The paper deals with an experimental activity carried out at Alta on a multichannel hollow cathode. The cathode has been operated at currents from 20 to 160 A, with argon mass flow rates ranging between 1 and 5 mg/s. During operation, the cathode external wall temperature has been measured using a bi-color video pyrometer, mounted on a 1-axis slide to record the temperature profile along the cathode axis. A 100-hr endurance test has been performed at discharge current of 150 A and mass flow rate of 4.5 mg/s. To assess the effect of cathode degradation cumulated during the endurance test, electrical characteristics at various mass flow rates have been measured before and after the 100-hr test. The maximum temperature measured at the cathode tip was 2500°C. The cathode mass difference between the beginning of life and the end of test was 2.32 g, from which an average erosion rate of about 33 ng/C is evaluated. Moreover, the results of the numerical model developed by the RIAME-MAI are compared with the data collected during the test activities in terms of electrical characteristic and erosion rate.

**Nomenclature**

\[
\begin{align*}
DAQ & = \text{data acquisition} & HV & = \text{high voltage} \\
IAC & = \text{ion accommodation coefficient} & MCHC & = \text{multichannel hollow cathode} \\
HC & = \text{high current} & MPDT & = \text{magneto-plasma-dynamic thruster} \\
HP & = \text{high pressure} & SCHC & = \text{single channel hollow cathode}
\end{align*}
\]

1 Ph.D Student, University of Pisa, m.detata@alta-space.com
2 Ph.D Student, University of Pisa, r.albertoni@alta-space.com
3 Project Manager, Alta S.p.A., p.rossetti@alta-space.com
4 Program Manager, Alta S.p.A., f.paganucci@alta-space.com
5 CEO, Alta S.p.A., m.andrenucci@alta-space.com
6 Assistant Professor, MAI, riame@sokol.ru
7 Vice Director, RIAME-MAI, riame@sokol.ru
8 Head of laboratory, RIAME-MAI, riame@sokol.ru

**Presented at the 32nd International Electric Propulsion Conference, Wiesbaden • Germany September 11 – 15, 2011**

M. De Tata¹, R. Albertoni²
*University of Pisa, Pisa, 56100, Italy*

P. Rossetti³, F. Paganucci⁴, M. Andrenucci⁵
*Alta S.p.A., Pisa, 56100, Italy*

*and*

M. Cherkasova⁶, V. Obukhov⁷, V. Riaby⁸
*RIAME-MAI, Moscow, Russia*
I. Introduction

The adoption of high-power electric propulsion systems in space is nowadays limited by the lack of in-space power, although they are considered as the most promising options for heavy-payload orbit raising and for deep space missions. In the high power range (100 kW - 1 MW), MPD thrusters are effective candidates, even though several aspects of design and operation must be improved to guarantee higher thrust efficiency and reliability. The cathode represents the life-limiting component, being the electron source in the plasma generation process, subjected to high temperature and fast erosion of material. At current levels typical of 100 kW-class steady-state MPD thrusters (10^3-10^4 A), the SCHC is not a valid option for a long time operation yet. To support high current levels and to guarantee a reasonable lifetime, a SCHC should have a very large channel diameter and an excessive mass flow rate, causing difficulties during ignition and thruster malfunctions. The MCHC represents an effective alternative, being able to sustain high current discharges with a limited mass flow rate, reducing operating temperature and discharge voltage.

In this scenario Alta, in collaboration with RIAME-MAI, is carrying on theoretical and experimental research activities for the assessment of MCHC operation. The experimental campaign presented in this paper is part of a wider research program aimed at the development of long-life cathodes for 100 kW AF-MPD thrusters. The main objective of the test activity is the assessment of the erosion process of a MCHC by means of measurements of electrical characteristics and wall temperature before and after a 100-hr test, visual observation and measurement of the eroded mass.

II. Experimental Equipment

A. Test item

The MCHC tested, shown in Figure 1, was designed by Alta and RIAME-MAI to operate at a nominal discharge current of 150 A with an argon mass flow rate of 4.5 mg/s. The high temperature expected during operation led to use materials with a high melting temperature, e.g. tungsten and molybdenum. The MCHC was manufactured by RIAME-MAI and assembled and tested at Alta.

![Figure 1 Schematic drawing of the MCHC](image)

The 36 rods of 1.4 mm diameter were packed inside the main tube, lain in the frontal cross section. The main tube was a 10 mm inner diameter cylinder, electron beam welded to the holder. In the early design the holder was screwed to the fixing flange, but a failure due to thermal cycles during operation led to a modification of the mechanical interface. Instead of a screwed holder, two stainless steel flanges tied together by bolt connections were introduced. In Figure 2 the bearing seat of the cathode tightened by the two flanges is shown. The gas connection was obtained by using a nut screwed to the back side of the holder. The gas sealing was guaranteed by a conical coupling between the gas connector and the holder. The four holes of the fixing flange were used to connect the cathode assembly to the support structure.

After the assembling process, i.e. the filling of the main tube with the 36 rods, a non-conformity with the design requirement on the frontal surface was observed. As emphasized in Figure 2, two rods were placed in the main cylinder slightly deeper than the other rods, creating a cavity. As discussed later, this caused a geometrical discontinuity that affected the cathode operation. Assuming a constant diameter of the rods, the actual open cross section of the cathode was measured around 17.4 mm^2.
B. Test Facility

The experiments were performed in the Alta’s IV-4 vacuum chamber. IV-4 is composed of two sections made of AISI 316L stainless steel: the auxiliary chamber 2 m in diameter, 3.2 m in length and the small chamber, 1 m in diameter, 1 m in length. The two sections are connected through a 1 m diameter gate valve. The chamber is equipped with a high performance pumping system, capable of maintaining the pressure level during cathode operation below $10^{-4}$ mbar. The chamber pressure was continuously monitored by three Leybold-Inficon ITR90 sensors.

The small chamber was used to accommodate the cathode setup, its electrical and gas feeding subsystems, while the auxiliary chamber allowed a free expansion of the plume reducing the interactions with chamber walls and accommodated the main pumping system.

C. Electrode Setup

In Figure 3 the experimental setup is shown. The cathode and the anode were mounted on two AISI 316 mounting flanges. A copper water-cooled anode was used in order to avoid the damage of the setup due to the high expected temperature.
acquisition boards using decouple optical modules. Both gas feeding line and water pipes were insulated with respect to the vacuum chamber, but 1 MΩ resistance was measured through the conductive pattern caused by the water itself, which allowed a slight current conduction to ground during operation (< 2 mA).

In Figure 4 the schematic diagram of the electrical circuit and of the gas feeding system is shown. The electric circuit includes a high voltage and a high current power supplies in parallel. The HV power supply was used to ignite the cathode discharge, as it was capable of delivering a maximum current of 12.5 A at 500 V. The HC power supply was used for the nominal subsequent operations, providing a maximum current around 200 A. Two Semikron SKN diodes able to sustain up to 1200 V and 500 A were used to protect the power supplies from reverse current. A ballast resistance of about 1 Ω was used to prevent the switching off of the HV power supply due to the sudden decrease of the electric load at the arc ignition.

Figure 4 Schematic diagram of the electrical circuit and the gas feeding system

The gas feeding system is depicted in Figure 4. It consisted of two independent lines: one line was fed with argon gas 5.0 purity grade, while the other line with xenon gas 4.8 purity grade. Each line had a dedicated mass flow controller (Bronkhorst F-201C-FAC-22-V for xenon and Tylan FC-261 for argon) and Swagelok valves. The xenon gas was used to ease the arc ignition and the transition from the diffuse mode to the spot mode.4,5

D. Diagnostics

The electrical parameters were measured by using current (LEM LT505-S) and voltage probes (LEM CV3-1500). The instrument accuracy at 25°C of the former was ±0.5% on the full scale of 1400 A, while the latter had a ±0.2% of accuracy on the full scale of 1500 V. The voltage probe measured the potential difference between the anode and the cathode, while the cathode reference potential, i.e. the cathode potential with respect to ground, was periodically checked during operation and a constant value around -6 V was measured. Therefore all the voltage data presented refer to the difference between the anode and the cathode voltages.

Eight K-type thermocouples provided the temperature measurement in the corresponding reference points of the setup assembly. Moreover 3 K-type thermocouples where used to monitor the water temperature at the inlet and outlet of the water cooling system. All the temperature measurements had an accuracy within the ±2%.

The accuracy of the argon mass flow rate was around ±1% on the full scale of 30 mg/s, while the xenon mass flow controller had an accuracy of ±0.6% on the full scale of 2000 mg/s.

All the sensing probes were connected to the DAQ system controlled by a LabView software.

The cathode temperature along the axis was measured using the DIAS Pyrospot DSR 10N bi-color optical pyrometer, which had a measurement accuracy of ±0.5%. The pyrometer was mounted on a 1-axis slide moved manually by a precision screw, mechanically aligned with respect to the axis of the cathode. During operation, once the high current arc was established and the thermal effects reached the steady state regime, the pyrometer was moved starting at the downstream tip towards the upstream direction with 5 mm-intervals (or 1 mm for fine
mapping) to record axial temperature profiles. The measurement error calculated using the standard deviation over the acquisition time interval accounts for the slow current variations tied with the non-ideal current stability of the power supply and for the non-linearity physical events.

The pyrometer was placed outside the vacuum chamber, at a distance of 650 mm from the cathode axis, as shown in Figure 5. According to the optical system specification, the spot measurement area was a function of the measurement distance. At the distance of 650 mm the minimum spot diameter was around 3.25 mm. Therefore each value of the measured temperature herein reported must be intended as the mean value of the temperatures in the area of 3.25 mm in diameter centered on the measurement point.

![Figure 5 DIAS Pyrospot DSR 10N bi-color pyrometer mounted on the precision slide](image)

To assess the cathode erosion rate during the endurance test, the METTLER-TOLEDO WM503-L22 high-precision balance was used to weigh the cathode before and after the test. The balance had a readability of 1 mg and an accuracy less than ±0.001% at 25°C on the full scale range of 510 g. It was calibrated before each measurement.

III. Cathode Test

The test campaign was divided in three phases: the cathode arc characterization, the 100-hr endurance test and the post-test characterization. The first phase was necessary to characterize the electrical behavior of the arc and the temperature profile along the cathode axis: the I-V characteristics and wall temperature profiles were recorded at mass flow rates ranging between 1 and 5 mg/s. During the second phase an endurance test of 100 hours at 150 A of current and 4.5 mg/s of mass flow rate was performed. This phase was split in 9 sessions for logistic reasons. After the endurance test the electrical characteristics and the temperature profiles were recorded again to assess the erosion effects on the cathode performance. The cathode underwent 103 ignition cycles, for a total of 140 hours of operation. The argon consumption was about 1200 g, while the xenon mass used during the first phase of the discharge was around 1000 g.

A. Test procedure

Before starting the nominal operation, a preliminary heating up phase of about 1 hour at 40 A with constant mass flow rate was operated in order to set the cathode at a thermal steady state regime. Then, the nominal operations were performed, i.e. the characterization tests or the sessions of the endurance test. Finally after the shut-down of the power supply, argon gas was flowed for about 1 hour, to force the cooling of the cathode preventing oxygen contamination of the tungsten at high temperature.

In Figure 6 the cathode ignition is shown in detail. On the left side the electrical parameters are reported with respect to the time. At the very beginning of the operation the potential difference between the electrode was set at 500 V using the HV power supply. The electric discharge was established once the xenon gas was flowed through the cathode. The decrease in the arc impedance allowed to switch to the HC power supply, which provided the necessary high current at a lower voltage. The mass flow rates are reported on the right side together with the chamber pressure with respect to the time. The arc discharge was ignited by using xenon gas flown at mass flow rate around 15 mg/s. After the switching to the HC power supply the cathode operation shifted from the diffuse to the...
spot mode\textsuperscript{4,5}, allowing to operate the transition between xenon and argon, down to a mass flow rate of 3.5 \textit{mg/s}, to perform the heating up phase.

B. Test Results

1. Characterization Test

The characterization test consisted in an investigation of different voltage-current operational points in order to assess the electrical characteristic of the arc discharge for different values of the mass flow rate as well as the operating temperatures. At each operative point a temperature profile along the axis was recorded.

The electrical characteristic recorded is reported in Figure 7. The discharge power as a function of the mass flow rate for different current levels is shown in Figure 8. The maximum power was observed at 130 A forcing the cathode to operate at 1 \textit{mg/s}: due to a clear cathode malfunction this mass flow rate value was not coupled with higher currents. According to the temperature measurements, the peak in such condition was about 2500°C.

![Figure 6 Detail of the cathode ignition](image)

![Figure 7 Electrical characteristic](image)

In Figure 9 and in Figure 10 samples of temperature profiles are shown, respectively for current values of 100 A and of 150 A.
Figure 8 Discharge power as a function of the mass flow rate

Figure 9 Temperature profile at 100 A discharge current

Figure 10 Temperature profile at 150 A discharge current
It was found that at high current levels lowering the mass flow rate led to unstable operational regimes characterized by high temperatures. Figure 11 confirms that the cathode temperature is almost independent on the mass flow rate, while it strongly depends on the discharge current.

2. 100-hr Endurance Test

The endurance test was performed at a current value of 150 A and an argon mass flow rate of 4.5 mg/s. These values were changed during the last sessions of the test because of cathode performance reduction, as shown in Table 1.

In order to continuously monitor the vacuum facility and the experiment, the endurance test was divided in 9 sessions. Each session was preceded by 1 hour of stabilization at 40 A and was followed by 1 hour of argon gas flowing, as described before. In Table 1 the average current, the potential difference between the electrodes, the temperature and the mass flow rate are reported together with the duration of each session and the figure of reference. In each figure the cathode temperature and the potential difference between the electrodes recorded during the test are shown: the data regarding the mass flow rate, the setup temperatures and the chamber pressure are not included for the sake of brevity.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>150</td>
<td>22.5</td>
<td>-</td>
<td>4.5</td>
<td>Figure 12</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>150</td>
<td>23.7</td>
<td>2625</td>
<td>4.5</td>
<td>Figure 12</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>150</td>
<td>23.3</td>
<td>2607</td>
<td>4.5</td>
<td>Figure 12</td>
</tr>
<tr>
<td>4</td>
<td>17</td>
<td>150</td>
<td>23.4</td>
<td>2600</td>
<td>4.5</td>
<td>Figure 12</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>150</td>
<td>24</td>
<td>2604</td>
<td>4.5</td>
<td>Figure 13</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>124.7</td>
<td>23.9</td>
<td>2536</td>
<td>4.5</td>
<td>Figure 13</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>128</td>
<td>24.2</td>
<td>2530</td>
<td>5.2</td>
<td>Figure 13</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>130</td>
<td>22.5</td>
<td>2537</td>
<td>5.9</td>
<td>Figure 14</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>129</td>
<td>22.6</td>
<td>2530</td>
<td>5.9</td>
<td>Figure 14</td>
</tr>
</tbody>
</table>

Table 1 Endurance test sessions

Figure 11 Tip temperature as a function of the current at different values of the mass flow rate
As shown in Figure 12, the cathode temperature was not recorded during the first session, because of a malfunction of the DAQ, but the manual acquisition made indicates that its trend was not different from that of the second session. As discussed before, at the beginning of each session the effect of the ignition method used during the test can be easily recognized.

The arc discharge proved to be stable during the first half of the endurance test, while the effect of the cathode erosion began to be significant by the fifth session of the test causing an increase in the discharge voltage oscillations, as showed in Figure 13.

This effect was coupled with the formation of a plasma glow (not characterized during the test) between the anode and the cathode mounting flanges, resulting in an anomalous increase in the temperatures measured by the thermocouples. Therefore, during the sixth session, the discharge current was decreased from 150 A to 130 A to prevent the damage of the setup. Consequently the mass flow rate was set to 5.2 mg/s during the seventh session and raised up to 5.9 mg/s until the end of the test, as reported in Table 1. This anomaly was most probably caused by a gas leakage due to the slow unscrewing of the cathode gas connector subjected to the thermal cycles introduced by the test strategy chosen.
The observed slow, continuous degradation of the cathode performance seems to strictly follow the erosion process. Figure 15 shows the pictures of the cathode frontal surface at the end of each session. After the early sessions, several rods appeared to be melted together. Subsequently, increasing the accumulated hours, a larger hole placed at the top of the frontal surface was observed. At the end of the endurance test, the frontal surface of the cathode completely lost its original shape.

3. Post-Endurance Characterization Test and Inspection

The endurance test was followed by a last characterization test, to determine the effect of the erosion process on the cathode performance.

As a consequence of the hole formed on the frontal surface, at mass flow rates higher than 3 mg/s, it was possible to ignite the cathode at current values higher than 100 A without anomalous temperature raising or high voltage.
oscillations. As reported in Figure 16 at mass flow rate values lower than 3 mg/s it was not possible to ignite the cathode at current values higher than 70 A. For the sake of convenience, the results found during the post-test characterization phase are reported in comparison with the data recorded during the first characterization test.

From visual observation of the cathode it was clear that not all the channels were ignited and the active zone was shifted inside the cathode in the proximity of the largest cavity. This was confirmed by all the temperature measurements. In Figure 17 is reported a comparison between the temperature behavior recorded before and after the endurance test at a discharge current of 100 A. The maximum of the temperature value is placed at several millimeters from the cathode tip.

The sudden temperature increase when the mass flow rate was set at values lower than 3 mg/s is likely due to the hole formed at the top, which increased the open area for gas injection. In Figure 18 the frontal surface of the cathode after the complete test is shown. At the end of this characterization phase the cathode was dismounted from the setup and weighed to determine the mass lost during the test. The mass difference between the beginning of life and the end of test was 2.32 g. According to this values and taking into account a contingency error of the 10%, the erosion rate is estimated in about 33 ng/C.

Figure 16 Electrical characteristic recorded before (left) and after (right) the endurance test

Figure 17 Temperature profile at 100 A discharge current recorded before and after the endurance test

The 32nd International Electric Propulsion Conference, Wiesbaden, Germany  
September 11 – 15, 2011
C. Discussion

The electrical characteristic of the arc discharge recorded during the characterization phase appears very regular and typical for this class of devices. The cathode seemed to operate correctly in the spot mode, since the voltage decreases with respect to the current in the high voltage zone of the electrical characteristic, while it increases with respect to the current in the high current zone. This behavior is strongly dependent on the mass flow rate.

Moreover, the data confirms the assumption made during the design phase as the minimum discharge power was requested during operation at 4 mg/s for discharge current of 100 A and 5 mg/s for discharge current of 130 A. This behavior is in accordance with results found in previous works and this means that in these conditions the discharge efficiency has a maximum.

The data gathered from the temperature measurements clearly point out the effects of the mass flow rate and the discharge current on the temperature profiles. It was found that increasing the mass flow rate leads to the decrease of the peak temperature at high discharge current values: as a matter of fact, the density of the neutral gas raises in the cathode channels, resulting in an increase of the convective cooling effect on the cathode wall. This effect is nearly negligible for low values of the discharge current, as the discharge current density does not dominate the heating process.

Differently from previous works, the shift of the peak temperature as a function of the mass flow rate was not observed: from the data presented the peak temperature is always located on the exit plane of the cathode. As discussed before, this is probably due to the accuracy of the pyrometer measurement.

During the fifth session of the endurance test it was clear that the main effect of the non-conformity of the cathode frontal surface was the local increase of the erosion rate. The surface discontinuity seems to have favored the local arc attachment, causing an increase of the local temperature and of the erosion even during the cathode ignition. This slow, continuous process led to the formation of a channel of 3 mm of diameter, that created a non-homogeneous distribution of the mass flow rate. From the fifth session until the end of the test, a progressive switching off of the surrounding channels was observed, as shown in Figure 15 and hypothesized in the literature. The increase in the open cross section had the same effect of the decrease in the total cathode mass flow rate. From the seventh session the only way to continue the endurance test at nominal operation was to increase the mass flow rate.

Contemporaneously, starting from the sixth session of the endurance test, a plasma glow appeared between the mounting plates and it was necessary to decrease the discharge current to continue the test avoiding discharge voltage oscillations and thermal related effects. This occurrence can be related to the slowly unscrewing of the gas connector from its housing caused by several thermal cycles that affected the test setup. This probably caused an increase of the local pressure between the mounting flanges leading to the formation of the undesirable discharge.

Figure 19 represents the last picture taken at the end of the endurance test: it can be noted that the plasma jet was mainly located at the top region of the frontal surface.
Finally, the calculated erosion rate of 33 ng/C is higher than the 0.1 ng/C requirement for a reasonably steady-state long life operation for MPD thrusters. Nevertheless, the high erosion rate found in this test campaign has been calculated without considering the erosion effect due to the 103 ignition cycles.

Figure 19 MCHC operating at the end of the endurance test

IV. Theoretical Results

The experimental activity has been carried out in the framework of a wider research program on SCHC and MCHC carried out in collaboration with the RIAME-MAI. The numerical model developed by RIAME-MAI was recently implemented to study the erosion process inside the cathode channel.

Here below the results of a simulation on a MCHC are presented. The test case shares the same dimensions of the cathode tested for an argon mass flow rate of 4 mg/s.

Figure 20 Electrical characteristic - comparison between numerical and experimental results

In Figure 20 the calculated electrical characteristic is shown in comparison with the electrical characteristic measured during the test. The agreement between numerical and experimental results is fairly good, mainly in the mid-range of the current discharge. The voltage discharge values calculated at current higher than 100 A have a little inconsistency with experimental data, since the latter are 10 V higher in value.
In Figure 21 the maximum calculated temperature as a function of the discharge current is reported in comparison with the test data. The numerical results significantly overestimates the value of the maximum temperature at all current values. In particular, for current values higher than 100 A, the difference between the calculated and the recorded temperatures is around 300°C, while at lower current values the difference is a higher, almost 500°C.

Moreover the numerical model permits also to calculate the erosion rate of the cathode. The calculated specific erosion rate depends strongly on the ion accommodation (sticking) coefficient (IAC). The model allows to estimate the IAC value relying on the experimental data. In Figure 22 the calculated results for two different values of discharge current are compared.

![Figure 21 Peak temperature as a function of the discharge current](image1)

![Figure 22 Average mass erosion as a function of IAC](image2)

At the preliminary stage of the calculation, IAC was taken to be 0.8. For this value and for a discharge current of 130 A, the specific erosion rate is 27.8 ng/C. While for a discharge current of 150 A, the result is 30.3 ng/C. This result is quite comparable with experimental data (within the 10%).
The total erosion mass was calculated for 65 hours of operation at discharge current of 150 A and 35 hours operated at discharge current of 130 A, according to the data of the endurance test. Taking the IAC value of 0.8, the total erosion mass is 1.11 g, while using the IAC value of 0.2 the calculated erosion mass is 1.6 g. This result does not agree with the experimental data, but the model takes into account only the mass eroded during the nominal operation and not the mass eroded during the ignition phase.

V. Conclusion

An extensive test campaign has been carried out on an argon-fed multichannel hollow cathode. The cathode has been tested at current level from 20 to 160 A, mass flow rate ranging from 1 to 5 mg/s. After the characterization of the arc discharge, an endurance test of 100 hours has followed. The erosion rate calculated does not correspond to the expected values for a multichannel hollow cathode and might be tied with startup erosion and asymmetric arc attachment, maybe caused by a defect in the cathode assembly.

The results of the RIAME-MAI numerical model have been compared to the experimental data, with satisfactory conclusions. The model predicts the voltage-current dependencies and the erosion rate within the 10% of accuracy, while the temperature calculation is affected by an error of about 20%.

The experimental campaign allowed to a better understanding of the dependency of the cathode temperature and mass flow rate with the electrical parameters, as well as the ignition process and mass flow distribution along the channels. The collected results may represent a good range of data to be used for numerical model validation.

Acknowledgments

The activity described in this paper has been partially carried out in the framework of the TRP project “Technical Assessment for High Power Magneto-Plasma-Dynamic (MPD) Systems” under the contract 21797/08/ML/PA between the European Space Agency and Alta S.p.A. and in the framework of the HiPER project.

References