ENPULSION NANO and MICRO propulsion systems: from flight heritage to design updates

David Krejci
ENPULSION
Vienna Airport, Austria
david.krejci@enpulsion.com

Davide Manna
ENPULSION
Vienna Airport, Austria
davide.manna@enpulsion.com

Valentin Hugonnaud
ENPULSION
Vienna Airport, Austria
valentin.hugonnaud@enpulsion.com

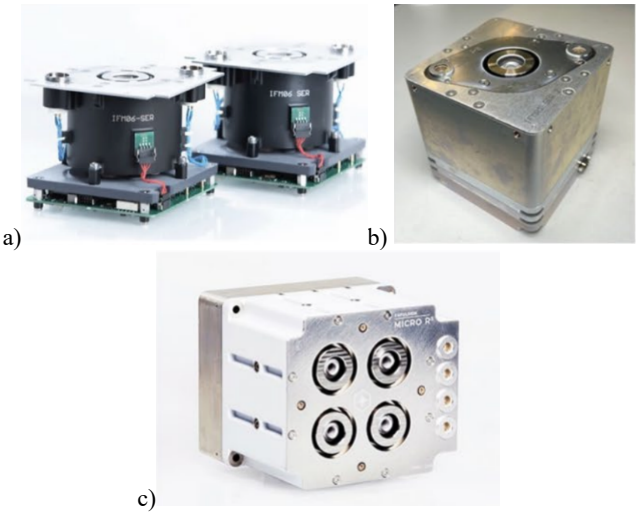
Alexander Reissner
ENPULSION
Vienna Airport, Austria
alexander.reissner@enpulsion.com

***Abstract*— Over 300 NANO and MICRO propulsion systems have been deployed in space, servicing a variety of customers, missions and applications in large number of different orbits and platform sizes. The significant flight heritage gained from these units has been continuously used to improve design and operations of the systems. While the NANO R³ propulsion system is operated at total system input power levels of up to 45W and is often utilized in multi-thruster configurations on platforms between 40 and 100 kg, the MICRO R³ is a propulsion system of up to 120W nominal total system input power oriented towards larger platforms. Both propulsion systems are based on liquid metal Field Emission Electric Propulsion (FEEP) technology, with a solid propellant during storage, integration and launch, that is later liquified on orbit. We present significant design updates to both propulsion systems, including the novel extractor geometries employed. We present the development process and ground testing of these new systems addressing the known extractor clogging phenomenon observed in FEEP propulsion systems, including exhaustive simulation efforts to optimize extractor geometries.**

Keywords—FEEP, field emission electric propulsion, electric propulsion, small satellite propulsion, flight heritage

I. Introduction

Field Emission Electric Propulsion (FEEP) has a long heritage building on liquid metal ion sources [1]-[4]. It utilizes electrostatic forces to extract, ionize and accelerate propellant from a bulk liquid metal. In the ENPULSION FEEP, liquefied Indium is fed by capillary forces from an integrated propellant reservoir to a porous multi emitter, which arranges 28 sharp needle emitters in a circular pattern. This emitter is biased to high voltage in positive polarity with respect to a negatively biased extractor electrode surrounding the circular ion emitter. The electrical pull on the propellant becomes large enough for the establishment of so-called Taylor cones on the tips of the needle ion emitters, and the electrical field at the apex of these Taylor cones can surpass the threshold for ion emission. Ions generated at these locations are then accelerated within the potential drop towards the high transparency extractor electrode, thereby generating thrust. To prevent spacecraft charging due to the emission of positive ions, a neutralizer is used to ensure emission of a negative electron current whenever ion emission is active.



a) b) c)

Fig. 1: ENPULSION FEEP propulsions systems that have achieved space heritage: a) NANO b) NANO R³, c) MICRO R³

Utilizing an inert propellant that is solid during ambient conditions and is only liquefied after launch allows to ship and integrate the propulsion systems fuelled and obviates any active means of propellant containment during launch.

The NANO, NANO R³ and MICRO R³ propulsion systems are fully integrated electric propulsion systems including ion emitter, neutralizer, propellant reservoir and power electronics (power processing unit). By actively controlling both emitter and extractor voltages, the propulsion systems can be operated over a wide range of thrust and specific impulse, including independent control of both parameters by decoupling ion emission current from the absolute ion acceleration voltage. The different types of propulsion systems are shown in Fig. 1.

Building on the extensive flight heritage gained by the NANO propulsion system and lessons learnt [5], the NANO R³ [6] was developed as direct successor of the NANO thruster. The NANO R³ performance allows to reach 350µN over 45W of input power, including propellant management and ion beam neutralization subsystems. It features improved electronics design and parts quality, more robust integration concept and automatic thruster control features. The MICRO R³ is a higher power and thrust unit that is based on the same heritage ion emitter, parallelizing 4 ion emitters increase maximum available thrust, increasing the total system input power to above 100 W for 1mN of thrust. These FEEP propulsion systems have been tested in multiple external facilities including direct thrust and beam diagnostics measurements [7], [10], [11].

II. Flight Heritage

A. Flight Statistics

All the FEEP propulsion systems in Fig. 1 achieved flight heritage on multiple systems and on multiple spacecrafts, with the longest accumulated thrusting times to date above 2000h, 1300h and 400h for a single NANO, NANO R^3 and MICRO R^3 respectively.

B. Launch statistics

In 2018, the NANO thruster (former: IFM Nano thruster) became the first FEEP propulsion system to achieve space heritage. The in-orbit demonstration was conducted onboard of a Nanosatellite [8] [9] together with FOTEC, which allowed for the first time ever to compare the existing thrust model developed during ground testing to the in-space performance. Comparison of orbital altitude change expected by thrust model based on measured ion emission current and emitter and extractor voltages to independent GPS measurements confirmed validity of the thrust estimated by the propulsion system onboard electronics within the measurement accuracies achieved by the GPS determination [8]. Since then, many more validation via GPS measurements, across different customers, confirmed the validity of the model.

To date, 249 NANO thrusters have been launched on more than 100 different spacecrafts. The successor product NANO R^3 was first launched in the first half of 2023, with steadily increasing launch cadence as they start replacing the heritage NANO thruster. As of today, 49 propulsion systems have been launched, on more than 46 different spacecraft.

The higher power MICRO R^3 was first launched in the first half of 2022, with currently 35 propulsion systems launched. Fig. 2 shows the launch evolution of FEEP propulsion systems since first ion orbit demonstration in 2018.

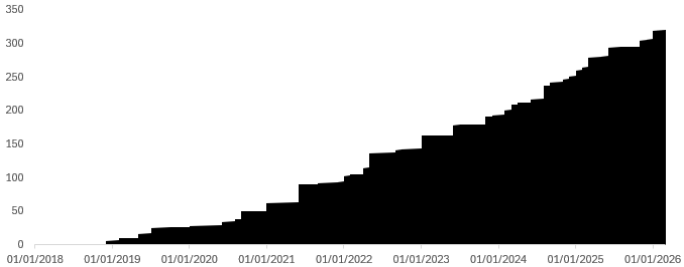


Fig. 2: Launch evolution of the ENPULSION FEEP Propulsion systems

Note that the numbers quoted for NANO, NANO R^3 and MICRO R^3 do not include propulsion systems lost in launch failures.

C. Orbit altitude distribution and applications

A large majority of ENPULSION FEEP systems were deployed, in the Beginning of life (BOL) range of 500-550 km altitude and decreasing number for 550-600km and 600-650km. This is in line with the commercial nature of most customers addressing different earth observation applications. In addition to most propulsion systems in LEO below 700km, there are several spacecrafts with ENPULSION FEEP systems deployed in the range of 950– 1250km.

D. Spacecraft sizes and applications

The majority of spacecraft carrying FEEP systems to date is in the range up to 50kg and 75 to 100kg spacecraft initial mass. Several larger spacecraft have been deployed with FEEP systems, including spacecrafts of 150-175kg and approximately 1 000 kg (employing multiple FEEP systems), showing the versatility with regards to the platforms the standardized FEEP propulsion systems have been integrated into. The standardized propulsion systems are not only used on a wide variety of platforms but also cater to different applications. To date, the standardized FEEP propulsion systems have been used in the following applications:

- Orbit acquisition
- Constellation Rollout
- Formation control
- Precise ground track
- Conjunction avoidance
- Momentum desaturation
- Deorbiting

III. Nano R^3 & Micro R^3 updated configurations

Thanks to the significant flight heritage, processed data as well as customer feedback, ENPULSION has been able to implement key new features on the NANO R^3 and MICRO R^3 products. For instance, 8 additional mechanical interfaces were added to the NANO R^3 casing, providing extra degrees of freedom for the user to integrate into the propulsion system, as depicted in Fig. 3. Moreover, upgraded electronics are now equipping the NANO R^3 and MICRO R^3 with improved efficiency. Nonetheless, in these new product configurations, main development efforts were put into improving designs of both propulsion system's extractor electrode.

During extended periods of FEEP emission, the presence of quasi-neutral droplets is known to accumulate on the extractor electrode, with visually observable impact over reported extended durations of firing in the order of thousands of hours [3]. During extended duration ground testing of the commercial propulsion systems, a dependency of the rate of extractor shrinkage on the emitter mass efficiency was found and modelled, resulting in possible extractor shrinking times in the order of 1500 hours for emitters that feature attractive emission parameters for several commercial mission applications.

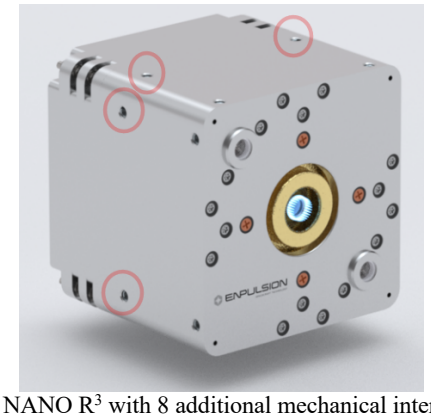


Fig. 3: NANO R^3 with 8 additional mechanical interfaces at the mid-level (red circles)

ENPULSION developed different models to predict the exact time required for each propulsion system until the extractor shrinkage becomes critical for the operation [12, 13]. Moreover, a maintenance procedure of the extractor has been developed to enlarge back the extractor diameter to its initial state. Although this maintenance procedure has been validated in orbit [13, 14] it is not possible to perform this procedure on ground testing in a 1g environment, because of gravitational effects putting at risk any long duration test over thousands of hours.

The updated design of the extractor for both the NANO R^3 and MICRO R^3 products is now enabling on-ground extractor cleaning maintenance procedures.

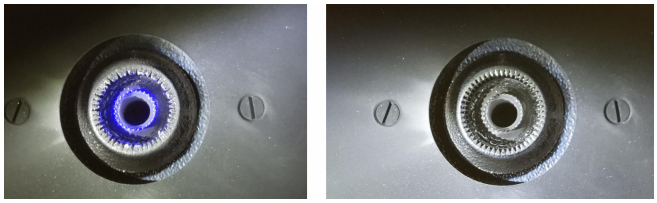


Fig. 4: Extractor cleaning maintenance procedure in 1g. Left is a firing emitter with a clogged extractor, and right is the "cleaned" extractor post maintenance procedure

The procedure was validated on ground, first on a NANO R^3 design, as depicted in Fig. 3 , and then on a MICRO R3, with all four emitters and extractors cleared out of the accumulated indium in parallel. Fig. 4 shows one extractor with accumulated indium over hundreds of hours of firing at high thrust point (left) and the outcome of the maintenance procedure (right) once the indium has been melted away and stored in dedicated storage locations within the extractor. Following this demonstration, a long duration test with a MICRO R^3 engineering grade module is being carried out showing more than 1700h firing at a thrust point of 1mN including several successful extractor maintenance procedures.

IV. Conclusion

This paper presents the flight heritage of the ENPULSION liquid metal ion propulsion systems, with over 330 FEEP systems launched to date. Based on the significant orbital heritage and large number of system integrations performed over a variety of customers and missions, we present design updates infused into the current products NANO R^3 and MICRO R^3, including the novel extractor electrode design that allows verification of the cleaning procedure in gravitational environments during long duration ground testing.

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