Flight heritage of Indium-based FEEP propulsion systems across different applications and orbits: In space cleaning of extractor electrode

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Abstract: Since the first flight of a Field emission electric propulsion (FEEP) thruster in 2018, more than 200 FEEP based propulsion systems have been launched, including 190 heritage ENPULSION NANO systems, 18 higher power MICRO systems and 9 novel NANO R^3/AR^3. The latter are the successor products of the heritage NANO, with the AR^3 version allowing for direct thrust vectoring capability without moving parts. All propulsion systems reported in this work are based on passively fed, Indium based liquid metal FEEP technology. This work reports the latest launch and flight heritage statistics. We present telemetry of different propulsion systems used in different applications and orbits, and present the successful on orbit extractor cleaning procedure conducted after 1350 hours of accumulated firing on a heritage NANO thruster in LEO.

Nomenclature

FEEP	=	Field emission electric propulsion
GEO	=	Geostationary orbit
IOD	=	In orbit demonstration
LEO	=	Low earth orbit

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I.Introduction

INDIUM based Field Emission Electric Propulsion (FEEP) technology has been developed over at AIT and later FOTEC in the frame of ESA supported science missions[1-4]. In this technology, thrust is generated through electrostatic acceleration of ions extracted from a conductive propellant. To achieve this, the liquified metal propellant is suspended in sharp emitter needles which are biased to high voltage with respect to a counter electrode to induce a Taylor cone on top of the emitter feature. This counter electrode is commonly denoted extractor. To increase thrust, multiple of emission sites are arranged in a characteristic crown shaped emitter geometry for the NANO thrusters surrounded by the negatively biased extractor electrode. This allows achieving thrust levels in the order of 350 μN for one crown shaped ion emitter in the NANO system. To increase thrust levels, 4 of these emitter crowns are operated in parallel in the MICRO thruster, allowing thrust levels at nominal 1mN. Depending on emitter and extractor voltage settings, propulsion systems can be operated in a specific impulse range from approx. 1000 s to beyond 4000 s. Indium is used as propellant, which is in solid state during ground handling, integration and launch, and only liquefied once in orbit or during acceptance testing. The high density of the metal propellant together with the high specific impulse of the system result in very high volumetric specific impulse of the FEEP systems, leading to very high total impulse capability in small volume. Once liquified, the propellant is fed entirely passive from the propellant tank to the emission sites via capillary forces, therefore not requiring any pressurization or movable parts. This translates to an inert system during launch that passivates automatically once unused without risk of debris creation.

II.Flight Heritage Propulsion Systems

Based on the long heritage of LMIS development for space missions, FOTEC developed the IFM Nano Thruster that was first verified together with ENPULSION in 2018 on a customer spacecraft in LEO[12,13]. This propulsion system was then successfully industrialized in a serial production with hundreds of systems produced and acceptance tested and in total, 190 systems have been launched. Building on the significant space and industrialization heritage of this NANO thruster, several successor propulsion systems have been developed, shown in in Fig. 1: The NANO R^3 as improved version of the NANO including improvements higher tolerant electronics and improved mechanical design to simplify integration[5], the NANO AR^3 that introduces thrust vector control without movable parts[6], and the increased power MICRO R^3 which expands thrust range beyond 1 mN. By now, all these new propulsion systems have been successfully operated on orbit on several missions each. Ground based thrust and beam measurements have been performed for each unit at different facilities, as reported in Refs 7 to 9.

These systems are manufactured and acceptance tested in a serial production line at ENPULSION including a final verification acceptance test that is used to calibrate the fully filled systems before shipping to spacecraft integration at the customer site.

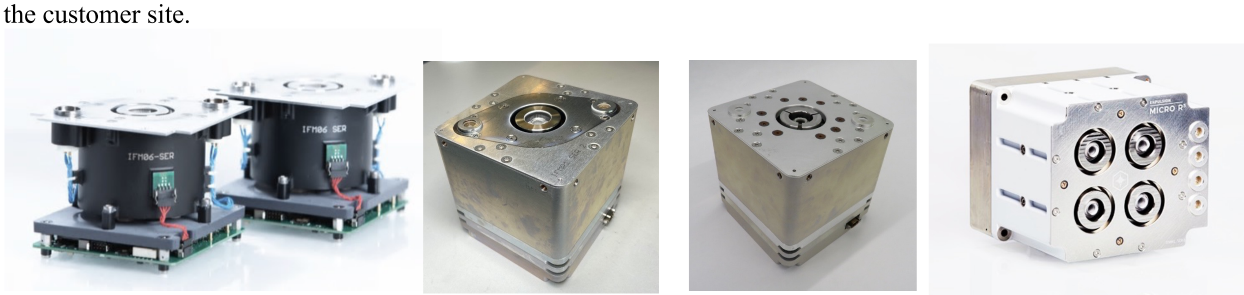

Figure 1. ENPULSION FEEP propulsions systems that have achieved space heritage from left to right: heritage NANO, NANO R^3, NANO AR^3 and MICRO R^3.

A. Design update

In Taylor cone-based emission of charged particles that is the basis of FEEP, the emission of ions from the Taylor cone is accompanied by emission of comparably large droplets. The droplets are of quasi neutral nature and are known to condense on surfaces in direct line of sight of the emission sites, including the extractor electrode surrounding the ion emitter. Over extended periods of firing, this condensed propellant can lead to a shrinkage of the spacing between emitter and extractor. An example of such extractor shrinking observed during the 50.000 hour test conducted on a FEEP emitter at FOTEC is shown in Refs. 10 and 11 where extractor shrinkage over thousands of hours was investigated. Recent characterizations of different ion emitters have shown stronger dependency of the rate of propellant accumulation based on emitter parameters and operation, resulting in decrease of times until which clogging may become measurable.

Removal of the attached Indium from the extractor electrode has been confirmed to restore firing conditions after extended accumulated firing durations beyond 1000 hours. Based on these results, extractor cleaning experiments have been conducted, during which the thruster was able to remove the accumulated propellant by changing the operational parameters. While these ground-based experiments suffered from limitations introduced by the gravitational environment given the characteristic length scales being larger than the capillary forces, these experiments have been used to develop cleaning procedures for on orbit operations.

FOTEC has developed a novel extractor geometry that improves the cleaning capability and allows in validation within a gravity environment. The design was validated in successful testing of two extractors to 8000 hours[4] and this novel extractor design will be integrated in the ENPULSION NANO R^3 and MICRO R^3 propulsion systems. Fig. 2 shows a closeup of one of an early version of the novel extractor design surrounding the ion emitter of a Micro R^3 during testing.

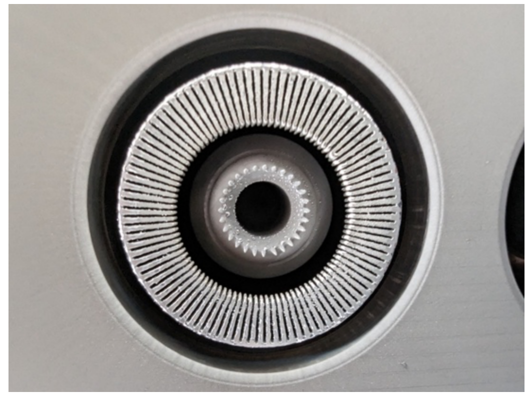

Figure 2. Updated extractor electrode design that allows verification of extractor cleaning procedure in gravity environment.[18]

III.Telemetry

Flight telemetry of ENPULSION FEEP propulsion systems has been previously reported, including the first firing of a FEEP thruster during the IOD of the NANO thruster[12,13], multiple NANO propulsion systems per spacecraft operated in parallel in LEO[14] and other uses of NANO thrusters[15]. FEEP systems have been used in a variety of different applications, including orbit acquisition, formation control and precise orbit keeping, eg. to improve repeated ground track in earth observing spacecraft[15] as well as conjunction avoidance maneuvers. In addition to telemetry acquired on LEO spacecraft, operation of FEEP systems outside of LEO has been reported[16,17].

A. LEO Extractor cleaning

This section presents a successful extractor cleaning procedure conducted on a thruster in LEO after approximately 1350 hours of accumulated thrusting time. As described in section II.A, accumulation of propellant droplets from the FEEP ion emission onto the extractor electrode of the propulsion system leads to a gradual decrease of the effective extractor electrode inner diameter, and therefore to a decrease of spacing between ion emitter needles and extractor electrode. The rate of clogging is found strongly dependent on specific emitter parameters, and can range from several thousands of hours[3,10] to emitters for which noticeable clogging can be expected at 1400-2000 hours.

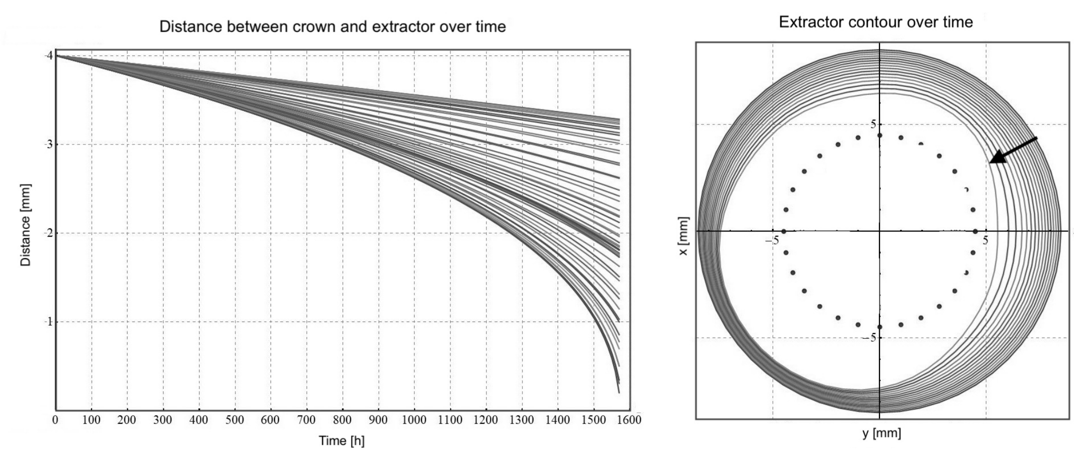

Figure 3. One of the modelling results of extractor clogging based on specific emitter and operational settings used throughout the mission showing the decrease of emitter to extractor spacing due to propellant accumulation within 1500 hours. Note that effects such as high voltage sparking are expected to occur when spacing decreases below certain thresholds necessitating cleaning of the extractor prior to full clogging.

A detailed model of the clogging phenomena including consideration of specific emitter parameters was developed, allowing to trace thruster behavior observed during this mission back to a clogging process. An example of a modelled extractor clogging process for a given ion emitter and specific operational parameters is shown in Fig. 3, resulting in significant reduction of the emitter to extractor spacing beyond 1200 hours for the modelled case. The simulation also shows the accelerating nature of the shrinkage process due to the emission amplification on closest needles caused by the reduced spacing and according change of the local electric field.

Fig. 4. shows the evolution of the measured ion emitter impedance of the operational mission as a function of days since propulsion system commissioning. The shown emitter impedance is calculated based on acceptance test onset voltage and is therefore a thruster specific value not incorporating eventual change of onset voltage with respect to the ground testing or throughout the mission. In this simple approximation of the onset voltage and impedance as constant values, the true observed impedance becomes dependent on thruster operational settings, as shown in Fig 4 by the spread of impedance based on different operational ranges used. Since the results presented stem from an operational customer mission, different operational settings were used during the course of the mission, including different thrust points, Isp settings and firing durations. In addition to the evolution of emitter impedance over the first 660 days since thruster commissioning, the extractor cleaning process conducted is highlighted in the plot. At the time of conducting the extractor cleaning, the thruster had accumulated approximately 1350 hours of thrust generation.

The plot in Fig 4. shows the early life trend of decreasing impedance commonly observed during system commissioning (impedance of early commissioning not visible in this plot as out of range) followed by stable operation primarily using operational setting 1. Starting around day 220, the decrease in impedance of the thruster is noticeable, which correlates to the decrease of the spacing between ion emitter and extractor, in accordance to the extractor clogging model shown in Fig. 3. The final decrease of the impedance was accompanied by an observed increase in the rate of sparking events likely between emitter and extractor electrode.

Based on the observed trend and in accordance to the extractor clogging model, the customer decided to conduct a cleaning procedure of the extractor. While ground testing of extractor cleaning using the heritage extractor design suffers from limitations in terms of maximum propellant mass and repeatability due to gravity constraints since the

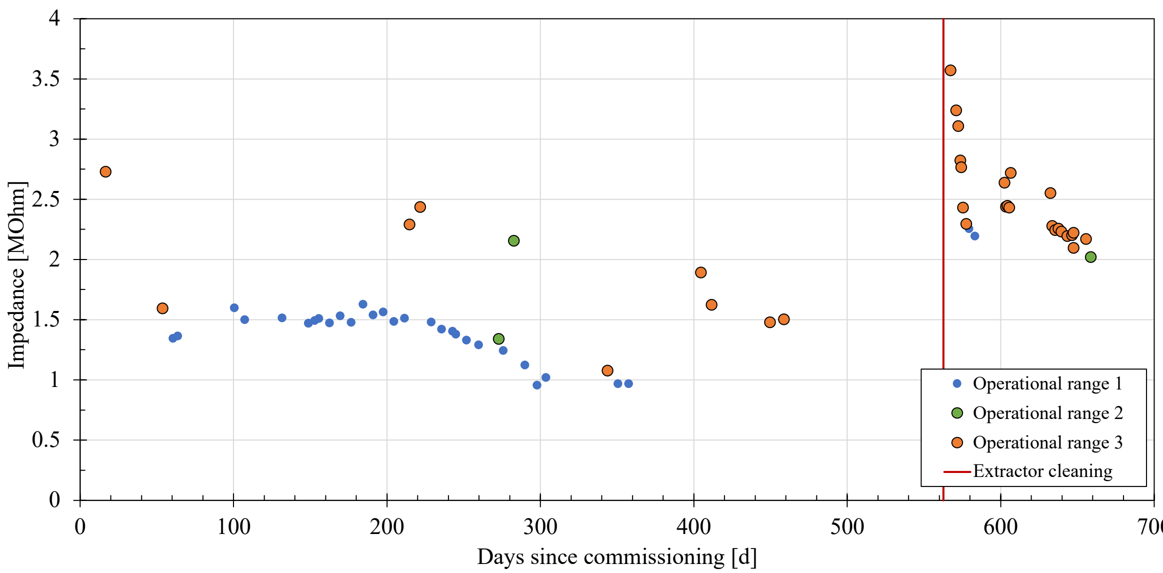

Figure 4. Impedance evolution over time for NANO heritage thruster used in LEO as a function of days since thruster commissioning. At time of extractor cleaning, the total accumulated firing duration amounted to approximately 1350 hours. The plot identifies different operational ranges (operational parameters and duration). The data shows the characteristic decrease of impedance due to extractor shrinkage beyond day 220. After performing the extractor cleaning procedure, an initial increase of the impedance followed by rapidly decreasing impedance similar to the behavior seen in initial commissioning and consistent with the again increased extractor diameter is noticeable.

characteristic dimensions far exceed capillary length of the system, these previously conducted ground tests could be used to derive and verify the cleaning procedure before application on orbit.

Following the extractor cleaning, the thruster successfully resumed ion emission. An increase in impedance was observed in both ground testing and on orbit following the applied procedure, which notably decreased similar to the behavior in first commissioning. This burnin behavior is traced back to removal of oxides and contaminants by the emission process. The observed impedance after cleaning levelled off at a higher level than the impedance levels observed just before the cleaning in accordance with the effective increase in extractor diameter due to the removal of accumulated propellant, confirming the successful cleaning procedure. Similarily, the rate of sparking that had increased ahead of conducting the extractor cleaning had dropped significantly after performing the cleaning.

Since the cleaning procudure, the thruster has been generating thrust for and accumulated firing duration of approximately 100 hours and continues to be used in the continuous operational mission of the customer

B. GEO: Thrust vectoring capability

As reported previously, multiple NANO AR^3 are currently employed in a small satellite mission in geostationary orbit, providing propulsion for the initial orbit acquisition from the launch ejection orbit as well as multiple transfers to drift orbits to change orbital slots[16,17,17]. In addition to providing thrust for orbit change, the thrust vectoring feature of the AR^3 has been used to reduce wheel momentum[16] in the absence of other means to desaturate momentum. The evolution of semi-major axis of the orbit during first acquisition of geostationary orbit has been reported in Refs. 16 and 18.

The NANO AR^3 features three extractor electrode segments surrounding the crown ion emitter. Each of these extractor segments can be individually controlled to a negative high voltage potential, therefore allowing preferential throttling of different sections of the ion emitter. As the total thrust vector produced by the system is a superposition of the individual beamlet thrust vectors, this allows to control the effective thrust vector.

Fig 5 shows previously reported low resolution telemetry of one of the NANO AR^3.

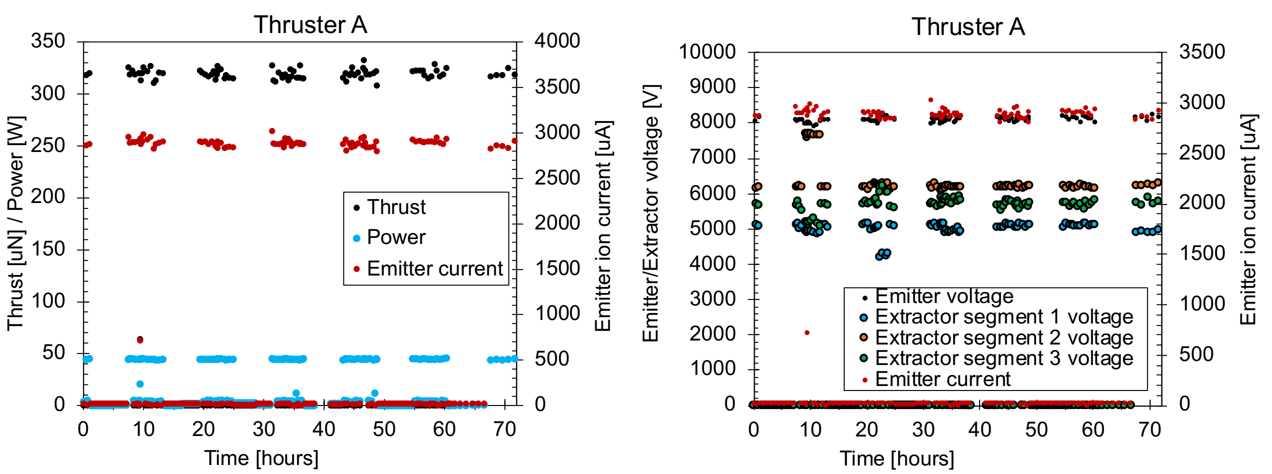

Figure 5. Telemetry of a NANO AR^3 system used in GEO: thrust, total system power including neutralization and propellant heating and ion emission current[17] (left) and emission voltage and current, as well as extractor segment voltages used to control thrust vector[17] (right)

IV.Flight Statistics

C. Launch statistics update

Table 1. Launch statistics of the ENPULSION FEEP propulsion systems

Propulsion System	Number of s/c	Number of Thrusters	Different launches
NANO	85*	190*	24*
NANO R^3 / AR^3	6	9	6
MICRO R^3	12*	18*	8*

*Annotation: *Propulsion systems lost due to launch vehicle failures not included*

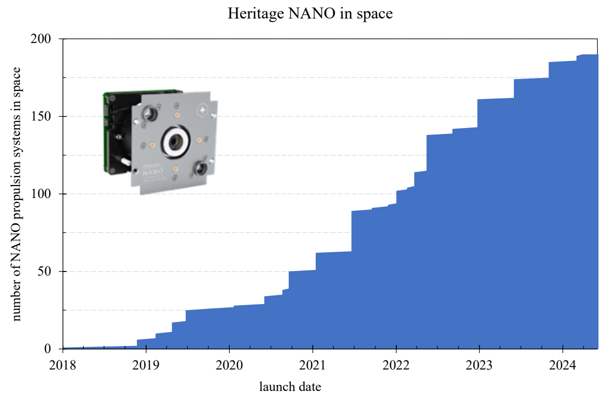

Figure 6. Updated launch history of the ENPULSION NANO propulsion system.

To date, 217 FEEP propulsion systems have been launched, not considering propulsion systems lost in launch accidents. Table 1 provides an overview of the launch statistics per propulsion system type. While the majority of FEEP systems on orbit continues to comprise of heritage NANO propulsion systems that remain at high launch cadence, the updated flight statistics also reflects the successful introduction of the successor products NANO R^3/AR^3 and MICRO R^3, reflected in increased numbers being deployed.

Fig. 6 shows an updated the launch history of the heritage NANO propulsion system, with 190 propulsion systems launched to date and continuing high launch cadence. Similar to previous reportings, the large increase in numbers corresponding to popular ride share launches is noticeable, with may instances of multiple systems on multiple different spacecraft sharing the same launch.

D. Data availability

The limited visibility on flight data, as well as biases introduced by the fact that access to telemetry is often coinciding with specific mission stages such as commissioning, while less visibility is generally possible during regular operations, has been discussed previously[15,19]. In an effort to gain visibility on historical telemetry in 2022/2023, a significant increase in the available historical flight data could be achieved for the timeframe up to 2022, increasing the flight telemetry available for this period by almost a factor of 3 compared to previously presented data availability, and confirming previous assumptions on data visibility leading to an underestimation of the actually achieved hours of operations on orbit. Fig 7 shows the currently available telemetry, including a significant increase for the time period previously reported[15,19]. Data reported includes a 20% margin to account for telemetry overlap.

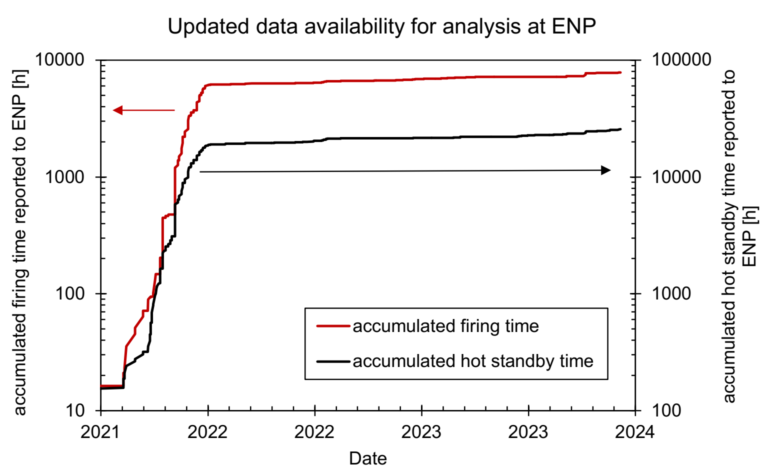

Figure 7. Updated flight telemetry data availability of ENPULSION NANO propulsion system at ENPULSION showing the increase in data made available compared to previous reportings[18].

To date, multiple individual propulsion systems, including R^3 systems, have surpassed accumulated firing times beyond 1300 hours of operations.

V.Conclusion

Over 200 FEEP propulsion systems have been brought to orbit within the recent yeas, providing a significant amount of flight data that can be used to inform new FEEP propulsion system design. We present an updated flight heritage statistics and discuss increased data availability. To date, all 4 different propulsion systems based on the heritage ion emitter have achieved flight heritage. This includes the heritage NANO propulsion system with 190 systems on orbit, the successor product NANO R^3 and AR^3 with 9 units, and the increased power MICRO R^3 propulsion system with 18 units in space at time of writing. We present telemetry and applications of selected on orbit use cases including a small satellite mission in GEO. We then present a successful extractor cleaning procedure conducted in LEO after approximately 1350 hours of accumulated thrusting time, based on procedures developed during ground testing of extractor cleaning. Since the extractor cleaning, the thruster has continued in the operational mission and has accumulated approximately 100 hours of thrusting time so far. Finally, we present and discuss a design update to address limitations imposed by gravity during ground verification of repeated extractor cleanings.

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