JOURNAL OF PROPULSION AND POWER
Vol. 20, No. 2, March–April 2004

2000-Hour Endurance Test of Indium Field Emission Electric Propulsion Microthruster Cluster

A. Genovese,* M. Tajmar,† N. Buldrini,‡ and W. Steiger§
ARC Seibersdorf Research, A-2444 Vienna, Austria

An indium field emission electric propulsion (In-FEEP) thruster was recently selected as a micropropulsion candidate for ESA's Gravity Field and Steady-State Ocean Circulation (GOCE) mission. Within a pre-verification phase, a cluster of two In-FEEP thrusters successfully completed a 24 h endurance test. This is the longest endurance test ever performed for field emission thrusters. Although the test did not include a neutralizer, the results show stable and good performance and suggest that lifetime is mostly limited by the propellant reservoir tank size. This information is very important for many upcoming missions that require ultraprecise drag-free control such as GOCE, LISA, Terrestrial Planet Finder/Darwin or SMART-2.

Introduction

FIELD emission thrusters are currently under consideration for a variety of drag free missions both in the United States and Europe that require ultraprecise attitude control such as Gravity Field and Steady-State Ocean Circulation (GOCE), LISA, SMART-2 or Terrestrial Planet Finder (TPF)/Darwin. Since 1995, we have been developing a field emission electric propulsion (FEEP) thruster using indium as propellant. This technology is based on a space-proven liquid-metal-ion source used for satellite potential control devices and mass spectrometers.[1] Our recent developments include a complete prototype equipped with a large propellant reservoir, thermal and electric insulation as well as direct thrust measurements, beam diagnostics, and plume simulation.[2–7] However, one of the most critical requirements for every thruster is the demonstration of adequate lifetime. Therefore, several endurance tests were started last year [820 h and 2 × 500 h (Ref. 3)] to investigate any possible wear-out mechanisms.

The In-FEEP thruster was selected by ESA and its prime contractors as a micropropulsion candidate for ESA's GOCE mission. GOCE is an Earth observation cornerstone mission to map the Earth's gravitational field with very high precision.[8] This mission requires a total impulse of 6045 N · s and a total operation time of 20,000 h. This mission can be accomplished using a cluster of 12 In-FEEP thrusters to provide a maximum thrust of 650 μN per thruster position. Within a preverification phase, a lifetime test of 2000 h had to be conducted. Based on the results of our previous endurance tests, the design was updated, and an extended endurance test of an In-FEEP cluster of two thrusters was successfully carried out between March and June 2002. Total firing time was more than 2000 h. This is the longest endurance test ever conducted with any kind of FEEP thruster and is a major step forward for this technology.

Thruster Description

The thruster shown schematically in Fig. 1 consists of an indium liquid-metal-ion source with a sharp needle protruding out of a propellant reservoir tank. This reservoir is heated to above 156.6°C to melt the Indium. If a sufficiently high electric field is applied between the needle and an extractor electrode, a so-called Taylor cone is formed, and ions are directly pulled out of the liquid metal surface at the tip of the needle (Fig. 1, see Ref. 9). These ions are accelerated out by the same electric field that created them. Typical beam profiles show a Gaussian/cosine distribution limited by the geometry of the electrode configuration.[4] The following equations determine the thruster performance with respect to thrust force F and specific impulse I_{sp}:

$$F = \dot{m}_{ion} \cdot v = (I_E - I_{extr}) \cdot \sqrt{(2 \cdot m_{ion} \cdot U_E)/e} \cdot c(I_E)$$
$$= 1.543 \times 10^{-3} \cdot I_B \cdot \sqrt{U_E} \cdot c(I_E) \qquad (1)$$

$$I_{sp} = F/(\dot{m} \cdot g) = 132.1 \cdot \sqrt{U_E} \cdot c(I_E) \cdot \eta_m(I_E) \qquad (2)$$

where I_E is the emitted current, I_{extr} is the extractor current, U_E the emitter voltage, and η_m the mass (propellant utilization) efficiency. These equations assume the use of either a thermionic or field-emission array neutralizer. Thrust losses due to beam divergence, described by the thrust coefficient factor $c(I_E)$, are usually $20 \pm 10\%$ (depending on the actual configuration and thrust level), which is in agreement with direct thrust and plume measurements.[4–6] Approximately, 10 μA corresponds to 1 μN. Typical voltages are between 6 and 8 kV for currents up to several hundred microampere. Those values correspond to a thrust range of 0–60 μN and specific impulses of 2000–8000 s (see Ref. 7). Whereas a neutralizer would be required for any flight application of In-FEEP, ground tests such as the one described herein can be conducted without one.

In addition to beam ions, slightly charged microdroplets are emitted due to instabilities at the emission site. Those droplets have an exponential distribution and are sharply peaked along the centerline. The amount of droplets emitted is given by the mass efficiency value, which is the ratio of mass emitted as ions to the total mass consumed. Depending on the emitted current, mass efficiency can vary from 100% (at a few tens of microamperes) down to a few percent (at hundreds of microamperes). As a result from previous endurance tests, droplet contamination on the extractor electrode is a serious lifetime limiting factor. A numerical model was developed to investigate beam sputtering and droplet deposition to predict lifetime for certain thruster performance parameters.[3] To eliminate this lifetime limiting factor, the extractor electrode was replaced by a thin ring that can be heated to evaporate all contamination (Fig. 2). The ring is supported by a ceramic tube within a nozzle. This nozzle has a diameter large enough to enable more than 20,000 h of operation.

Figure 3 shows a cluster of three In-FEEP thrusters mounted on a flange before the start of the endurance test. Only two thrusters were used for the test. Each thruster contains a propellant reservoir tank of 15 grams which corresponds to a total impulse capability of

Received 18 July 2002; revision received 14 November 2003; accepted for publication 14 November 2003.

*Staff Member, Space Propulsion; angelo.genovese@arcs.ac.at.
†Staff Member, Space Propulsion; also Lecturer, Aerospace Engineering Department, Vienna University of Technology, A-1040 Vienna, Austria; martin.tajmar@arcs.ac.at. Member AIAA.
‡Contractor, Space Propulsion; nembo.buldrini@arcs.ac.at.
§Senior Staff Member, Space Propulsion; wolfgang.steiger@arcs.ac.at.

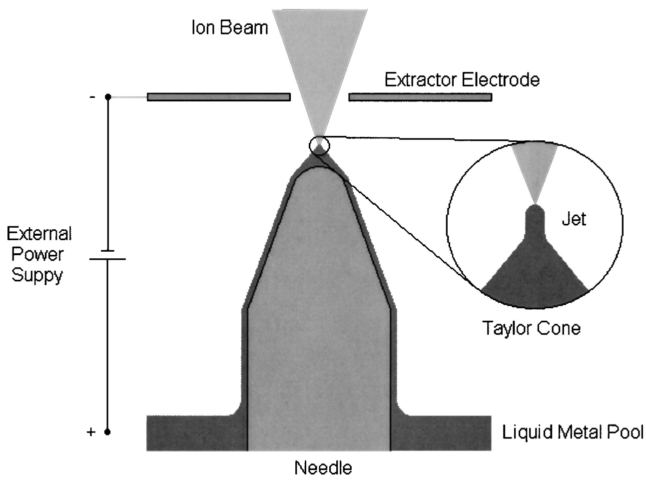

Fig. 1 In-FEEP thruster principle.

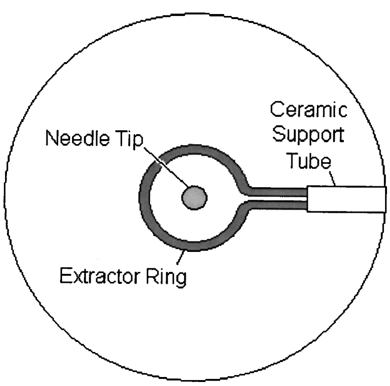

Fig. 2 Ring extractor principle.

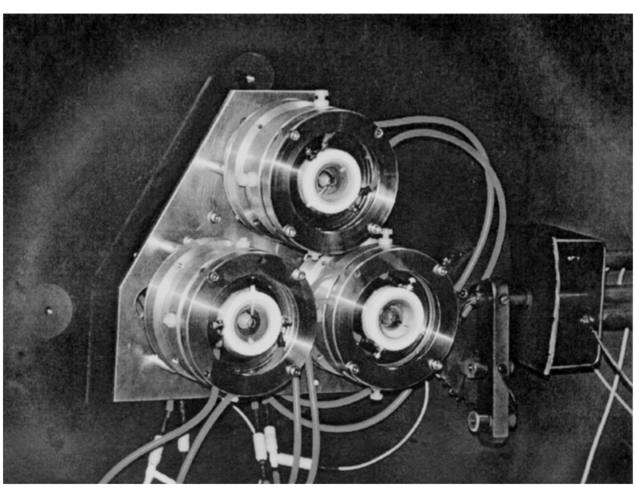

Fig. 3 In-FEEP cluster before start of endurance test.

around 400 N · s. (The empty weight of the thrusters is about 8 g) The extractor ring had a diameter of 4.2 mm and an emitter tip–extractor ring distance of 0.2 mm. The heating power per module was approximately 1 W.

Experimental Setup

The endurance test was carried out at in the ARCS Large FEEP Test Facility 1, which is made out of a cylindrical, stainless steel vessel of 1 m diameter and 1.5 m length with a volume of 1.2 m^3. The tank is pumped using a turbo pump/mechanical pump combination that provided a facility base pressure of 8×10^{-8} mbar. The pressure during thruster operation was always below 2×10^{-7} mbar at maximum thrust once the facility was outgassed.

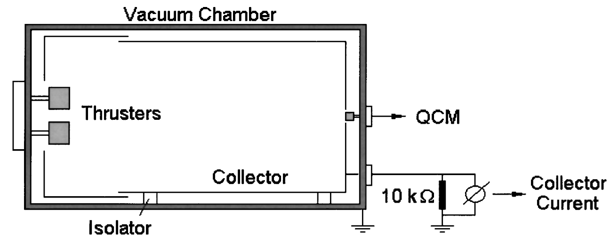

Fig. 4 Vacuum chamber setup.

An aluminium ion beam collector has been mounted inside the chamber. It has a chevron configuration, which results in large angles (typically greater than 50 deg) between the expected ion trajectories and the direction normal to the aluminium surface.[3] This greatly reduces the collector sputtering yield and the amount of sputtered material directed back toward the thruster. The thruster cluster is mounted on flange with the necessary feedthroughs for low and high voltage. Electron backstreaming from secondary electrons generated on the collector walls into the thrusters was analyzed by installing a grid before the collector, which was biased to −100 V to reflect electrons originating from the collector surface back to the collector and, therefore, to prevent backstreaming. It was found that the emitter current is influenced less than 10% at high currents by those electrons. In the present configuration, a negatively biased cover plate is used to repel these electrons completely[7]; however, this configuration was not ready for the 2000-h endurance test.

The chamber was also equipped with a Quarz-Crystal-Microbalance (QCM) in the centerline of the collector (Fig. 4). This enables the investigation of any variation in the ion/droplet current ratio. Ions sputter the crystal, whereas droplets deposit Indium on the crystal. Hence, a change in the ion/droplet current ratio also causes a change in the deposition rate on the QCM. When sputter/deposition rate of the crystal is monitored over time, the stability of mass efficiency during the endurance test can be analyzed. (Depending on the actual mass efficiency either sputter or deposition rate will be dominant.) In addition, a powerful lamp inside the chamber, together with a shutter-window, mirror, and digital camera, was installed to allow optical inspection of the thrusters during the test.

In this setup, the thruster heaters were all on high voltage; therefore, the heater power supplies were operated at high voltage through an isolation transformer. A program was written to record emitter current, voltage, extractor current, and chamber parameters such as pressure, QCM, and collector current. The measurement accuracy was always better than 0.1% of the maximum value obtained during the test. This program was also used to drive the thrusters along a current profile according to the mission requirements. The sampling rate was 1 s, fast enough to detect major sparks throughout the test. (A spark duration is typically 1 ms; however, it causes the power supply to go into current limit that can be seen in the monitor signals that are recorded.) The pressure gauges were connected to a relay to shut off all heater and high-voltage power supplies in case the pressure rises higher than 10^{-5} mbar. The data acquisition personal computer and the vacuum gauges were connected to an uninterruptible power supply.

Endurance Test

Thrusters 1 and 3 in this cluster were active throughout the test, thruster 2 was not ready in time for testing.

Test Profile

The GOCE mission requires two operation modes, a nominal $\sin^6$ profile of up to 33 μN per thruster with a period of 5000 s (Fig. 5), and a half-sinus calibration profile in which a 0.1-Hz frequency and an amplitude of 21 μN is superimposed on the nominal profile. Calibration has to run every 200 h for a period of 6 h. To a good approximation, the thrusters were commanded in current control mode; no thrust control electronics were used to simplify the setup.

(Voltage was free to vary.) Hence, the thruster operated in open loop.

Pretest Run

To validate the setup and to compare mass efficiency before the test and after the test, a pretest had been conducted. Originally planned for 24 h, the test had to be stopped after 6 h due to a vacuum leak that had to be repaired. After a visual check of the thruster modules, the cluster was again mounted on the flange prepared for the final endurance test. Mass efficiency was 20% for thruster 1 and 35% for thruster 3 averaged over the GOCE profile during the 6-h test.

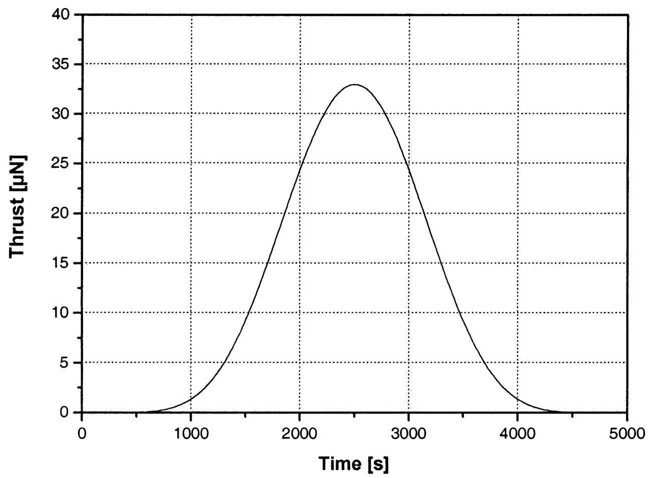

Fig. 5 Nominal profile.

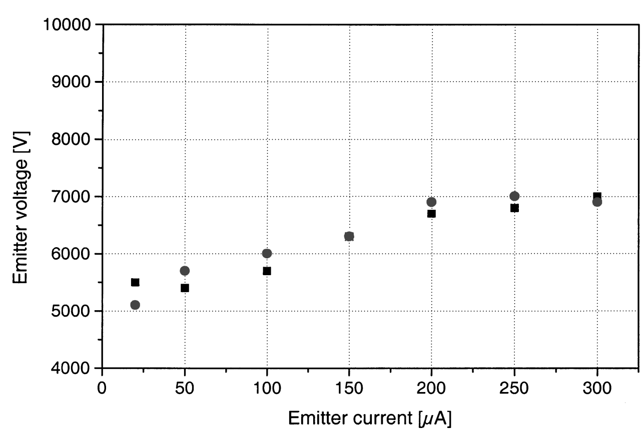

Fig. 6 Current–voltage characteristic before test start: ■, thruster 1 and ●, thrust 3.

Main-Test Run

First-Half

The endurance test was started on 15 March 2002 at 0915 hrs. The vacuum pressure was 1.7×10^{-7} mbar, the current–voltage characteristics of the two thrusters at the beginning of the test are shown in Fig. 6. The thrusters were commanded with the GOCE nominal profile going from 0 to 300 μA. Because the maximum thrust was around 30 μN instead of 33 μN, the current range was increased after 24 h from 0 to 325 μA.

Figure 7 shows the collector current profile at 100 h. It looks similar to the commanded nominal profile in Fig. 4 and shows no anomalies. In addition, Figs. 8 and 9 show the emitter voltage and extractor current of thrusters 1 and 3, respectively for the same current profile at 100 h. Because of the property of the Heinzinger high voltage (HV) power supply, the voltage of thruster 3 does not go to zero at zero current. At the end of the test, the Heinzinger HV power supply was replaced by an FUG HV power supply, and the voltage dropped to zero just as for thruster 1. The extractor currents for both thrusters were in the order of 1 μA along the current profile. This is a very low value and indicates good performance as well as good centering of the needle tip inside the extractor ring.

Figure 10 shows the QCM data up to the time it failed at hour 130. The data indicates a stable, though slightly increasing, ion/droplet current ratio. This can be interpreted as stable and even slightly increasing mass efficiency. At 420 h, the temperature dropped to low temperatures during the night and the indium propellant in thruster 1 froze (Fig. 11). After increasing heating power the following day, the thruster started without any problems with similar characteristics and no performance degradation. This happened again at 550 h. Calibration was executed every 200 h without any problems.

The first extractor electrical evaporation cleaning was carried out after about 300 h. After heating the extractor wire, all indium evaporated as witnessed by optical inspection. This step was repeated after 200–300 h for both thrusters.

Second-Half

The current–voltage characteristics and extractor currents from thrusters 1 and 3 at 1100 h are shown in Figs. 12 and 13, respectively. The extractor current from thruster 3 is rising at higher currents due to a displacement of the extractor ring with respect from the needle (as seen by optical inspection). This was possible because the extractor wire was not fixed on the back side of the ceramic support tube. Therefore, when the wire was heated during evaporation, it could slide through the tube resulting in a displacement after cooling down. This mistake was corrected in the present design.

At 1313 h, an overheated thermocouple shut down the turbopump and the pressure increased up to 10^{-3} mbar (Fig. 14). The relay immediately switched off the heaters and the HV power supplies and put the thrusters in safe mode. After 4 days of repair, the thrusters started with similar characteristics and showed no sign of performance degradation.

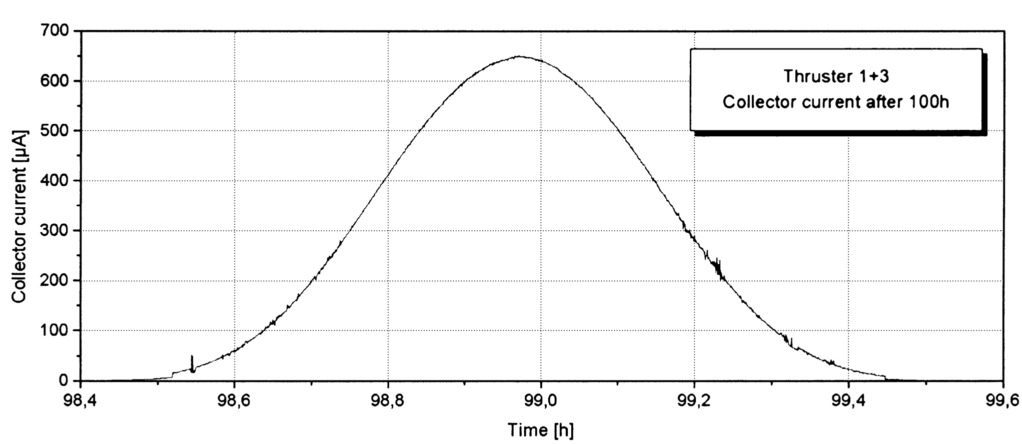

Fig. 7 Collector current of thrusters 1 and 3 at 100 h.

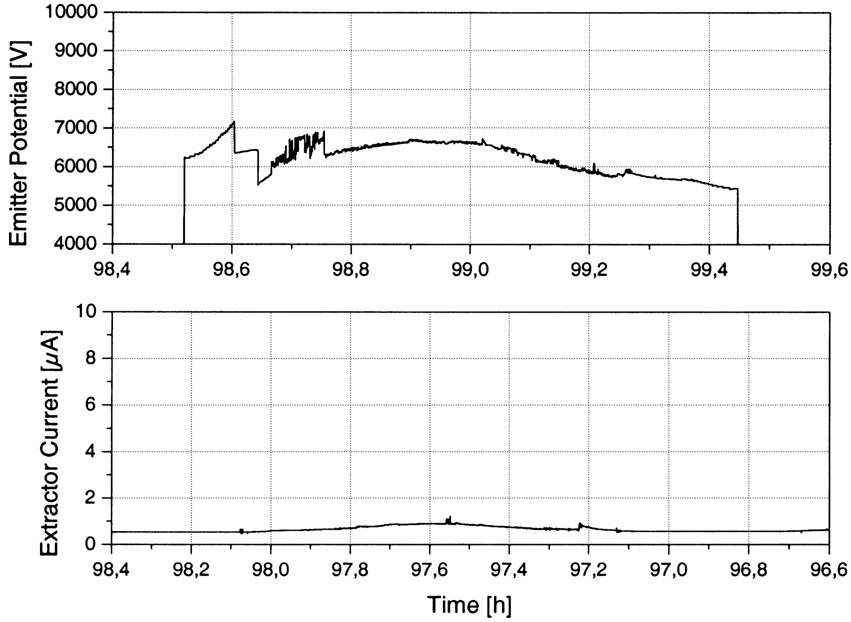

Fig. 8 Emitter potential and extractor current of thruster 1 at 100 h.

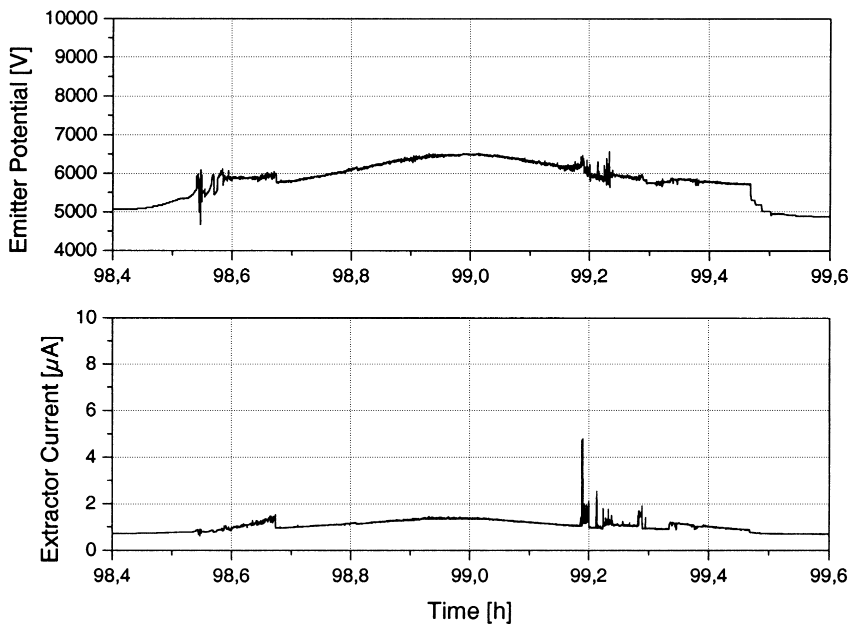

Fig. 9 Emitter potential and extractor current of thruster 3 at 100 h.

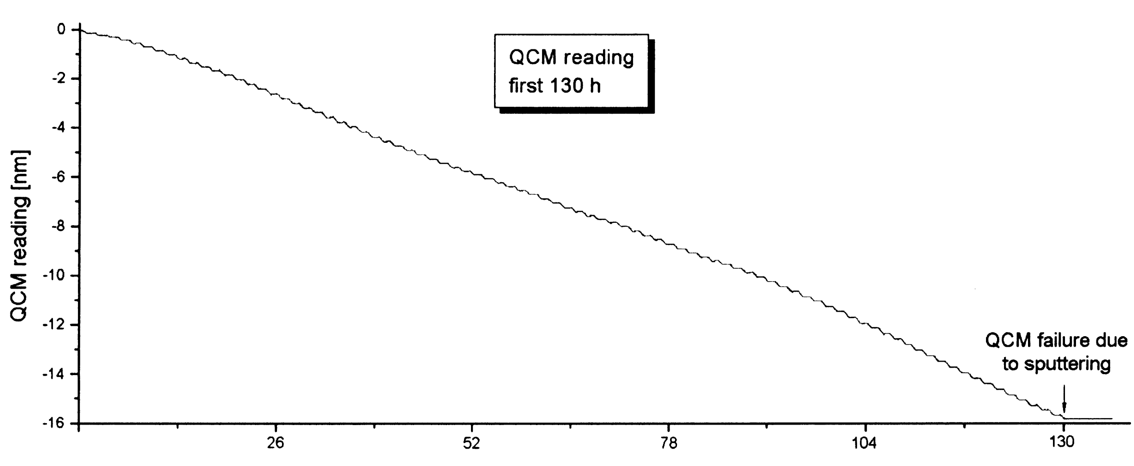

Fig. 10 QCM reading up to 130 h (accuracy 0.05 nm).

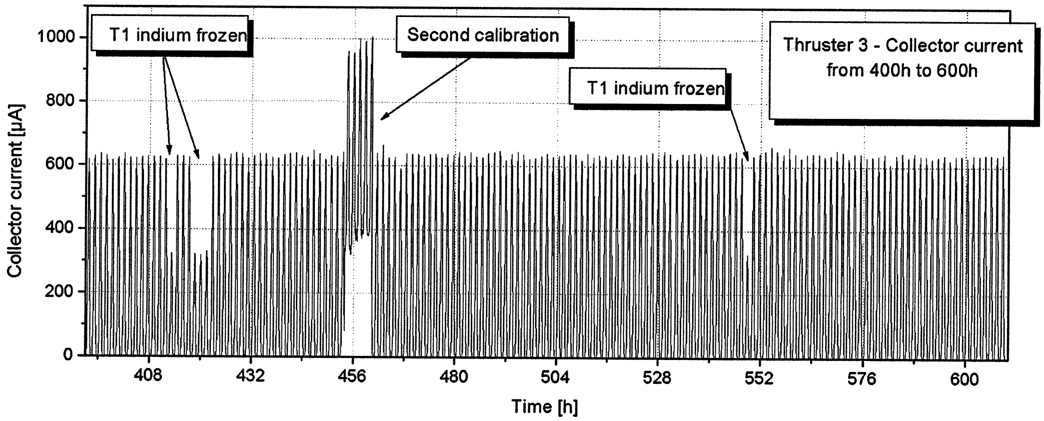

Fig. 11 Collector current from 400 to 600 h.

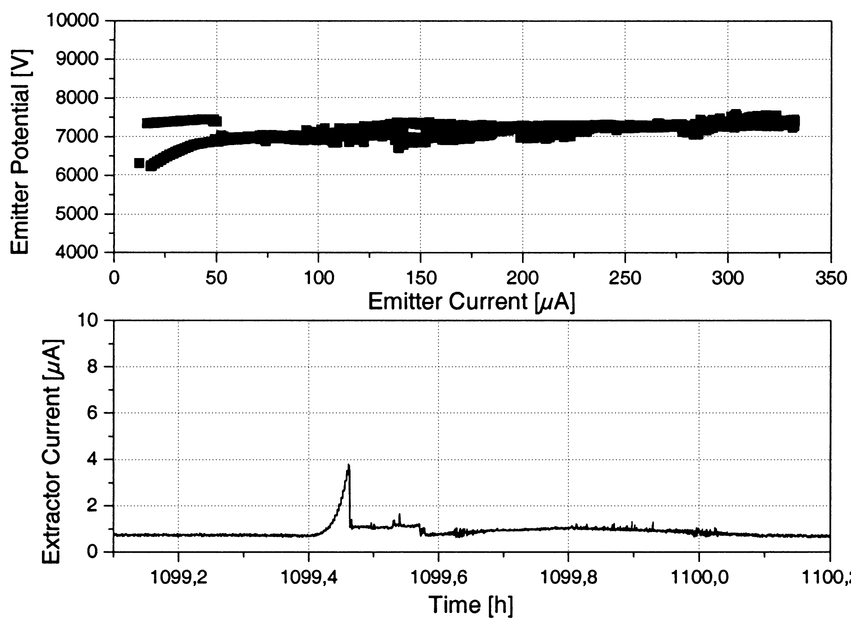

Fig. 12 Current–voltage characteristics and extractor current of thruster 1 at 1100 h.

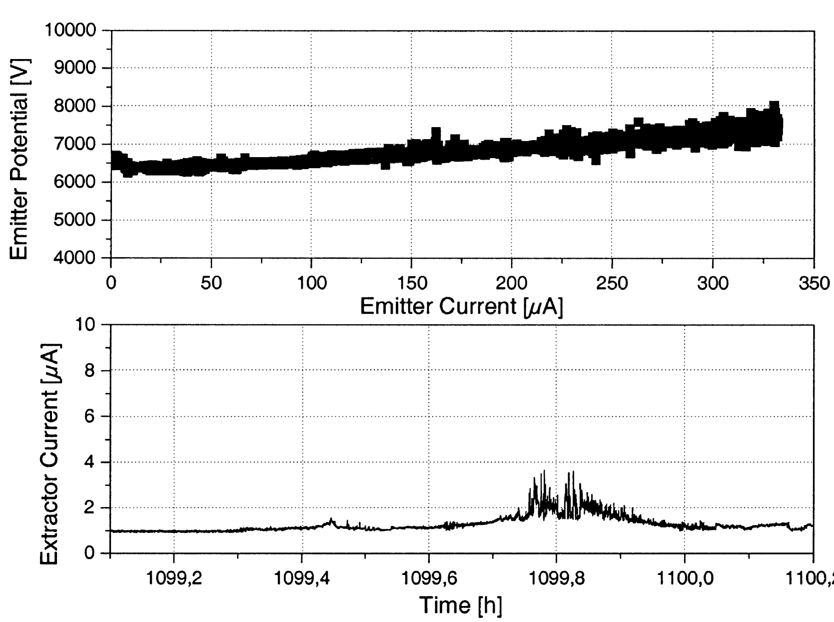

Fig. 13 Current–voltage characteristics and extractor current of thruster 3 at 1100 h.

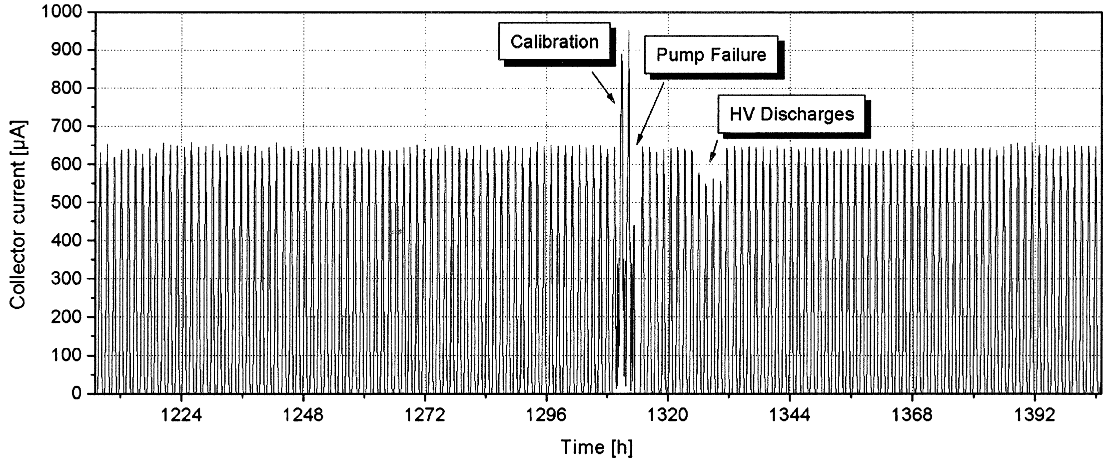

Fig. 14 Collector current from 1200 to 1400 h.

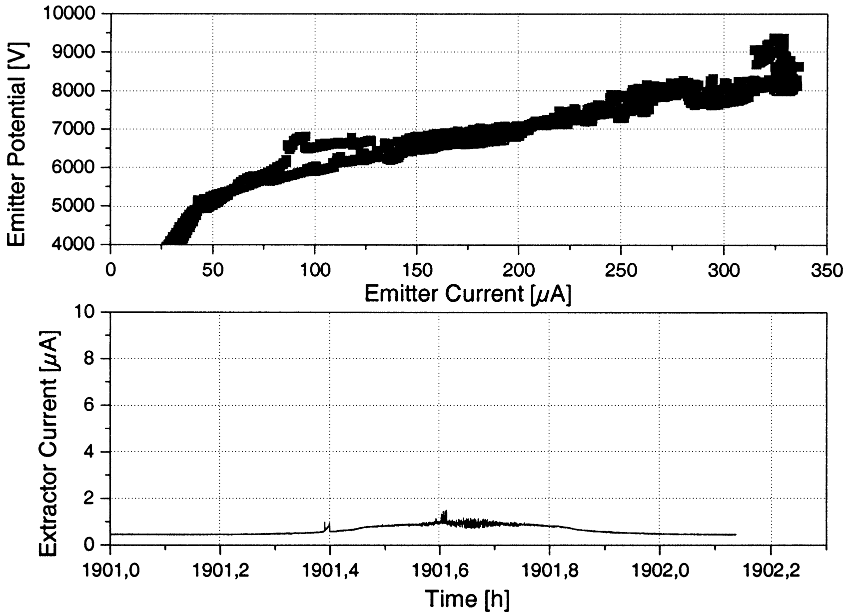

Fig. 15 Current–voltage characteristics and extractor current of thruster 1 at 1900 h.

Unfortunately, the extractor ring of thruster 1 moved because of the same design as thruster 3. The droplet contamination on the ring came close to the needle tip and initiated a HV discharge at 1330 h. This discharge melted the contamination on the extractor ring, which again enlarged the distance needle tip–extractor. Therefore, the discharge stopped automatically after about three profiles. However, the discharge also changed the film thickness on the needle and caused a 1 kV increase in the emitter voltage of thruster 1. Mass efficiency is linked to the current–voltage characteristics of a thruster.[9] The higher the voltage for a certain current, the higher will be mass efficiency. Hence, the voltage increase caused an increase in mass efficiency as well. This was evident because much fewer droplets deposited on the wire extractor of thruster 1 after this event. In fact, no evaporation was necessary for thruster 1 up to the end of the test.

Figures 15 and 16 show the current–voltage characteristics and the extractor currents for thrusters 1 and 3, respectively. Clearly, the extractor current from thruster 3 was rising again, which indicated a further displacement of the extractor ring. Figures 17 and 18 show the thrust noise of thrusters 1 and 3, respectively, in open loop (no thrust control) compared to the GOCE mission requirement. This shows that the two thrusters fulfill this requirement even in open loop. Closed loops are expected to give at least one order of magnitude less noise.[10]

The thrusters were switched off on 11 June 2002 at 1920 hrs, with more than 2000 h accumulated. Up to this event, the thruster produced the thrust profile as commanded.

Discussion

After the test, the chamber was opened, and the thrusters were disassembled. Backsputtering from the collector was clearly evident (Fig. 19). The extractor ring displacement from thruster 1 was 0.3 mm and from thruster 3, 1 mm. Thruster 1 increased mass efficiency from 20 to 26% (due to the 1-kV increase in emitter voltage after the HV discharge), and thruster 3 decreased from 35 to 10%. This can be explained by the large displacement of the extractor ring that caused increased backsputtering of indium from the extractor ring to the needle and thereby increasing the film thickness. The small displacement of thruster 1 did not cause a decrease in mass efficiency.

Figures 20 and 21 show the maximum emitter voltage of thrusters 1 and 3 throughout the endurance test. They stayed well within their limits of ±1 kV. At the end of the test, the emitter voltages were very similar to the values at the start of the test. The endurance test demonstrated the following results.

1) Both thrusters showed a thrust noise below the GOCE requirement in open-loop configuration.

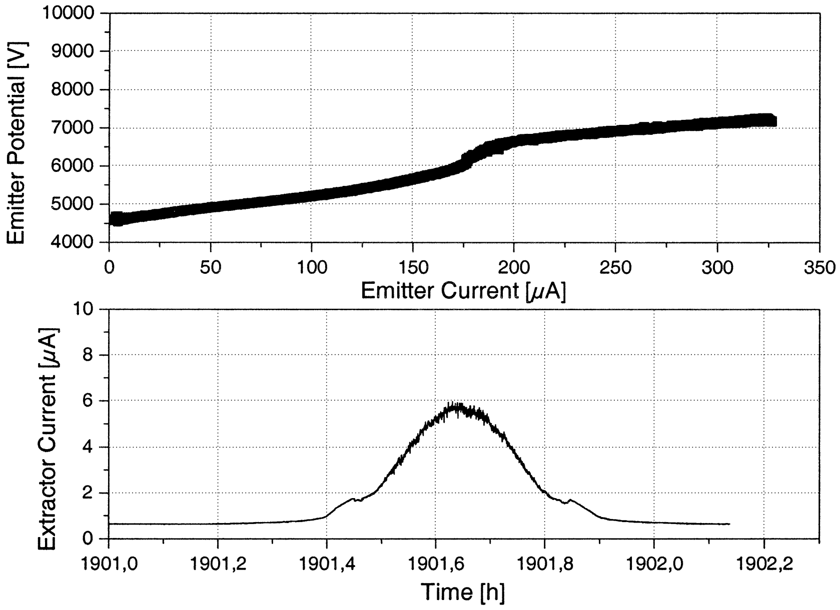

Fig. 16 Current–voltage characteristics and extractor current of thruster 3 at 1900 h.

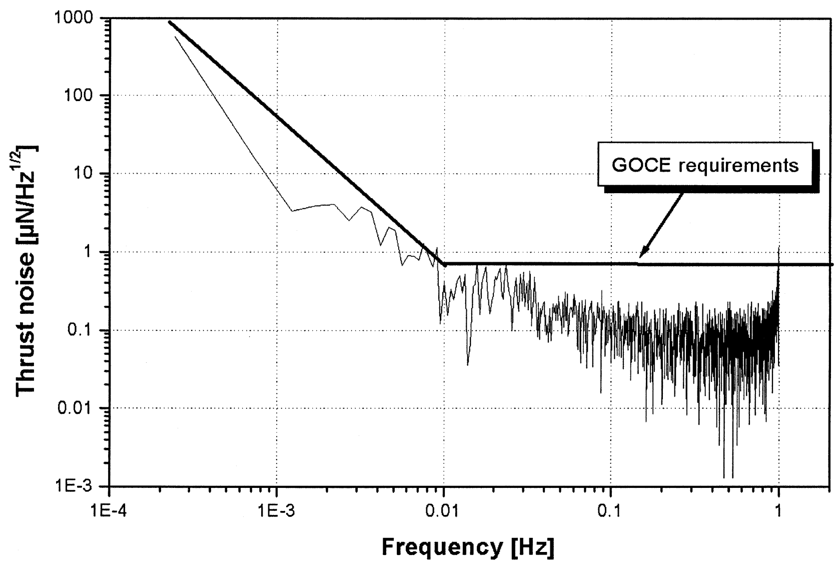

Fig. 17 Thrust noise of thruster 1 at 1900 h (sampling frequency 1 Hz, digital accuracy 12 bit).

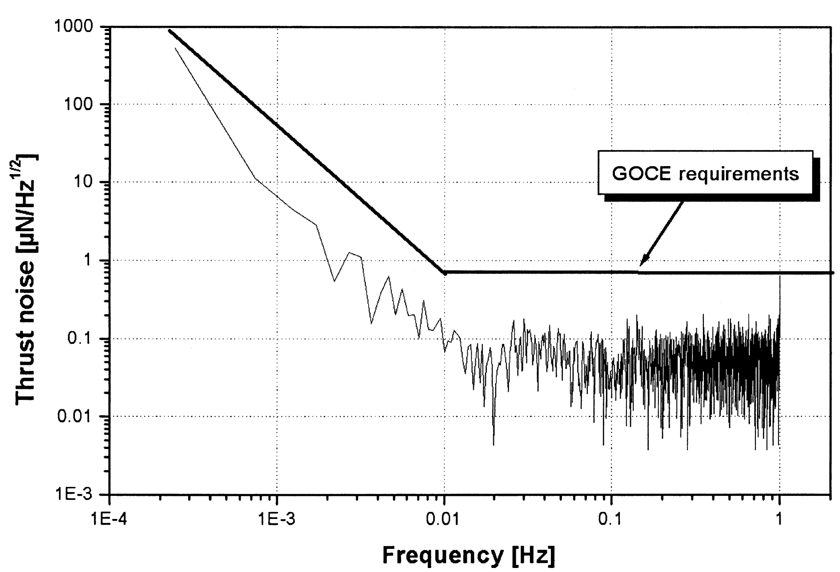

Fig. 18 Thrust noise of thruster 3 at 1900 h (sampling frequency 1 Hz, digital accuracy 12 bit).

2) Both thrusters operated at the expected thrust levels.

3) No beam interaction between the two thrusters was noticeable.

4) Both thrusters stayed in the predicted current–voltage limits. (Changes were most probably due to the HV discharge and movement of extractor ring toward emitter tip, corrected in the next design.)

5) Both thrusters showed no sign of isolation problems, the isolators stays clean throughout the test.

6) Evaporation of contamination from the wire extractor was successful and is not a lifetime limiting factor.

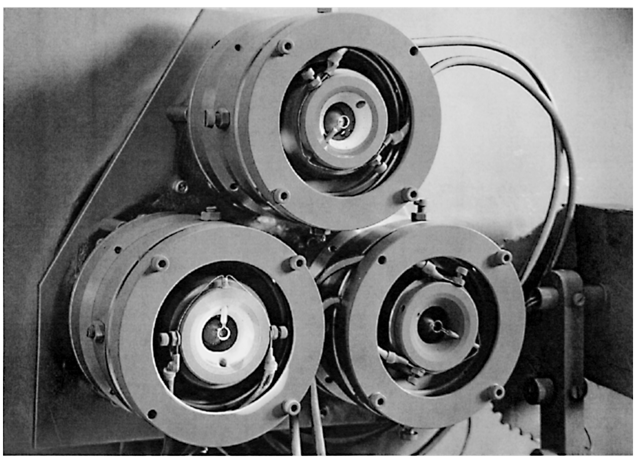

Fig. 19 In-FEEP cluster after end of endurance test (backsputtering on all top surfaces and cables).

7) Propellant consumption was successfully demonstrated. In particular, thruster 3 consumed 9 out of 15 g of propellant out of the reservoir tank without difficulty.

8) The turbopump failure and the HV discharge was survived by the thrusters demonstrating the robustness of this technology.

The endurance test demonstrated the feasibility of stable performance and showed no serious lifetime limitations. A total impulse of 72 N · s per thruster was demonstrated throughout the test. A critical design element was identified (fixing of extractor wire in ceramic support tube) and transferred to the present design. This endurance test suggests that, in the present design, lifetime is only limited by the propellant reservoir size.

Conclusions

For the first time, a 2000-h endurance test was carried with on a field emission thruster. Although neutralizers were not included in the tests, cluster of two In-FEEP thrusters could be operated successfully throughout the test, commanded with a thrust profile ranging from 0 to 33 μN and 0 to 55 μN according to the requirements of ESA's GOCE mission. The test revealed no major lifetime limitations and suggests that, in the present design, lifetime is only limited by the propellant reservoir size.

Acknowledgments

The authors gratefully acknowledge the support of their company, ARC Seibersdorf Research, in the success of this research program. This work has been carried out under PATP with MTA-Prequalification Activities Ref. GOCE-AFG-0161/2002. We would like to thank A. Popescu, G. André, J. Wohlfart, and J. González for their support and useful discussions, as well as H. Posch, E. Semerad,

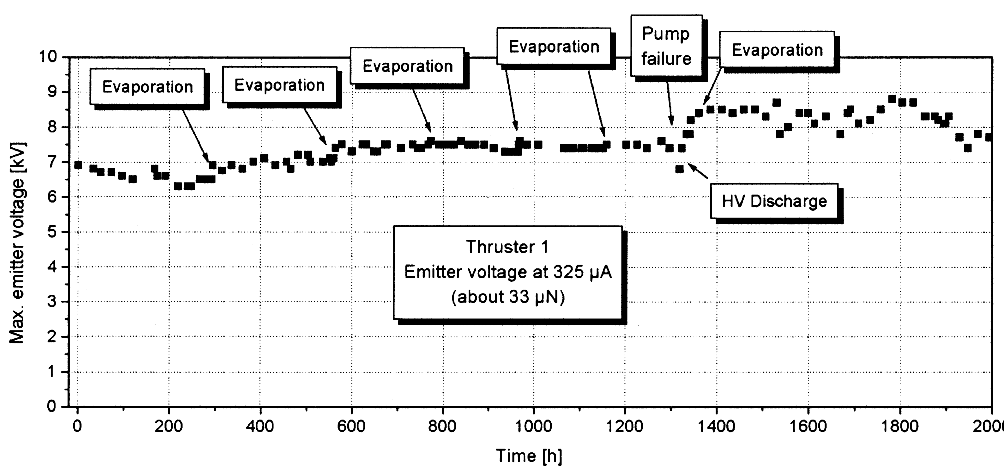

Fig. 20 Maximum voltages of thruster 1 during 2000-h test.

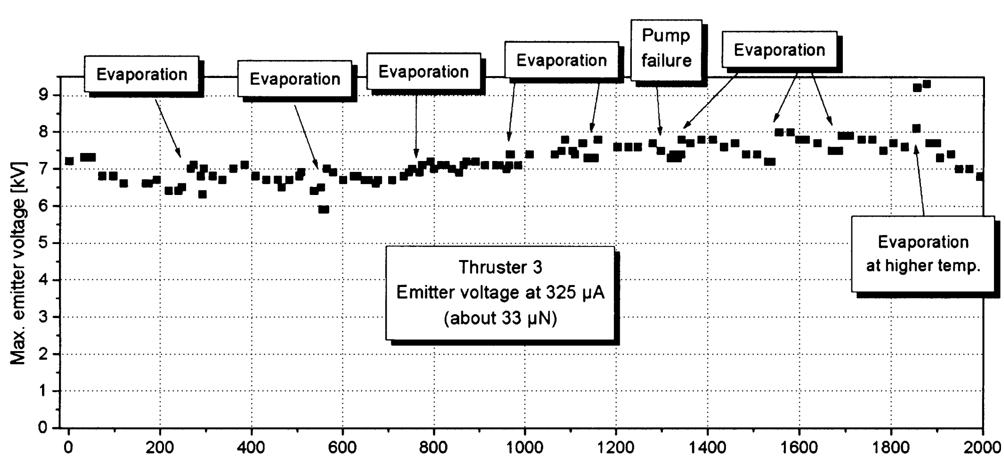

Fig. 21 Maximum voltages of thruster 3 during 2000 h test.

P. Sattler, and A. Fenz for the many hours of encouragement, management, and proposal preparation.

References

[1] Fehringer, M., Ruedenauer, F., and Steiger, W., "Space-Proven Indium Liquid Metal Field Ion Emitters for Ion Microthruster Applications," AIAA Paper 97-3057, July 1997.

[2] Genovese, A., Steiger, W., and Tajmar, M., "Indium FEEP Microthruster: Experimental Characterization in the 1-100 μN Range," AIAA Paper 2001-3788, July 2001.

[3] Genovese, A., Tajmar, M., and Steiger, W., "Indium FEEP Endurance Test: Preliminary Results," International Electric Propulsion Conf., Paper IEPC-01-289, Oct. 2001.

[4] Tajmar, M., Steiger, W., and Genovese, A., "Indium FEEP Thruster Beam Diagnostics, Analysis and Simulation," AIAA Paper 2001-3790, July 2001.

[5] Bonnet, J., Marque, J. P., and Ory, M., "Development of a Thrust Balance in the microNewton Range," 3rd International Conference on Spacecraft Propulsion, ESA-SP-465, CNES/ESA, Noordwijk, Oct. 2000.

[6] Ziemer, J., "Performance Measurements Using a Sub-Micronewton Resolution Thrust Stand," International Electric Propulsion Conf., Paper IEPC-1238, Oct. 2001.

[7] Tajmar, M., Genovese, A., and Steiger, W., "Indium Field Emission Electric Propulsion Microthruster Experimental Characterization," *Journal of Propulsion and Power*, Vol. 20, No. 2, 2004, pp. 211–218.

[8] Johannessen, J. A., and Aguirre-Martinez, M., "Gravity Field and Steady-State Ocean Circulation Mission," *Reports for Mission Selection*, ESA SP-1233, 1999.

[9] Tajmar, M., and Genovese, A., "Experimental Validation of a Mass Efficiency Model for an Indium Liquid Metal Ion Source," *Applied Physics A*, Vol. 76, No. 6, 2003, pp. 1003–1006.

[10] Steiger, W., Genovese, A., and Tajmar, M., "Micronewton Indium FEEP Thrusters," 3rd International Conference on Spacecraft Propulsion, ESA SP-465, CNES/ESA, Noordwijk, Oct. 2000.