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Abstract

The performances of two Hall thrusters with different designs are compared. The first one, SPT100-ML, is derived from the flight qualified SPT-100. The second thruster, A53, is a prototype developed by French manufacturer SNECMA for its SPT M2 program, following the ATON concepts first developed in Russia by Pr. Morozov. The main differences between these two thrusters are the anode, propellant injection and magnetic field configurations. At nominal operating points, the A53 performances are found to be better: higher specific impulse and efficiencies, lower plume divergence and discharge current oscillation magnitude. During tests of this thruster, two operating modes with different discharge characteristics were observed. The underlying plasma physics are believed to be more complex in an ATON discharge.

Introduction

Due to their high performances (specific impulse, efficiency), the plasma devices known as Hall-effect thrusters (HET) are particularly interesting for missions such as station-keeping or attitude control of satellites. They allow a great improvement of the thrust/mass ratio, which induces, for the same spacecraft total mass, an increase in the payload mass and/or mission duration.

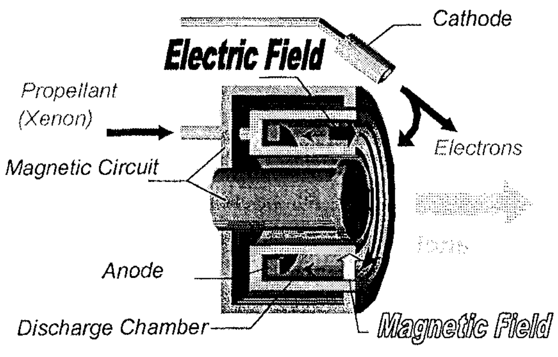


Figure 1: Schematic section of a HET

In a typical HET, the propellant (usually xenon) is injected near the anode of an annular discharge chamber. The electrons, produced by an external hollow cathode or created by the ionization reactions, are confined by an applied radial magnetic field. The ions, having a much lower Hall coefficient, are only accelerated by the mainly axial electric field created in the discharge chamber by the retarded electron flow. In this crossed fields configuration, the electrons drift along the azimuthal direction, and this Hall current interacts with the magnetic field to produce thrust. Outside the thruster, the space charge of the ion jet is neutralized by some of the electrons supplied by the cathode.

The physics and technology of the HET were first intensively studied in the 60s in Russia by Pr. Morozov's team[1,6]. Since 1972, tens of HET-based propulsion systems have flown on Russian satellites, and now some of them are qualified according to Western standards. In France, a joint research program involving the French Space Agency CNES, the rocket engine manufacturer SNECMA and several CNRS, ONERA and university laboratories started in 1996 to better understand the physics and to improve the performances of HET systems.

Many practical variations of the Hall thruster technology have been considered by scientists since the 60s. In this paper, we investigate two of them, which were chosen by SNECMA due to their proven or potential performances. The first one, SPT100, has been developed in Russia by the MAI-RIAME institute and Fakel manufacturer. The second HET technology, ATON, was first proposed in 1976 by Russian scientists, and developed by Pr. Morozov and Pr. Bugrova's team at MIREA institute. Our experimental studies were carried out at the PIVOINE plasma propulsion test facility operated by the CNRS-Aérothermique laboratory in Orléans, France.

SPT100 Design vs. ATON Design

The most common HET technology, very often named Stationary Plasma Thruster (SPT), has the following particular features:

- The discharge chamber walls are made of a dielectric material. Since the walls are exposed to ion bombardment, their sputtering yield should be as low as possible to increase the thruster lifetime.
- The propellant is uniformly injected through the anode ring, placed at the back of the discharge chamber.
- The magnetic field is produced by an inner coil and one or several outer coils. A magnetic circuit is used for shaping the flux lines: for discharge stabilily and better efficiency, the radial component of the magnetic field should increase from the back to the exit of the channel; modern SPTs also use a "magnetic lens" configuration for better focusing the ion jet.

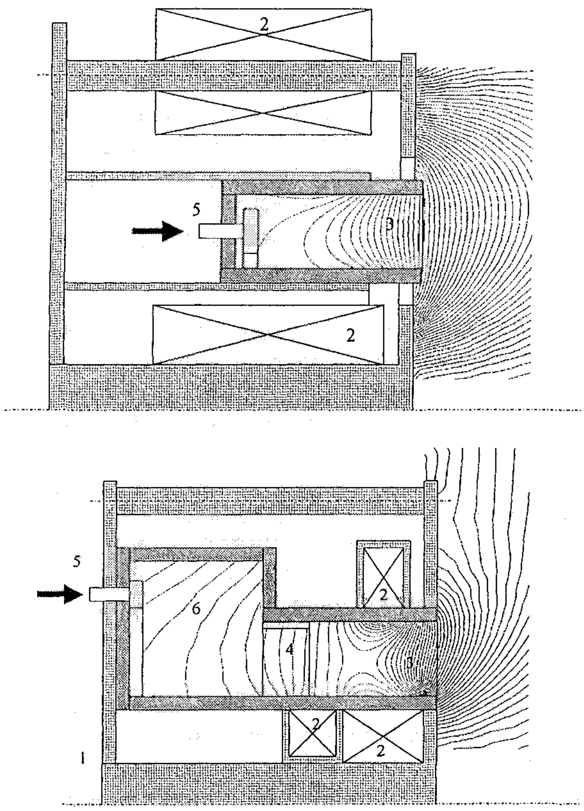


Figure 2: Schematic half section and magnetic field lines top: SPT100 ; bottom: ATON
1: Magnetic circuit ; 2: Magnetic coils ; 3: Ionization and acceleration channel ; 4: Anode ; 5: Gas injector ; 6: Buffer chamber

One famous member of the SPT family has a 100 mm outer diameter channel, hence its designation SPT-100. Flight models of this thruster have successfully worked on Russian spacecrafts (Meteor, Gals), and they are also to be used on future European satellites (STENTOR,...) or interplanetary probes (SMART-1,...). The SPT-100 has also been qualified in the U.S.A.[2].

Despite its remarkable performances (specific impulse and efficiency higher than 1600s and 50%, respectively), the SPT-100 has still one major drawback: the ion stream divergence is rather high (about 45°). This induces a loss of thrust and an acceleration of the wall erosion resulting in a reduced thruster lifetime and adverse effects on the spacecraft (solar panel pollution, etc.), which cause lots of engineering troubles. In order to minimize this drawback, the ATON concept was proposed.

In an ATON thruster, the anode is separated from the gas injection by a "buffer chamber", where the propellant flow is made uniform. The magnetic field near the channel exit is very similar to an SPT one (i.e. mostly radial, increasing towards the exit, "magnetic lens"), but differs greatly towards the anode. There, the flux lines are shaped to obtain a zero-magnetic field point (see Fig.2, bottom). In this particular configuration, the electric potential lines are made convex towards the injection plane (contrary to the SPT configuration) and the ions are thus better focused. Experiments performed at the MIREA Institute support this conclusion[5].

Experimental Setup

The PIVOINE test facility and the SPT100-ML thruster are described in details in other papers[7,8]. We recall here only the main features. The PIVOINE stainless steel vacuum tank is 4 m long and 2.2 m in diameter. The pumping system maintains the pressure inside the tank at about 2×10^{-5} mbar when the SPT100-ML works at its nominal operating point (see below). Thrust is measured by a scale designed and built by the Aerothermique laboratory[8].

The SPT100-ML is derived from the SPT-100 flight model. It has been specially modified for laboratory studies: modular configuration, easy access for diagnostics, etc. The A53 is an ATON prototype manufactured by SNECMA for its SPT M2 program[3], under US patent 5,581,155[4]. The nominal operating points of these thruster are given below:

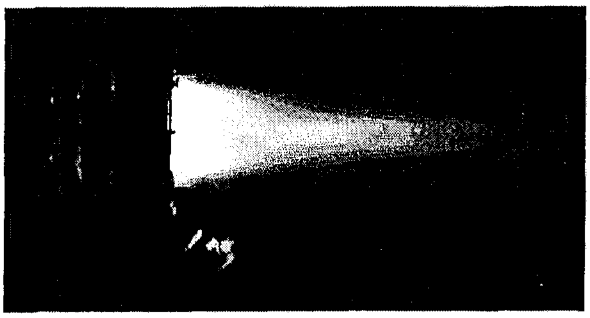
	SPT100-ML	A53
Discharge Voltage	300 V	345 V
Anode Xenon Flow Rate	5 mg/s	4 mg/s
Inner Coil Current	4.5 A	4.3 A
Outer Coil Current	4.5 A	3.5 A

During all the tests, the hollow cathode was a laboratory model provided by the MIREA institute. Both discharges were electrically floating, and the electromagnets had separate power supplies.

Operating Modes

Visual Aspect of the Jet

At low discharge voltages (below 100 V), the plasma jet of both thrusters has the visual aspect of a diffuse purple-blue cloud. At higher voltages, the color changes towards blue-green, and a bright spike appears at the symmetry axis, extending 5-20 cm from the channel exit. With the A53, it was also possible to change the shape of this spike into a cone by varying the currents in the electromagnets. In this operating mode, the cone looked like a swallow tail (see picture). We never had such a mode with the SPT100-ML, and maybe this is a sign that the A53 plume divergence is lower. A comparison with Gas Dynamics models should be done in order to verify this hypothesis.



A53 thruster in "swallow tail" mode

Morozov *et al.* also operated their ATON thruster at MIREA in another mode, characterized by a cylindrical jet and very high performances[5]. We never found this mode at the PIVOINE facility, but it should be pointed out that the pressure was one order of magnitude lower than at the MIREA facility, and that the discharge modes of HET are much affected by the vacuum conditions: due to the backflow of neutrals, more ions are created at higher pressure, which leads to an increase of the thrust and discharge current. Figure 3 shows this effect with the SPT100-ML, from 2×10^{-5} to 1.2×10^{-4} mbar. At nominal operating point, the current and thrust increases are respectively 0.5 A and 5 mA. We will see in the next section that variations of the same order of magnitude are observed with the A53 between "spike" (S) and "swallow tail" (ST) modes, at constant pressure but varying magnetic field.

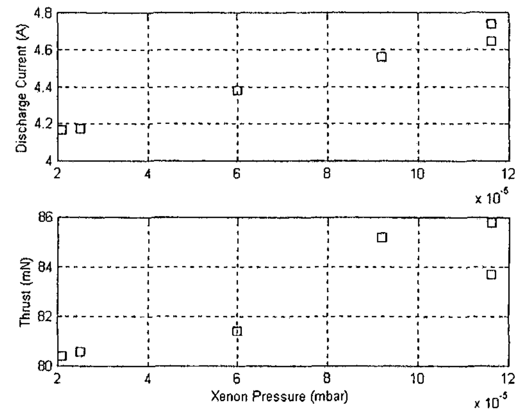


Figure 3: Influence of PIVOINE vacuum conditions on SPT100-ML performances (nominal operating point).

Magnetic Field Optimization

Hall thrusters of the SPT design are known to have an optimum value of the electromagnet current[6] I_C, which minimizes the discharge current I_D. The SPT100-ML has a robust design according to this criterion: at nominal operating point, I_D does not vary more than 0.1 A when I_c is varied within the 4.5-6.5 A range, keeping the inner/outer coil current ratio I_{IC}/I_{OC} constant. We investigated more extensively this relation between coil and discharge current with the A53: I_{IC} and I_{OC} were varied independently within the 2.2-4.8 A range. The Xenon anode flow rate was then 4.6 mg/s and the discharge voltage, 300 V. In the resulting contour plot, shown in Fig. 4, we can notice that there are 2 regions of low I_D. These regions are associated with the ST mode, the others with the S mode. There is also a "border" defined by the relation:

$$I_{OC} - 3.8 = I_{IC} - 2.4$$

The discharge current below this border can be 0.5 A higher than above it, with an abrupt transition. Other series of experiments confirmed this result.

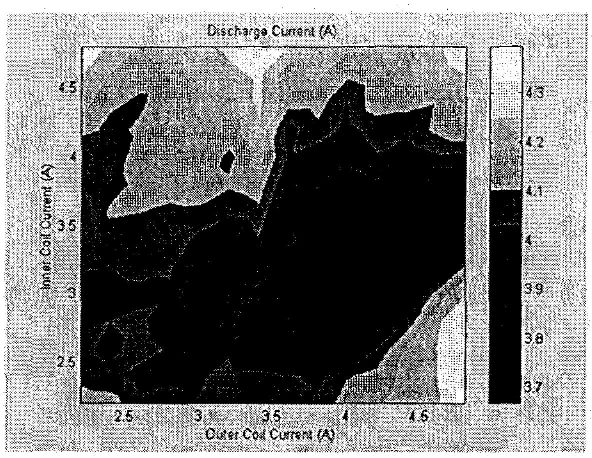


Figure 4: A53 discharge current as a function of the magnetic coil current

I-V Characteristics

The current-voltage characteristics of both thrusters were measured for various set points (see Fig. 10, at the end of this paper).

Set Point	Q_{Xe} (mg/s)	I_{OC} (A)	I_{IC} (A)
SPT100a	3.5	4.5	4.5
SPT100b	5.0	4.5	4.5
A53a	4.0	4.3	3.5
A53b	4.6	4.6	3.5
A53c	4.6	4.5	2.7

Set points A53b and A53c are respectively in ST and S mode at discharge voltage $U_D = 300$ V.

The SPT100-ML and the A53 have typical HET I-V characteristics: from low to high voltages, 3 parts can be identified: partial ionization (PI), "negative resistance" (NR) and current saturation (CS). Compared with the SPT100-ML, the A53 NR part is longer and, as for the magnetic field parameter, the low current modes are more sensitive to voltage changes. A recent paper by Olendarev[9] provided a good interpretation of the SPT I-V characteristics with an analysis of the ionization and electron transport rates within the discharge. Since the ATON I-V characteristic is less simple, it can be assumed that the ionization and transport processes are consequently more complex for this kind of thruster.

Performances

Tables 1 and 2, at the end of this paper, give the performances of both thrusters for various discharge voltages, starting from their nominal operating point. The specific impulse I_{sp} and the efficiency η concern only the discharges, they do not include the losses due to the cathode xenon flow, the electromagnets power supply and cathode heater. The A53 Isp and η are higher: at nominal operating point, 1908 s and 63%, compared with 1759 s and 58% for the SPT100-ML.

In their already mentioned paper about ATON thrusters
[5], Morozov *et al.* gave a set of simple formulas for calculating the relative shares in the total ion flow of singly- and doubly-charged ions and ions lost to the discharge channel walls (we will name these quantities m_1, m_2 and m_w, respectively). The needed measurements are the discharge current I_D, the thrust T and the anode flow rate Q_{Xe}. Three parameters are estimated: Δ, the difference between the discharge and effective acceleration voltages, ε; the number of ionization events undergone by an ion arriving to the channel wall, and κ, which is related to the electron axial flow in the discharge. In our calculations, we took the same values as Morozov *et al.* for Δ and ε, but we chose to lower the value of κ (0.05 instead of 1), because otherwise we obtained a negative m_2 share at $U_D = 300$ V. The other shares were not unreasonably affected by this change. The results are gathered in Tables 1 and 2.

It is strongly possible that for some values of U_D that we chose (especially the low ones), the formulas for calculating m_1, m_2 and m_w are not valid. Assuming that they hold near the nominal operating points, we find some agreement with Morozov's conclusion: the share of lost ions is lower in the A53 case. The difference was bigger at MIREA, but it must be reminded that the thruster operated there in a very peculiar mode.

Measurements in the A53 Ion Jet

A rotating probe holder has been mounted at the end of PIVOINE's diagnostic arm. Another arm, perpendicular to the first one, was used for translating the thrusters (see Fig. 5). Translation along the X and Y axis and rotation are controlled using step-by-step motors interfaced with personal computers outside the tank. The ranges for α are $-20°$ to $+100°$, the reference being the X axis, looking towards the thruster. With this system, it is possible to perform a measurement mapping at constant radius or angle and up to 670 mm from the channel exit, looking at a particular point in the plasma stream.

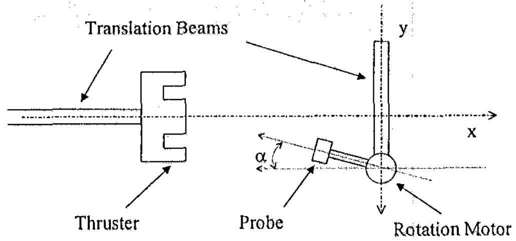


Figure 5: PIVOINE translation/rotation system

The electrostatic probes used are Langmuir cylindrical and planar probes and a Retarding Potential Analyzer. These diagnostics, along with optics ones operated by the GREMI and LPGP laboratories, are detailed in another paper[10].

Another planar electrostatic probe was placed at a fixed position relatively to the tank and in the channel symmetry axis. Figure 6 shows two series of measurements made with this probe in the A53 plume, for various thruster-probe relative positions. One series was recorded in ST mode ($I_D = 3.7$ A), the other in S mode ($I_D = 4.2$ A). The only operating parameter that was changed between the two series is the coil current. The probe was biased at -48 V relatively to ground (vacuum tank) potential for repelling the electrons. The probe current is thus proportional to the ion current at this location. Other measurements showed that at the selected distances from the thruster (far away from the "spike"), the angular ion current distribution is bell-shaped.

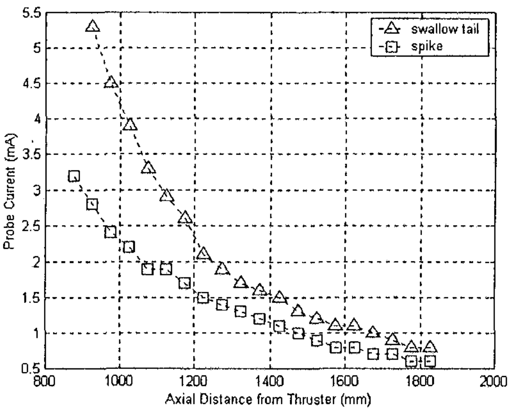


Figure 6: Ion current along the A53 plume axis

For all positions of the probe in the series, the ion current in ST mode is higher than in S mode. This effect can be explained in the following ways:

- The ion jet is better focused.
- The ionization efficiency (and thus the total ion current in the plume) is higher.
- The share of multiply-charged ions is higher.

The low discharge current observed in ST mode support the first two explanations and infirm the third one. We also estimated the relative plume divergence for the two A53 operating modes with RPA measurements at 600 mm from symmetry center of the channel exit. After integration over the ion energy distribution functions, we found a 26° divergence in S mode and 18° in ST mode. Further experiments with Langmuir probes are planned in the near future to check this divergence difference and to compare the SPT100-ML and A53 plumes.

Oscillation Modes

The discharge current oscillations were measured through a 0.01 Ω shunt. The signals were filtered by a Preston amplifier set to 100kHz low-pass and digitized at 5MS/s sampling rate with a National Instruments NI-DAQ acquisition board controlled by a PC.

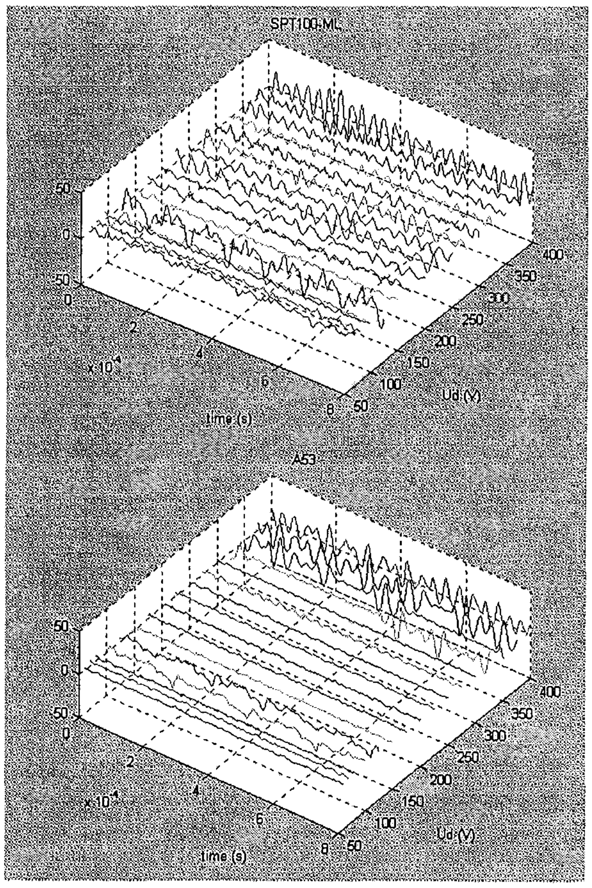
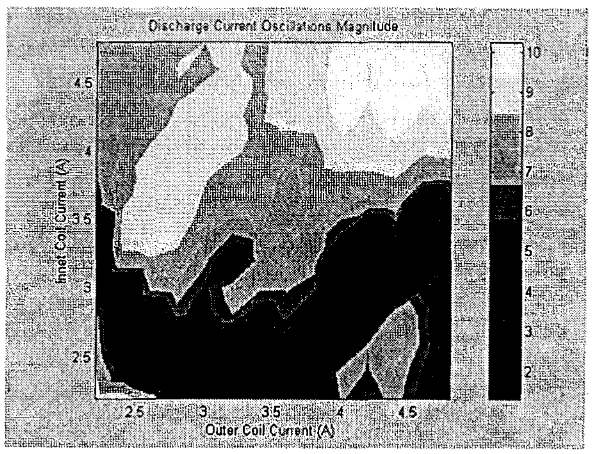


Figure 7: Discharge current oscillogramms for different discharge voltages, SPT100-ML (top) and A53 (bottom)

For both thrusters, several oscillation modes can be identified, depending on the position in the I-V characteristics (see Fig. 7). With the A53, we also mapped the oscillation magnitude depending on the coil current (Fig. 8).



Figure°8: A53 oscillation magnitude

We can see that in ST mode, the oscillation magnitude is very low.

It is also worth commenting the transition between low magnitude (LM) and high magnitude (HM) oscillations modes. Slowly varying the coil current or the discharge voltage from a "quiet" LM mode (Fig. 9, center), some high magnitude bursts appear (Fig. 9, bottom). These bursts then appear more and more frequently, and with longer and longer durations, until there remain almost no LM oscillations.

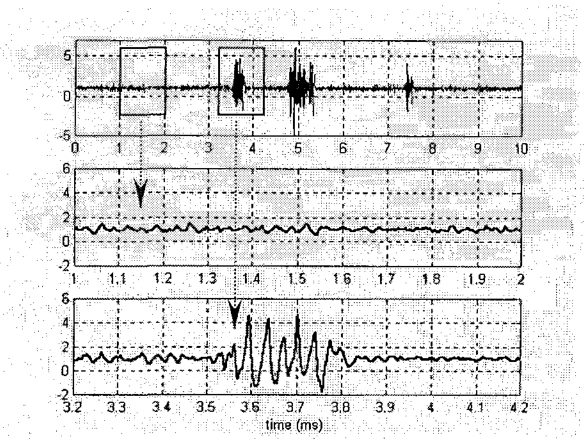


Figure 9: A53 discharge current oscillations

With the SPT100-ML, the LM modes had more frequent bursts and the oscillation magnitude was generally 2 to 3 times higher (relatively to the mean discharge current) than the A53 ST mode. This feature of the ATON design is interesting for propulsion systems, because current oscillations generated by the discharge can have bad consequences on the Power Processing Unit and can notably reduce its lifetime.

Conclusion and Outlook

Compared with the well-known and qualified SPT100, the ATON Hall thruster seems to be an interesting alternative. The tests undertaken at PIVOINE facility tend to prove that at nominal operating mode, the ATON plume divergence and discharge oscillations are lower and the specific impulse and discharge efficiency are higher. However, explaining the observed differences between these two kinds of thruster is surely a difficult task: the special magnetic fields configuration inside the ATON channel must add complexity to the Hall thruster physics, which is already far from being completely understood.

Acknowledgement

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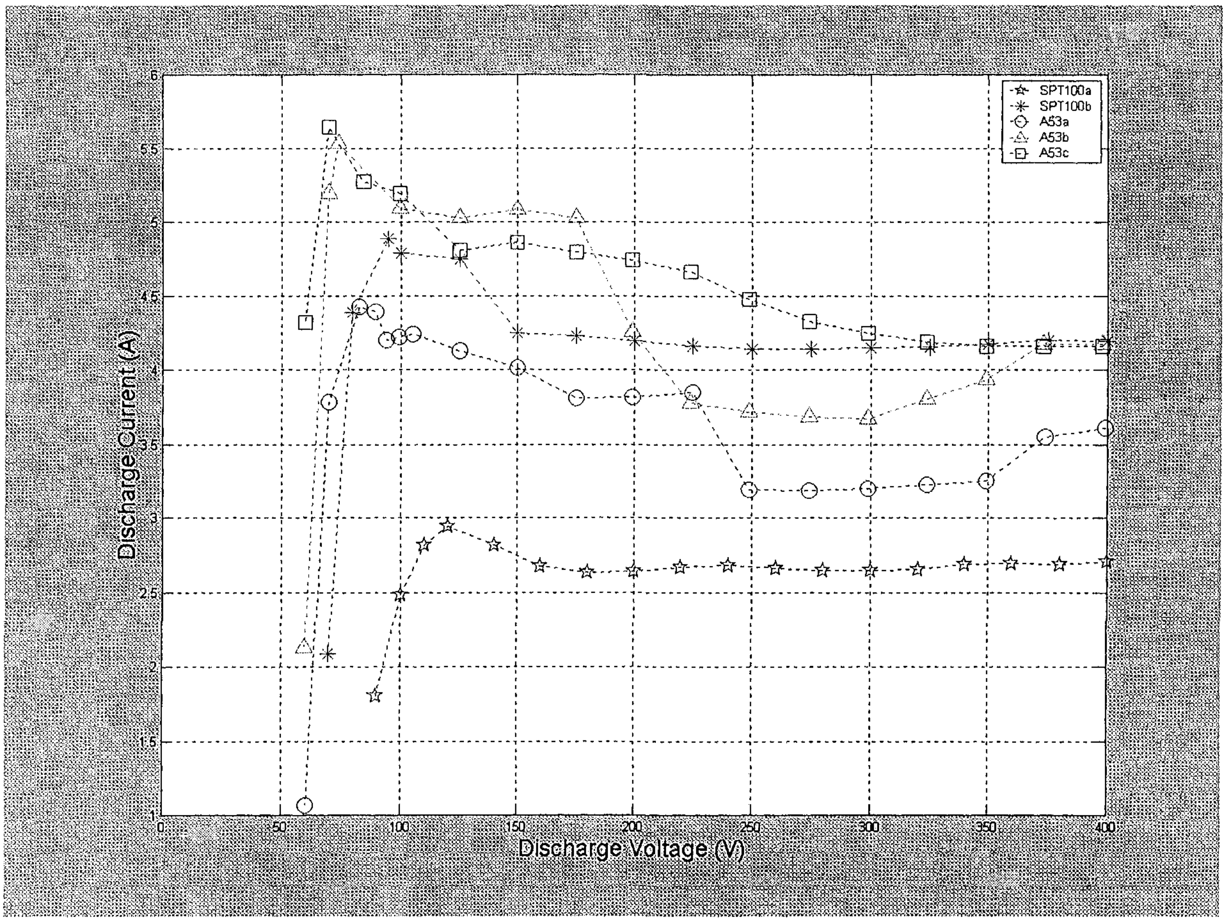

Figure 10: SPT100-ML and A53 I-V characteristics

U_D (V)	I_D (A)	T (mN)	I_{sp} (s)	η	m_1	m_2	m_w
150	4.564	45.2	921	30%	48%	19%	33%
199	4.314	63.3	1291	47%	68%	12%	19%
250	4.287	76.3	1556	54%	73%	12%	16%
299*	4.324	86.3	1759	58%	73%	12%	15%
349	4.384	93.9	1914	58%	70%	14%	16%
398	4.322	99.8	2035	58%	71%	12%	17%

Table 1: SPT100-ML, 5 mg/s anode flow rate

U_D (V)	I_D (A)	T (mN)	Isp (s)	η	m_1	m_2	m_w
100	4.223	24.2	613	17%	18%	37%	45%
199	3.796	53.2	1346	47%	57%	23%	20%
299	3.196	69.0	1744	62%	85%	4%	11%
344*	3.280	75.4	1908	63%	81%	7%	12%
399	3.530	84.2	2130	62%	72%	15%	13%

Table 2: A53, 4 mg/s anode flow rate

* Nominal Operating Points