Electric Propulsion on SMART-1

A Technology Milestone

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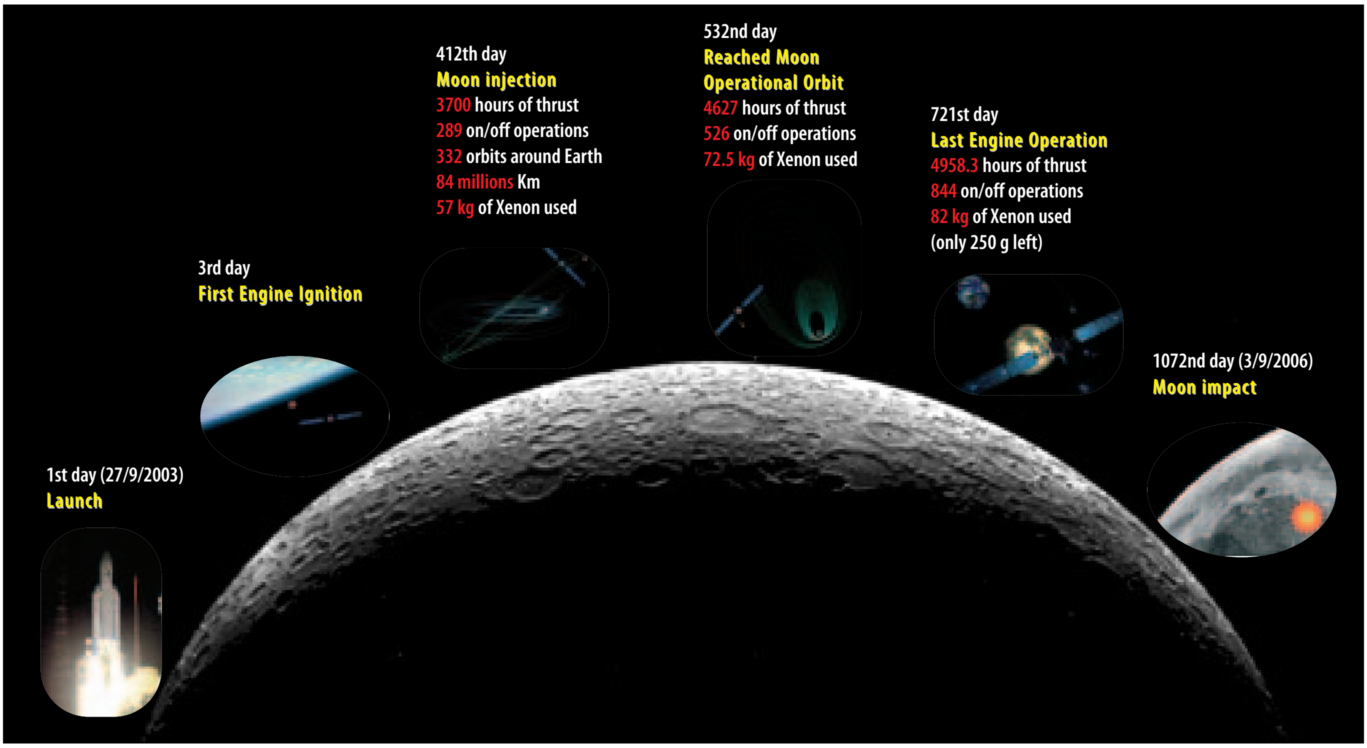
In December 2002, when France's Stentor satellite was all set to use electric propulsion for stationkeeping, ESA's SMART-1 was just completing its first end-to-end spacecraft test. Then Stentor was lost in the Ariane-5 launch failure, making SMART-1 the first and only technology demonstration mission with Hall-effect plasma propulsion. As a result, there was a great deal of interest in the electric propulsion community in SMART-1's flight.

Introduction

SMART-1 was the first of ESA's Small Missions for Advanced Research in Technology. The objective was to test new enabling technologies for the forthcoming ESA Cornerstone science missions, the next being the BepiColombo Mercury orbiters. SMART-1 was launched from Kourou, French Guiana, on 27 September 2003, as an auxiliary passenger on an Ariane-5; its highly successful mission concluded with a deliberate impact on the Moon on 3 September 2006.

The critical technology demonstrated by SMART-1 was the main solar-electric propulsion using a PPS-1350G Hall-effect plasma thruster, developed



and qualified by SNECMA (F). This demonstration created an impressive number of 'firsts' and broke a number of ESA, European and world records.

A Number of Firsts

The SMART-1 electric propulsion system (EPS) was directly managed and procured by the Electric Propulsion Section of ESA's Directorate of Technical and Quality Management, and delivered as 'customer-furnished equipment' to the SMART-1 Project in ESA's Science Directorate and then to the industrial prime contractor, the Swedish Space Corporation. This was the first time that EPS was used for something as critical as primary propulsion. It was also the first time that:

- electric propulsion was used to escape Earth from a geostationary transfer orbit;
- electric propulsion was in conjunction with gravity-assist manoeuvres;
- electric propulsion achieved capture using the weak-stability boundaries and a descent around a celestial body;
- ESA flew a lunar orbiter;
- a lunar orbiter had a propellant fraction as low as 22% (only 82 kg of xenon propellant).

Finally, from a technology point of view, it was the first time that:

- a Hall-effect plasma thruster was used for primary propulsion;
- a Hall-effect propulsion system was used under variable power conditions;
- a plasma thruster had operated continuously for more than 240 hours in space;
- a plasma thruster had accumulated nearly 5000 hours of operations in space.

A demonstration mission was key for full acceptance of the maturity of electric propulsion (EP), and to show that it could benefit from the latest advances in space power generation. The mission not only showed that the propulsion system performed as expected, but also that the system reliability (designed mostly as 'single string') was very good, despite the challenging environmental conditions throughout the mission (repeated crossings of radiation belts, solar flares, lunar albedo).

In addition, an understanding of flight operations with EP was fundamental. EP was often viewed as inconvenient owing to the long thrust periods needed to compensate for the low thrust. Compared to the much shorter thrust periods required by chemical propulsion, EP must be paired with relatively high onboard autonomy and accurate pointing of the thrust vector and solar array over long periods.

This certainly requires a new way of controlling missions from the ground. SMART-1 has paved the way while collecting important experience, such as in the sensitivity to the proton environment, the need to interrupt thrust during eclipses and open-loop onboard power regulation.

From a mission point of view, the long low-thrust manoeuvres have the great advantage that, because changes occur slowly, errors can be easily corrected at negligible propellant cost. Failures can be more easily recovered from than with traditional manoeuvres because there is much more time available for a second attempt or to decide on a fall-back solution. Finally, EP is very often a mission 'enabler' for propellant-demanding scientific missions or long-duration commercial missions.

With its mission, SMART-1 has made a very valuable contribution to spreading the use of EP.

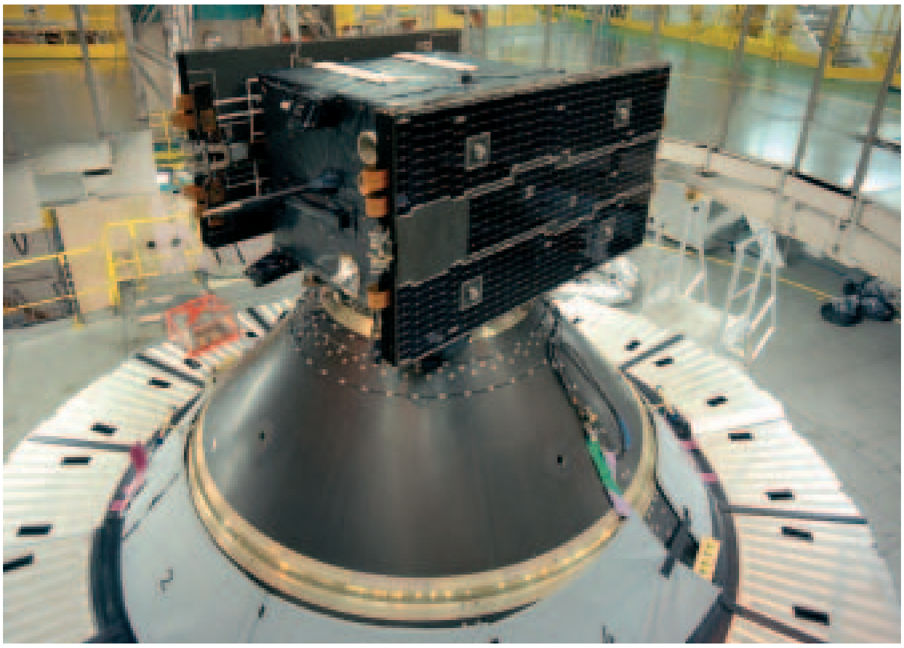
EP Mission Phases

The 3-day Low Earth Orbit Phase starting after separation from Ariane, commissioned all the critical subsystems and rapidly raise the altitude in order to limit radiation exposure of the solar cells and sensitive electronics. The Van Allen Belts Escape Phase used near-continuous thrust to minimise the passage time through the radiation belts, although battery capacity was not enough for thrusting during eclipses. Also, thrusting below 3600 km altitude was not possible because blurring of the startracker images prevented fine pointing. During this phase, the thrust was directed along the velocity vector in order to raise the perigee height quickly above 13 600 km, well beyond the radiation belts.

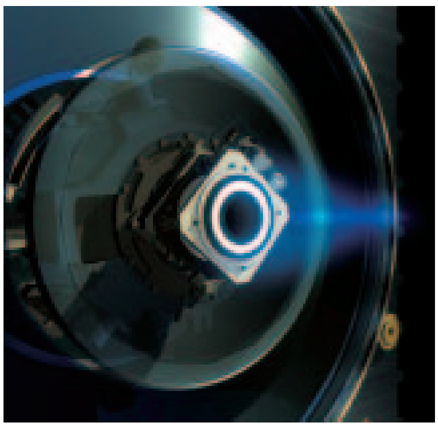
During the Earth Escape Cruise Phase, EP was active for only half of each orbit because thrusting was performed only around the perigee, where it used the propellant more efficiently.

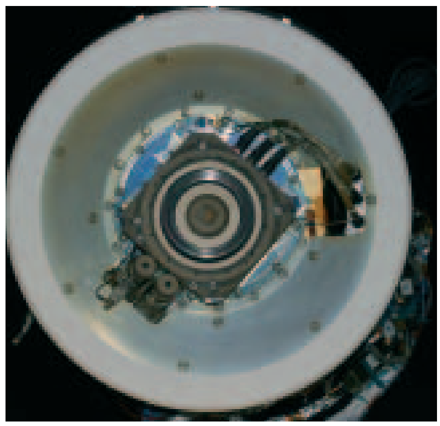
As SMART-1's orbit spiralled out beyond 200 000 km it began to feel significant tugs from the Moon's gravity, until the critical capture manoeuvre with 4.5 days of EP thrust. During 950 hours of cumulative thrust, EP then lowered SMART-1 into a polar orbit of 2000 x 4600 km, where the Lunar Science Phase began in February 2005.

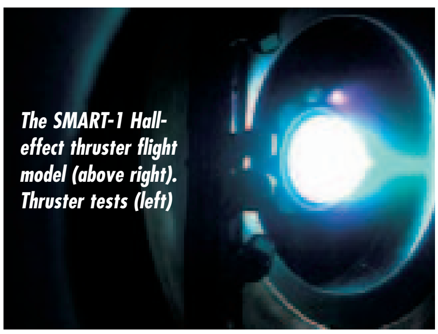
After 6 months of science operations in 'free drift', a new EP phase of 340 hours of thrusting extended the life of the lunar observation orbit by 1 year.



SMART-1 ready for encapsulation on its launcher (ESA/CSG)







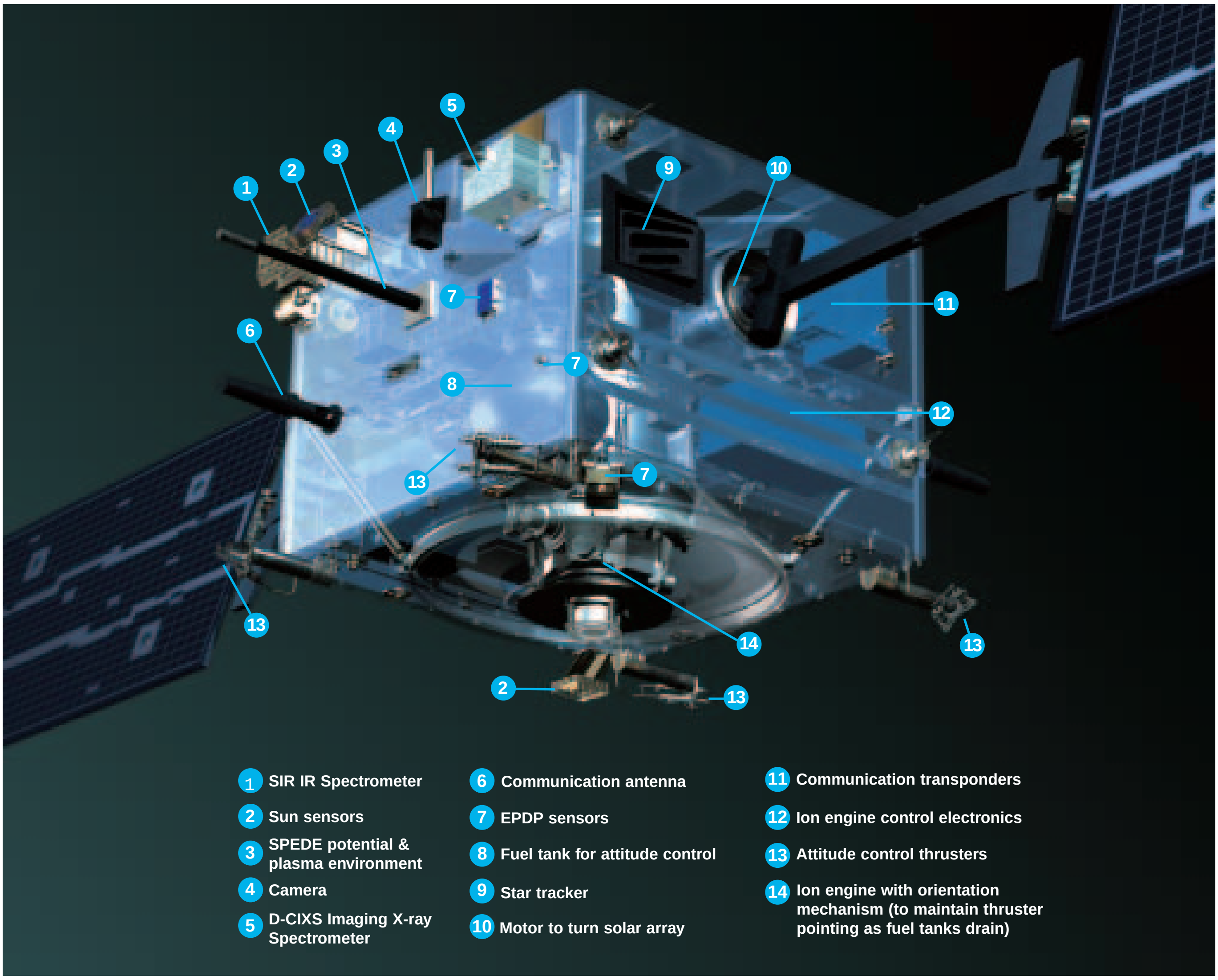
The SMART-1 Hall-effect thruster flight model (above right). Thruster tests (left)

The SMART-1 Platform

Using EP required a 3-axis stabilised spacecraft with two solar wings. The central structure was designed around a 49-litre cylindrical tank containing 82 kg of xenon at launch. Since the thrust vector and solar wings had to be optimally pointed simultaneously, the wings were fitted with a drive mechanism. For maximum power, they used integrated triple-junction gallium-arsenide solar cells of 23.7% efficiency (beginning of life), reduced to 18–19% in the 40–50ºC operating temperature range, with cover glass and at fixed bus voltage. They were sized to deliver 1850 W at the beginning of the mission.

Power was delivered to the EPS via a 50 V fully regulated bus. State-of-the-art lithium-ion batteries provided power during eclipses, for a maximum 2.1 hours without thrusting.

The thruster was mounted on an orientation mechanism (developed by Contraves Space AG) to point through a centre of mass that was moving owing to propellant depletion and thermal effects. SMART-1 also demonstrated the use of a gimballed electric thruster for unloading the reaction wheels, thereby saving precious kilograms of hydrazine.



A key milestone in the project was the full-scale integrated test of the propulsion system. During the end-to-end test in December 2002, SMART-1 (sans solar array) was installed in the HBF-3 vacuum chamber in ESTEC for a 1-hour trial of the thruster and its orientation mechanism, thereby validating all the interfaces and control hardware.

The SMART-1 Electric Propulsion System

The SNECMA PPS-1350G Hall-effect thruster is the European version of the Russian Fakel SPT-100, but using European technologies and quality standards required by western telecommunications satellites. The thruster's ground qualification totalled 9200 hours of cumulative operation and 7200 on/off cycles for a total impulse of 2.9 MNs. This covers the Alphabus requirement, for which the PPS-1350G(4) engine has been chosen, to perform 15 years of daily stationkeeping in geostationary orbit.

Hall-effect, or plasma, thrusters operate with a noble gas such as xenon, well-known for good storability and user-friendliness during ground operations. This is a major advantage over chemical propulsion, which requires costly safety procedures during propellant handling.

The xenon is ionised and accelerated to 60 000 km/h by an electric field, thereby producing thrust. Ionisation occurs when an electron current is generated by the external cathode. This current is constrained by a radial magnetic field. The Hall effect means that the ions and electrons swerve in opposite directions in the magnetic field, creating an electric field. This expels the xenon ions as a propulsive jet. Electrons from an external cathode neutralise the beam to prevent the spacecraft from becoming electrically charged.

On SMART-1, the xenon was stored in the central tank under supercritical conditions, at 1.7 times the density of water and high pressure (up to 150 bars). A pressure regulator, designed by SNECMA Moteurs and Iberespacio (E), reduced the xenon pressure to a nominal 2 bars. The low-pressure gas was then fed into the Xenon Flow

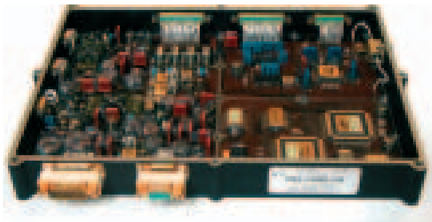
Controller (XFC). A simple and robust control loop algorithm in the regulation electronics (PRE Card) controlled the pressure delivered by the regulator by opening or closing two solenoid valves in series following a predefined sequence. Then the XFC delivered, in a control loop with the discharge current, the xenon flow to the thruster anode and cathode.

The thruster was controlled and powered by the Power Processing Unit (PPU), developed and qualified by Alcatel ETCA (B). All telemetry and telecommands were interfaced through the PRE Card. An electrical Filter Unit, produced by EREMS (F), reduced the thruster discharge oscillations to an acceptable level and protected the PPU electronics. Both the PRE Card and PPU carried software with 'automatic mode' subroutines that minimised the number of commands to be supplied routinely to the EPS through spacecraft telemetry.

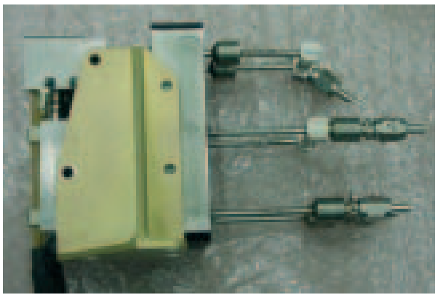
To cope with decreasing and varying power from the solar array as the mission progressed, the EPS was designed to be throttled easily over a wide range of input power. The PPU allowed 117 power levels to be specified, ranging from 462 W up to 1190 W. It also performed the automatic ignition sequence. After the 'auto exec' command was given, the cathode was heated, the xenon flow began and the thruster was turned on by the ignition pulse.

The EPS was a single-string system, but with some internal redundancy. The pressure regulator valves were duplicated, as were the thruster's hollow cathodes and their XFC connections.

In routine operation, EPS was relatively simple to manage. It was commanded to thrust by a pre-built sequence of 35 commands, and switched off by one unique command. It was then a simple matter of supplying the desired thrust level and ignition time whenever a thrust arc was required. Based on the desired orbital change, there were only two events and one parameter for each thrust arc: EP-ON time, thrust level, and EP-OFF time. This information was then processed by the control system and automatically incorporated into the SMART-1 command sequence and the mission planning system as part of the routine command uplinks.



The PRE Card controlled the xenon flow



The Xenon Flow Controller delivered the propellant to the thruster

Electric Propulsion Performance

SMART-1 launch mass	370 kg
Cumulative EPS duration	4958 hours
Cumulative regulated thrust	4913 hours
Total impulse	1.2 MNs
Velocity increment	3.7 km/s
Longest burn duration	240 hours
Number ON/OFF cycles	844
Number valve activations	1 256 505
Xenon at launch	82 kg
Xenon remaining at impact	0.28 kg
Discharge power range	462–1190 W
Average discharge power	1140 W
Average projected thrust	65.7–9.1 mN
Average measured thrust	67 mN
Average effective mass flow	4.44 mg/s
Average effective specific impulse	1540 s

SMART-1 Plasma Diagnostic Instruments

The potentially undesirable effects from EPS included surfaces contaminated with sputtered material and eroded by ion impingement. The Electric Propulsion Diagnostic Package (EPDP) was developed by Alcatel Alenia Space (I) to measure the effects and prove whether they affected spacecraft operations. Surfaces could have charged up, creating electrical problems. Measurements in vacuum chambers were not very representative and the real spacecraft configuration could not be reproduced; flight experience was essential.

In order to measure these effects, EPDP included:

Retarding Potential Analyser (RPA): measured the ion energy and current density distribution.

Langmuir Probe (LP): measured the plasma potential, electron density and electron temperature. The LP and the RPA were on the same panel with the thruster at the centre; RPA's axis was oriented towards the thruster.

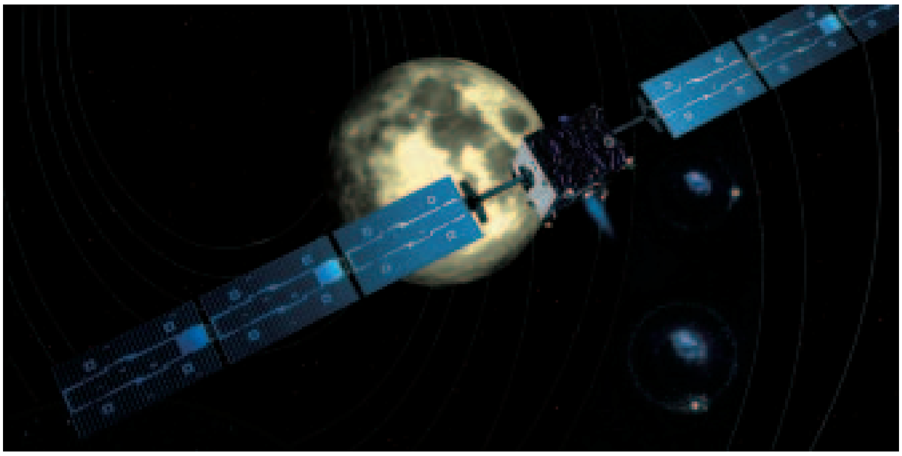
Solar Cell (SC): positioned away from the solar array.

Quartz-Crystal Microbalance (QCM): used to 'weigh' deposited material, providing real contamination data. SC and QCM were installed on the spacecraft's outer –X panel.

EPS Flight Performance

SMART-1 successfully completed all of its EP operations, including some advanced low-pressure thrusting for the 1-year extended mission up to the impact in September 2006. Orbital changes were monitored by ESA's European Space Operations Centre (ESOC) in Darmstadt (D), and the craft's acceleration measured. From these data, the actual thrust levels were accurately determined – valuable feedback from SMART-1 to compare with ground data and to confirm the good behaviour of the thruster and EPS overall.

During ground tests, the thrust was measured with an accuracy of ±2.5% and the variable thrust-versus-power relationship was mapped using an older Qualification Model thruster. These correlated data were used to predict the thruster's flight performance.



The EPS was used in the variable power mode, especially at start-up, but the thruster power used remained close to its maximum (1140 W *vs.* 1190 W). The average measured thrust over almost 5000 hours was well within the predicted average thrust range (67 mN *vs.* 65.7–9.1 mN), even though the projection was done using measurements from a different, older thruster. SMART-1 therefore demonstrated the very good reproducibility and stability in time of thruster performance.

Operation History of the EPS

Up to 1.3 million valve activations were counted, with no signs of propellant leakage even though the qualification limit of 1 million cycles was well exceeded. The procedures developed during flight allowed the residual xenon mass in the tank to be reduced from 1.8 kg to 0.28 kg.

Thanks to the plasma diagnostic instruments, correlated data from the local plasma potential and from the energy of the backflow particles showed the very good operation of the cathode. A cathode is usually considered to be a sensitive component and is therefore made with redundancy. The main parameter for controlling its good health is the working reference potential. Because of the periodic variations of the spacecraft reference potential, a second independent reference potential was required. However, the potential of the nominal cathode was shown to be highly stable throughout the mission. In addition, the thruster always (844 times) started at the first ignition pulse on the cathode. Thus SMART-1 proved this type of hollow cathode developed by SNECMA.

Furthermore, none of the EPS performance parameters was affected by the artificial plasma surrounding the spacecraft or by the periodic oscillation of the spacecraft potential.

Interaction with the Environment

In the initial stage of the mission, the main effect on SMART-1 from its environment was on the solar cells, damaged by the protons in the radiation belts. Taking into account the Earth-Sun distance changing with season, the solar array power fell by around 8%, which included the effect of the very intense solar flare of October 2003. The degradation ended after only 2 months, when the perigee altitude rose above 5900 km. The solar array was sized to cover a 12.3% drop in power at 40ºC, and 17.7% at the maximum cell temperature of 100ºC. Most of the time during EPS operation, the cell temperature was around 60ºC.

From the analysed EPDP flight data, the artificially generated plasma from the propulsion system had no critical effect on SMART-1. No indication of increased erosion or contamination was found; no surface-charging effects were detected. On the contrary, the dense artificial plasma generated by the EPS had a neutralising and stabilising effect on the spacecraft potential, which could otherwise have had a large positive potential, in particular when crossing the radiation belts.

The spacecraft potential was extremely neutral, stable and fully independent of the surrounding natural plasma, including that of the proton and electrons belts. This would have certainly not been the case for a spacecraft without EP and unprotected by a dense, surrounding artificial plasma. Furthermore, the small variations in spacecraft potential are fully understood and exactly correlated to specific thruster operating conditions and solar array attitude with respect to the thruster plume.

Conclusions

By exceeding its mission objectives, SMART-1 has made a very significant contribution to the promotion of electric propulsion. The impressive results from Europe's first scientific lunar experiments have also helped EP enormously in gaining a larger audience around the world.

In addition, thanks to the EPS performance, the limited degradation of the solar arrays and the optimised transfer strategy, SMART-1 completed a 1-year mission extension, thereby tripling the scientific observation period. On 11 November 2004, SMART-1 became the first ever mission to escape Earth using electric propulsion, and the first to use it for capture by the gravitational field of another celestial body.

All the operational elements of this highly successful spacecraft were demonstrated, paving the way for future missions. The performance of a single thruster, in various operating and environmental conditions, is clear evidence of the robustness of the SMART-1 EPS design, and of the capability of this type of thruster to accomplish a wide range of space missions, including scientific and commercial.

Detailed information on SMART-1 and its mission can be found at www.esa.int/smart1