Solar electric propulsion based on Xenon propellant (ion or plasma thrusters) is being adopted as the main propulsion system for an important number of ESA scientific missions. Secondary propulsion systems such as resistojets commonly use different propellants such as methane, ammonia, and hydrazine, but since the total momentum required for attitude control by these missions is in general relatively low, important mass savings could be achieved by eliminating independent tanks for the secondary propulsion system. This paper will discuss the potential of this technology, showing how realistic performances would allow it to be competitive in the AOCS (Attitude and Orbital Control System) trade-offs of current, future and candidate ESA missions like SMART-1, Bepi-Colombo and Mars Exobiology. This paper also presents performance test results of two existing SSTL resistojet thrusters using Xenon as propellant, performed in the ESA Electric Propulsion Laboratory.

Introduction
The use of a resistojet with Xenon has two important potential applications. It is ideal for attitude control on spacecraft with an existing xenon supply system for an electric propulsion system as an Ion Thruster or a Hall Thruster. But also Xenon gives a better density Isp than traditional Nitrogen systems (i.e. greater impulse per unit volume). This is important on small spacecraft with small propulsion systems with low delta-V requirements.

The possibility to have satellites with single propellant management system has already been considered in several feasibility studies of future European scientific missions assessed in the ESA Concurrent Design Facility.

The most remarkable examples are the two All-Solar-Electric-Propulsion versions of the missions Mars Exobiology (to Mars) and Bepi-Colombo (to Mercury). In both cases the advantages in terms of mass performance of eliminating redundant tanks and propellant control hardware are substantial, and the increased overall mission risk, due to the employment of a technology still considered under development, is mitigated by its intrinsic robustness characteristics. In both cases Xenon resistojets have been identified as very promising solutions, although they have not been retained as final baseline.

On account of Xenon resistojets relatively low specific impulse, the benefits involved by their employment for interplanetary mission attitude control are stronger when the required total angular momentum is reduced. The trade-off limit is obviously reached when the increased Xenon mass overtakes the savings in the corresponding propellant system mass. It is worthy to underline, however, that the total angular momentum of long missions with main electric propulsion on-board is in general lower than the one required for analogous missions involving chemical propulsion, because thrust misalignments and center of mass
variations can be counterbalanced by fine engine regulation and apposite gimbals mechanisms. In addition, when more than a single engine is present (as it is the case for missions exceeding thruster qualification lifetime), apposite thrust strategies can supply two-axis control (pitch and yaw).

Possible Applications of Xenon Resistojets for Interplanetary Mission Attitude Control

The preliminary study for the mission to Mercury aimed at assessing the possibility to send in 2009 a 500 kg Planetary Orbiter (MPO) with a Soyuz-Fregat launcher and a Solar Electric Propulsion Module (SEPM) based on 3 Ion Thrusters for both cruise phase (3.4 years) and orbit acquisition (240 days). The mission strategy included an intermediate lunar fly-by. A previous version of this study was based on a chemical 400N thruster for insertion in Mercury orbit; in this case possible engine misalignments produced high level of transverse disturbing torques (up to 12 Nm), requiring high thrust reaction control systems. In the new study, on the contrary, the prominent disturbance was environmental (mostly due to solar pressure), producing a total angular momentum of about 15000 Nms only. In these conditions a simple mass trade-off (Table 1, where a 1.8m lever arm has been assumed for the calculations together with 70 s for the specific impulse [1]) can show the competitiveness of resistojets with respect to other possible actuators.

![Figure 1: All-SEP mission to Mercury, attitude control strategy during orbit acquisition](image)

Xenon resistojets were not finally selected because the thermal control of the spacecraft, once in orbit around Mercury, required turning the whole stack of 180° during no-thrust phases to orient the radiators (Figure 1); a safe mode maneuver requires a rotation of the S/C in some tens of seconds, whereas resistojets need at least one minute and half. Moreover, the SEPM was designed to be jettisoned short after the final orbit acquisition. This means that the AOCS actuators would have been best located on the MOP, preventing any possible tank sharing with the main propulsion stage. At last a set of 12 bi-propellant 10 N thrusters was suggested for this mission.

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Table 1: All-SEP mission to Mercury, actuators trade-off
In the case of Mars Exobiology [2], the very tight power budget once in the destination orbit was the main reason for finally excluding Xenon resistojets. Also, a special effort was dedicated in this study to find a reliable solution with a high level of redundancy. Since the main propulsion system was composed by 5 Ion Thrusters in cross configuration, it would have been possible to use the corner engines to control rotations around 2 axes. It was decided instead to consider this option only in case of failure of the AOCS system, which had therefore to provide a total momentum sufficient to adjust the thrust vector during the whole mission, to compensate all external disturbance torque, and to comply with spacecraft pointing requirements set by the different subsystems. The total angular momentum was thus higher, about 40000 Nms, at the very limit of Xenon resistojets suitability domain. The final proposed solution consisted in 6 clusters of 2 hydrazine thrusters (fully redundant), for a total mass of 44kg (in this case the lever arm was also constrained to 0.7 m).

In both cases the Xenon Resistojet option was already at preliminary mission study level an interesting option. Considering also other advantages at system level an enhanced performing Xenon Resistojet could become without doubt an attractive option. In fact even without considering an EP spacecraft already equipped with Xenon, so with all the related advantages by saving an additional tank and its propellant management system, a small spacecraft with low delta-V requirements can benefit anyway from a lighter and smaller propellant tank, because of Xenon’s high density and low pressure storage.

**SSTL Resistojet Characterization Test using Xenon**

In order to assess the performance of the Surrey Satellite Technology Ltd. (SSTL) low power resistojet while using Xenon as propellant, a complete characterization test with the thruster was performed at the ESA Electric Propulsion Laboratory (EPL) both with Nitrogen and Xenon. The thruster was designed to fly on the ALSAT-1 spacecraft using 15-Watt redundant heaters and using butane as the propellant [3]. The design of the thruster has the flexibility to increase the power up to 50-Watt redundant heaters. The ALSAT-1 qualification model has been previously tested with butane propellant. ALSAT-1 was launched on November 28, 2002 so these thrusters have now flight heritage.

Two resistojets were tested in the EPL: one unit with 50-Watt redundant heaters (T50), and another with 15-Watt redundant heaters (T15). The T50 thruster was tested without its flight heat shield fitted (Figure 4), while the T15 had the heat shield installed.

**Test Description**

The test set-up is shown in Figure 2. A Mettler-Toledo AX Precision Balance was used for the thrust measurement. This was modified with the factory supplied remote operation kit, and further by replacement of some leads and connectors with vacuum compatible ones and a vacuum port feedthrough.

![Figure 2: Test set-up](image)

A Bronkhorst Model F-111C Mass Flow Rate Controller measured the propellant mass flow. This can be used to either supply the desired mass flow rate, or simply as a mass flow meter if the valve is commanded fully open. Gas was supplied using the custom built feed system (Figure 3) at the desired pressure. The resistojet was mounted on a support to fire upwards and placed on a Mettler-Toledo precision balance. The
resistojet was fed by a flexible hose, which supplied xenon or nitrogen at the desired pressure or mass flow rate. Electrical connections supplied power to the resistojet heaters, and monitored the temperature by thermocouples. Immediately before entering the tank, the temperature and pressure are recorded by Omega Electronics RTD-810 Immersion Temperature Sensors and Kulite ETM-375M Pressure Transducers.

A test was conducted to measure the error induced by the stiffness of the feed wires. Without the feed wires connected a thruster simulator (solenoid/magnet combination) was placed on the thrust stand. The force applied to the balance was then measured as a function of the current applied to the solenoid. This was performed in air and also under vacuum and no change was seen in the force-current characteristic. The feed lines were then connected and the test was repeated. The error was seen to be less than 2%, and this was considered an acceptable error so was not corrected for in the performance tests.

Once the resistojet was started and all the hardware and software working correctly, a test was done on the effect of the background pressure in the vacuum tank on the thruster performance. The tank was pumped down to $10^{-5}$ mbar and pumps switched off. The thruster was then started. The pressure jumped quickly to 0.1 mbar, but there was no noticeable affect on the performance (measured thrust) until the pressure reached 1 mbar and no significant effect until 10 mbar, which was after several minutes of firing. By using just the roots pump we were able to keep the tank below 1 mbar when firing, which allowed us to switch off the cold panels, cryopump and turbopump whose vibrations were a considerable source of noise for the balance.

Performance tests were then done on the T50 and T15 resistojets, using nitrogen and xenon. The mass flow controller was commanded fully open and just used as a flow rate sensor, and the propellant pressure was adjusted from 1 to 4 bar, and the thruster left to reach equilibrium between each change. The power supplied to the thruster was systematically varied from 0 to 65W for the T50 thruster and 0 to 30W for the T15, making sure not to exceed the maximum of 600 °C.
**T50 Test Results**

The results reported were obtained by applying power to the heater at different levels and then by increasing the supply pressure in steps of 1 bar up to 4 bars, once the thruster was thermally stable (Figure 18).

**Figure 5: T50, Specific Impulse – Thrust Graph**

**Figure 6: T50, Thrust – Supply Pressure Graph**

**Figure 7: T50, Thruster Temperature – Heater Power Graph**
As seen in Figure 5, the 30-Watt and 40-Watt $I_{sp}$ curves are inverted on the performance graph. The 40-Watt curve should correspond to a higher specific impulse than the 30-Watt curve. This is due to a higher background pressure during the 40-Watt measurements on thruster T50 (see Figure 10) that was not noticed during the test execution. In fact the thruster temperature is higher for the higher power mode, and the mass flow rate is lower. Only the thrust measured is lower than expected.

According to theory, by using a simple one-dimensional model, the specific impulse should be independent from the thrust level. The results from our test show instead non-negligible decrease in specific impulse as the thrust increases. This is because of the decrease of the average gas temperature as the mass flow increases for a fixed heater power and could be also because of viscosity effects and other second order effects not considered in the simple theoretical model, but surely the increase of tank (background) pressure as the thrust (mass flow) increases is one of the factors that causes this specific impulse drop at the higher pressure regimes.

This implies that the measured performance in terms of specific impulse is probably closer to the expected flight one when at the lower mass flow rates, reaching 54 s at 65 W of heater power and 20 mN of thrust on T50 without heat shield and 57 s at 30 W and 10 mN on T15 with heat shield. The other ones being possibly slightly better in flight conditions.

It is worth mentioning that the thruster was designed to meet SSTL’s low cost approach using the 80 : 20 rule, i.e. 80% of the performance at 20% of the cost. Hence the performance figures obtainable could be exceeded if a performance optimization exercise were to be undertaken.
Figure 10: T50, Tank Pressure – Thrust Graph

T15 Test Results

Figure 11: T15, Specific Impulse – Thrust Graph

Figure 12: T15, Thrust – Supply Pressure Graph
Again it should be noted that the test on T15 was performed with the flight heat shield installed, which reduces the thermal dissipation of the thruster. In fact the shield was installed after the dismounting of T50 showed an excessive heat load on the thrust stand’s electronic box.
Also in this case the graph showing the tank pressure against the applied thrust is reported for completeness (Figure 16). In the figure below an example of the performance measured with Nitrogen.

A more detailed discussion of the results is out of scope of this paper, and will be presented in future papers.
Conclusions
Xenon Resistojets as secondary propulsion system can be competitive to other more performing systems when on EP equipped spacecrafts. An increase in performance could make them the most efficient solution, especially in applications where the AOCS delta-V requirements are not very high.

Two low power resistojets developed by SSTL were characterized in the EPL at ESTEC with Xenon. The tests show that good performance can be obtainable already from this low-cost and robust thruster. Applications are foreseen also on small satellites where density Isp can be a driving performance requirement.

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Bibliography