrequency Ion Thrusters.

Many of the parts composing the neutralizer FM's have been manufactured. Additional analyses and tests have been carried out with the objective of confirming the final design for the FM's. In particular, a random vibration analysis of the neutralizer with the new input spectrum (taking into account the amplification factors introduced by the gimbal) has been done with reference to:

- definition of the mechanical model and evaluation of natural resonance frequencies;
- Power Spectral Density (PSD) versus frequency for the significant points of the neutralizer structure;
- relative displacements with reference to different significant points of the neutralizer structure;
- rms stresses and strains distribution.

The displacement distribution, referred to the XY plane is shown in Fig. 1; the distributions presented in the pictures corresponds to the first resonance frequency (worst case).

![Displacement distribution along the neutralizer structure as a consequence of the new random vibration levels](image)

The maximum stress, concentrated at the end of the truncated cone section, is lower than the breaking load for the material, with an adequate safety margin. The displacement is maximum on the tip of the cathode region; due to design of this part, any cathode-keeper impact is however not possible.
With regard to the neutralizer performance, further data confirming the technology long term operation capability have been obtained.

Endurance tests [1] of neutralizer critical parts (namely cathode heater, cathode insert, brazings/weldings close to the cathode tip), without gas flow in sealed-off container (automatically running in PROEL since 1989), have till now produced the following results:

- Five neutralizer items have exceeded 90000 cycles (10 min on/10 min off), with a total "on" time in excess of 15000 hrs. One item of the lot has been tested throughout 137000 cycles with an "on" time of about 23000 hrs.

The endurance test is planned to continue up to reaching the failure of some critical part (e.g. the heater) or the reduction of thermionic emission from the insert below an acceptable threshold level (e.g. few hundreds \( \mu A \)).

Besides, an additional neutralizer, submitted in PROEL to a functional lifetime test (with gas flow), has now accumulated 12000 hrs operation. This test, carried out by PROEL as a self financed activity, is still running with a set-up quite similar to the one used in ESTEC-YPE lab. to validate the neutralizer technology for 15000 hrs of operation. The results obtained at PROEL labs provide a further confirmation of the neutralizer technology viability for what concerns long term operation in a cycled mode (105 min on, 15 min off).

**Neutralizer test under "adverse atmosphere"**

One important concern about the use of impregnated cathodes for ion propulsion neutralizers is related to the capability of these cathodes to operate, without any significant degradation, after a prolonged exposure to "adverse conditions", that can typically be present in the satellite integration room of a sub-tropical or equatorial (like CSG, Kourou) launch site.

The term "adverse conditions" is here referred to an air atmosphere characterized by a temperature \( \geq 25^\circ C \) and by a relative humidity \( \geq 60\% \).

In principle, neutralizers based on impregnated cathodes, should be installed onto the ion thrusters shortly before the launch, where the term "shortly" indicates a time span of hours or one day maximum. It is known in fact [7] that exposure of impregnated cathodes to moisture or a high degree rel. humidity can bring to hydration of compounds contained in the cathode matrix. The subsequent heating of the cathode can lead, in the worst case, to a stress of the tungsten matrix due to blisters or micro-fractures.

"Late access" installation of these neutralizers had been initially envisaged to avoid any risk, in particular in the case when the neutralizer/s had been already activated and operated during the propulsion system acceptance test.

It is obvious that the time constraints from such a procedure imply severe constraints on the launch activities preparation. What the satellite prime contractors would like to have is an ion propulsion system where the neutralizer/s, activated and operated during the thruster acceptance test, can be integrated, at spacecraft level, and stored up to some months before the launch.

Taking into account this strong motivation, that can affect in a significant way both the viability and commercialization of the ion propulsion technology, PROEL has undertaken a preliminary test activity to validate the neutralizer technology for long term storage at spacecraft level. A systematic and a more extended test activity on this topic will be formally carried out in the near future on the neutralizer EQM's, in the frame of ARTEMIS program, under ESA/DASA contract.
The test set-up used by PROEL for the preliminary test of the neutralizer in "adverse conditions" is shown in Fig. 2.

In a clean room class 100,000 with controlled humidity and temperature (50% R.H., 22°C) a humidifier is used to raise the relative humidity, from 50% to 62% ±2%, in the plexiglass tank. Besides, a heater and a temperature probe are respectively used to raise and monitor the temperature.

Two neutralizers have been submitted to the "adverse conditions" test according to the sequence shown in Tab. 1.

<table>
<thead>
<tr>
<th>Neutralizer Item</th>
<th>PHASE A</th>
<th>PHASE B</th>
<th>PHASE C</th>
<th>PHASE D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item 1</td>
<td>Storage in vacuum (since end of fabric.)</td>
<td>Activation and functional test (2/3 days)</td>
<td>Exposition to adverse conditions (2000 hrs)</td>
<td>Activation and functional test (2/3 days)</td>
</tr>
<tr>
<td>Item 2</td>
<td>not activated</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tab. 1: Neutralizer test under "adverse conditions": time sequence of the events

The results of the test are summarized in Tab. 2.

<table>
<thead>
<tr>
<th>Measured Parameters</th>
<th>ITEM 1</th>
<th>ITEM 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Activation or re-activation without gas flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heater voltage (Vrms)</td>
<td>Phase B: 10.5</td>
<td>Phase B: 10.6</td>
</tr>
<tr>
<td>Cathode temp. (°C)</td>
<td>1160</td>
<td>1150</td>
</tr>
<tr>
<td>Thermionic current (mA)</td>
<td>Phase D: 2.4</td>
<td>Phase D: 2.3</td>
</tr>
<tr>
<td>(2) Functional test: verification of internal discharge with gas flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Keeper voltage (V)</td>
<td>Phase D: 14.15</td>
<td>Phase D: 14.56</td>
</tr>
<tr>
<td>Keeper current (A)</td>
<td>Phase D: 0.530</td>
<td>Phase D: 0.515</td>
</tr>
<tr>
<td>Cathode temp. (°C)</td>
<td>Phase D: 930</td>
<td>Phase D: 930</td>
</tr>
</tbody>
</table>

(1) Heater current = 1.6 Arms; (2) Gas flow rate = 0.5 sccm, keeper power = 7.5 W

Tab. 3: Results of activation/functional test after the long term exposure of 2 neutralizers to "adverse conditions"
The slight differences on some parameters are due to the statistical dispersion of the neutralizer operation parameters: no significant degradation of the neutralizer technology can be highlighted after the exposure to adverse conditions.

**Neutralizer for the ESA-XX ion thruster**

The ESA-XX [8] is an ion thruster currently under development with ESA sponsorship. The thruster is conceived for primary propulsion applications, i.e. for missions (such as interplanetary missions) where very high velocity increments (several km/s) are required. For these missions thrust levels (100-300 mN) one order of magnitude higher than the typical NSSK thrust levels (10-30 mN) are typically required. The ESA-XX thruster technology is based on both the German (radiofrequency electrodeless discharge) and British (simple and reliable grid system) experience accumulated in this field. PROEL TECNOLOGIE is involved in the program for what concerns the development of a suitable neutralizer for the thruster operation.

For the ESA-XX a nominal thrust level of 200 mN has been selected to meet the basic requirement of possible interplanetary missions. A beam voltage of 2 KV has been chosen for thruster operation at the nominal thrust level. As a consequence, a nominal value of about 2.7A is obtained for the beam current. A neutralizer dedicated to the ESA-XX thruster should therefore be capable of a total emission of at least 3A. A reasonable value for the necessary power to sustain the discharge when 3A of electrons are extracted is roughly around 50W. With these input specifications the utilization of the basic neutralizer design developed for RIT 10 (300 mA, 7W) was not possible and the definition of a brand new design has been retained as mandatory.

The cross section drawing of the new neutralizer (named NccA 3000) currently under development at elegant BB/EM level, is shown in Fig. 3.

![Fig. 3: Cross-section of the neutralizer NccA/3000, in course of development for the ESA XX thruster (ESA/DASA contract)](image)

The general guideline that has been followed in the neutralizer design scaling-up, starting from the baseline neutralizer technology developed for the RIT10, has been that of maintaining a thermal regime, both in the heating-up phase and in the steady-state operation, reasonably close to the one successfully experienced for the RIT 10 neutralizer.

Preliminary test performed on the new NccA/3000 model have confirmed the neutralizer capability to extract an electron current of at least 3A from the plasma discharge, in accordance with the
received operation requirements. The NccA/300 most important functional parameters are reported in Tab. 3:

<table>
<thead>
<tr>
<th>Heater (on during, heating up, off during steady state operation)</th>
<th>Keeper</th>
<th>Xe flow rate (mg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance (Ω)</td>
<td>Voltage (VRms)</td>
<td>Current (IRms)</td>
</tr>
<tr>
<td>Cold 0.25±10%</td>
<td>1.5±10%</td>
<td>11</td>
</tr>
<tr>
<td>Hot</td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

Tab. 3: Main operating parameters of the neutralizer model NccA/3000

A picture of the Ncc/A 3000 neutralizer is shown in Fig. 4.

Fig. 4: The neutralizer NccA/3000 for the ESA-XX ion thruster (ESA/DASA contract)

It is worth to point out that a neutralizer, quite similar (with an emission current of 3-5 A) to the one developed for ESA XX thruster, could be successfully utilized also in a Stationary Plasma Thruster, such as the Russian SPT 100, TAL (Thruster with an Anode Layer) and the French Mark 2 (SEP). In fact, the adoption of a neutralizer technology based on an impregnated cathode (instead of the current lanthanum-hexaboride cathode technology) would provide, most likely, a significant contribution for the improvement of the stationary plasma technology viability.

**High Current Plasma Contactors for Tethered System Applications and Space Station Charging Prevention Neutralization**

A family of Plasma Contactor devices has been developed up to engineering model under ASI (Italian Space Agency) contract, to cover applications (namely Tethered Space Systems and for neutralization of space stations) where current levels up to 10 A are required.

The main operating parameters of the NccA/5000 and Ncc/10000 models of the family are presented in Tab. 4.

<table>
<thead>
<tr>
<th>Model</th>
<th>Discharge Voltage (V)</th>
<th>Discharge Current (A)</th>
<th>Power Consumption (steady state) (W)</th>
<th>Heater power (only start up) (W)</th>
<th>Gas flow rate (sccm)</th>
<th>Ion emission (mA)</th>
<th>Electron emission (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NccA/5000</td>
<td>11-13</td>
<td>5</td>
<td>50-70</td>
<td>60-70</td>
<td>2-3</td>
<td>1</td>
<td>up to 5</td>
</tr>
<tr>
<td>NccA/10000</td>
<td>9-12</td>
<td>10</td>
<td>90-120</td>
<td>60-70</td>
<td>3-5</td>
<td>2</td>
<td>up to 10</td>
</tr>
</tbody>
</table>

Tab. 4: Operation parameters of high current plasma contactor developed by PROEL (ASI Contract)
The development of this device family has been supported by computer simulations: the thermal aspects (ESATAN Code) and the internal discharge mechanisms (home developed emission process model and relevant simulation code) have been diffusively analyzed. The use of an emission process model has provided the design criteria for hollow cathode performance optimization and scaling laws. In particular the model has been developed for lower current devices and then used to verify large current device behaviour (specifically for what concern I/V characteristics) [9].

One very significant output obtained with the code is the simulated discharge voltage (cathode-keeper voltage at steady-state operation) when a given flow rate and discharge current are provided as inputs.

In Tab. 5 the input and calculated output parameters of the developed computer code are presented.

<table>
<thead>
<tr>
<th>Physical Constants</th>
<th>Geometry and Material Data</th>
<th>Gas Data/Experimental Parameters/Laws</th>
<th>Input Device Working Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>k (Boltzmann constant)</td>
<td>do (orifice diameter)</td>
<td>m (ion mass)</td>
<td>m (gas flow rate)</td>
</tr>
<tr>
<td>ne (electron mass)</td>
<td>d1 (insert diameter)</td>
<td>e (gas ioniz. potential)</td>
<td>Id (discharge current)</td>
</tr>
<tr>
<td>e0 (vacuum diel. constant)</td>
<td>t (orifice thickness)</td>
<td>ε0 (ion to neutral partition function ratio = 1280 for Xe)</td>
<td></td>
</tr>
<tr>
<td>h (Planck constant)</td>
<td>l1 (Tip-keeper distance)</td>
<td>C1, C2, C3 (gas type parameters for pressure model)</td>
<td></td>
</tr>
<tr>
<td>a0 (thermionic constant)</td>
<td>d2 (keeper hole diameter)</td>
<td>C4 (I/d1/d2) ratio</td>
<td>C4, C6 (cathode param. for thermal model)</td>
</tr>
<tr>
<td>s (Stefan Boltzmann constant)</td>
<td>d3 (keeper front diameter)</td>
<td>Te (el. temp. at orifice)</td>
<td></td>
</tr>
<tr>
<td>g (specific heat ratio)</td>
<td>le (cathode length)</td>
<td>(\Psi) (neutral exp. angle)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INPUT</th>
<th>Cathode Interior calculated Parameters</th>
<th>Orifice calculated Parameters</th>
<th>Calculated Parameters in the keeper region</th>
<th>Discharge calculated Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>n0 (neutral density)</td>
<td>n01 (neutral density)</td>
<td>n02 (neutral density)</td>
<td>Vd (discharge potential)</td>
<td></td>
</tr>
<tr>
<td>P1 (pressure)</td>
<td>ne (plasma density)</td>
<td>ne2 (plasma density)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ne (plasma density)</td>
<td>Je1 (electronic current density)</td>
<td>ΔVd2 (interior double sheath drop)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vp (plasma temperature)</td>
<td>Ji1 (ion current density)</td>
<td>ΔVh (ohmic sheath drop)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ts (emissive insert temperature)</td>
<td>Ji (ion current density)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ji (thermionic current density)</td>
<td>Jih (thermionic current density)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ji (ion current density)</td>
<td>Qhs (power absorbed by the emission region)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tab. 5: Summary table of input/output parameters of the computer code developed by PROEL for high current cathode design definition

The 10 A devices have been characterized in vacuum chamber. In particular, the internal and external (vs a target) I/V characteristics, as a function of gas flow rate for single devices [6] and the current exchange between two plasma contactors devices have been obtained and analyzed.

In fig. 5 the current exchange between two plasma contactors, as function of chamber pressure and relative bias voltage, is shown.
This test has confirmed the capabilities of these devices to collect electron current up to 10 A and also the capability of the two plasma contactors to exchange, each other, high currents with a relatively low voltage drop. These features are extremely interesting both for Tethered System applications and for spacestation / large space structure charging prevention/neutralization.

**Plasma Contactor Technology for Spacecraft charge Neutralization:**  
*on Ground Tests and Assessment of an in-flight Experiment*

The accumulation of electrostatic charge on a spacecraft in orbit is an important phenomenon of concern both to the satellite manufacturer and the spacecraft user alike. This is because the built-up of absolute and, in particular, differential charge on the spacecraft often leads to uncontrolled discharge events which adversely affect the functioning of electronic systems of the satellite[11], [12], [13], [14], [15].

One of the most effective active charge control methods is based on a hollow cathode plasma source (plasma contactor).

A plasma contactor in fact is capable of generating a low energy plasma cloud from which electrons or positive ions can be extracted, according to the sign of the potential difference between the device itself and the surrounding environment: in this way a low impedance electrical contact, between the spacecraft and the environment plasma or between spacecraft parts (initially) at different potentials can be established and maintained.

PROEL TECNOLOGIE assessed, under ESA contract, the suitability of this system for its use on board future European satellites.

This assessment activity was carried out both by analysis and test [10], mainly focusing on two critical environments:
- the geosynchronous orbit;
- the low polar orbit.

The most significant aspects of spacecraft charging were evaluated for both environments using a simple numerical method, which roughly estimated the accumulated charge and the consequent current flow that the plasma contactor system should produce to neutralize that charge. These calculations indicated that the plasma contactor can maintain the potential of the spacecraft within a range of a few volts both in geostationary and low-polar orbit. Requirements for these model missions were developed and a suitable plasma contactor system and its main characteristics were then defined.
An on-ground test activity has been, beside, accomplished to evaluate the plasma contactor effectiveness as a charge neutralizer both for absolute and differential charging situations.

The set-up used for the test is shown in Fig. 6 [10].

![Fig. 6: Schematic of the experimental set-up for the evaluation of the plasma contactor effectiveness as a spacecraft charge neutralizer (ESA contract)](image)

Insulated metallic objects were charged to different levels, positive or negative, and the variations in their potential under the action of the plasma contactor were observed. The time required to remove the accumulated charge from the metallic object was also assessed.

Results of analyses and tests have shown that a plasma contactor system, based on the hollow cathode technology, can be a very powerful tool for spacecraft charge control both for geostationary and low polar orbit satellites.

The next logical step would be the development and the validation in space of a plasma contactor system. On this purpose an in-flight demonstration experiment had been initially proposed by PROEL and approved by ESA within the TDP 2 program. More recently the experiment has been re-oriented and re-formulated by ESA, to cover a wider application area of the spacecraft-space environment interactions.

The new experiment is conceived and proposed with a modular philosophy: depending on the flight opportunity and the budget (mass and power) available, different configurations of the flight hardware may be chosen, which will make possible different experiments.

A maximum of 5 boxes (assemblies) will form the flight hardware:

- **PCA** Plasma Contactor Assembly (core assembly of the payload)
- **CDA** Conditioning/Diagnostic Assembly
- **BCA** Body Conditioning Assembly
- **SAA** Solar Array Assembly
- **CIA** Control/Interface Assembly

With these 5 boxes, 4 types of experiments are feasible:

A. Plasma Contactor I-V characterization (with PCA+CDA+CIA),
B. S/C charging control via the Plasma Contactor operation (with PCA+CDA+CIA),
C. Forced charging of a reference metallic body and discharging via the Plasma Contactor operation (with PCA+CDA+BCA+CIA),
D. Solar Array Samples electrostatic discharge test (with PCA+CDA+SAA+CIA).
Experiment A has the purpose of validating the plasma contactor technology in the real space environment, through the detection of current-voltage characteristics.

Experiment B aims at verifying the plasma contactor capability to control the spacecraft electrostatic charging up.

In experiment C the plasma contactor capability to perform a "grounding" of the structure (reference metallic body, insulated from the S/C frame) to which it is connected, is tested. Experiment C is accomplished w.r.t two different cases:

c1) Continuous injection of current into the body. This configuration simulates the operation of the plasma contactor in presence of a constant impingement of charged particles onto the spacecraft. In this case the successful plasma contactor operation is obtained if the potential growth of the body is prevented beyond a certain threshold.

c2) The body is charged up to a certain voltage level, then the current source is disconnected. Afterward, the plasma contactor is operated to verify its capability to completely discharge the body.

Experiment D has the purpose of detecting and characterizing possible discharge events on solar array samples biased and exposed to the space plasma.

The following situations are considered:

d1) Discharge detection and characterization when the plasma contactor is switched off;

d2) Discharge detection and characterization when the plasma contactor is on and connected to the S/C frame (grounded plasma cloud);

d3) Same as d2 but with the plasma contactor floating with respect to the S/C frame (floating plasma cloud);

d4) Discharge detection and characterization in presence of a neutral plasma cloud (plasma contactor switched off but gas flow valve open).

At present ESA, with the support of PROEL, is evaluating the possibility to set-up a multinational team to promote the accomplishment of the in-flight experiment (currently included in the ESA priority list) pursuing the support of different European nations.

Conclusions

The latest developments of the neutralizer/plasma contactor activities at PROEL TECNOLOGIE have been presented with particular reference to:

- Manufacturing and test of the FM neutralizer for the RIT 10 thruster (ref. ARTEMIS mission).
- Development, manufacturing and test of an elegant BB/EM neutralizer for the ESA-XX thruster (ref. primary propulsion for interplanetary missions).
- Scaling-up design criteria identification, development, manufacturing and test of high current plasma contactor for Tethered System applications and for controlling the electrostatic charge accumulation on large space structures (ref. Italian activities on Tethered Space Systems).
- Studies, analysis and test of the plasma contactor technology for presentation/neutralization of satellites spacecraft charging in GEO and polar LEO environments (ref. safety of telecom/earth observation satellites).
- Definition of an in-flight experiment for the demonstration of the plasma contactor technology effectiveness.

The activities in this field have been successfully carried out by PROEL TECNOLOGIE both under ESA and ASI contract. Near term plans foresee the development of a payload based on the plasma contactor, in view of a demonstration mission, as well as the space qualification of medium/high current neutralizer devices.
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