138 Propulsion Units Launched in 4 Years: A Review and Lessons Learned

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ABSTRACT

After the first launch of an ENPULSION NANO thruster in 2019 together with FOTEC[1,2,3], which verified for the first time the operation of a propulsion system based on liquid metal Field Emission Electric Propulsion (FEEP) in space, ENPULSION has delivered hundreds of flight systems to 36 different commercial customers. To date, 135 additional ENPULSION NANO systems have been launched on a variety of spacecraft across different platforms and customers. In addition, the ENPULSION MICRO R^3, an increased power and thrust unit, has been developed, which was successfully demonstrated in orbit in 2021. Recently, the first new generation ENPULSION NANO AR^3 propulsion system was launched to debut on orbit. To date, hundreds of flight models have been manufactured, acceptance tested and delivered to customers. Based on lessons learnt during manufacturing, AIT and in-space operation of the ENPULSION NANO, a new generation of propulsion systems with increased resilience has been developed, denoted R^3. In this paper we provide an overview of the onorbit statistics of the ENPULSION propulsion systems. This includes the evolution of launch history of the ENPULSION NANO over time, the accumulated orbit life for all operational propulsion systems that ENPULSION has visibility on confirmed thrust generation, as well as the accumulated orbit life for operational thrusters between launch and last telemetry of thrust maneuver made available to ENPULSION. We then present efforts undertaken in AIT, onorbit operation support and ground testing campaigns conducted in different independent facilities. Based on this, we derive lessons learnt, best practices and limitation over a large number of customers of the smallsat community, over different systems and different implementations for a standardized electric propulsion system based on the ENPULSION NANO.

INTRODUCTION

Miniaturized, high propellant efficient propulsion systems have been identified as an enabling technology for a variety of Small- and Nanosat missions and a multitude of comparative propulsion studies dedicated to miniaturized systems is available.[4-8] Electrostatic FEEP propulsion is one of the low power candidate propulsion technology for such missions due to its simplicity of an inert and solid propellant during AIT and launch, compactness, high specific impulse, and the absence of any moving parts. The first FEEP thruster to be launched was the ENPULSION NANO, which was successfully demonstrated in orbit in 2019 in an IOD conducted together with FOTEC.[1-3] Since then, 135 additional ENPULSION NANO systems (formerly IFM Nano Thruster) were launched. In addition, a higher power and total impulse thruster, the ENPULSION MICRO R^3 has been developed, which was successfully demonstrated in orbit in 2021. To date, hundreds of flight models have been manufactured, acceptance tested and delivered to 36 customers. Based on lessons learnt during manufacturing, AIT and in-space operation of the ENPULSION NANO, a new generation of propulsion systems with increased resilience has been developed, denoted ENPULSION NANO R^3. The first propulsion model in AR^3 configuration with thrust vectoring capability was recently launched.

PROPULSION SYSTEM DESCRIPTION

The ENPULSION NANO shown in Figure 1, is based on FFEP ion emission, which generates thrust by extraction and acceleration of ions by an electrostatic field from the liquified propellant by means of a Taylor cone. This principle allows a passive (non-pressurized, no active components) propellant feed from the propellant reservoir to the emission sites by capillary forces. The ion emitter has been developed at FOTEC (former Austrian Institute of Technology) for decades and is based on the development of Indium Liquid Metal Ion Sources (LMIS) with exhaustive flight heritage.[9-12] The thruster utilizes Indium, a metal propellant, that is in solidified stated during ground handling, integration, and launch. The thruster features two neutralizers in cold redundancy, and a digital PPU which provides power and control for all necessary subsections to operate the thruster and provides telemetry back to the spacecraft onboard computer using standard communication protocols. By controlling voltages of both the emitter and the extractor, the emission current, and thus the resulting thrust, can be decoupled from the acceleration potential, and hence the specific impulse. This allows to operate the propulsion system in an envelope of specific impulse and thrust.

To increase thrust, multiple emission sites, allocated in a crown shaped emitter, are operated in parallel.

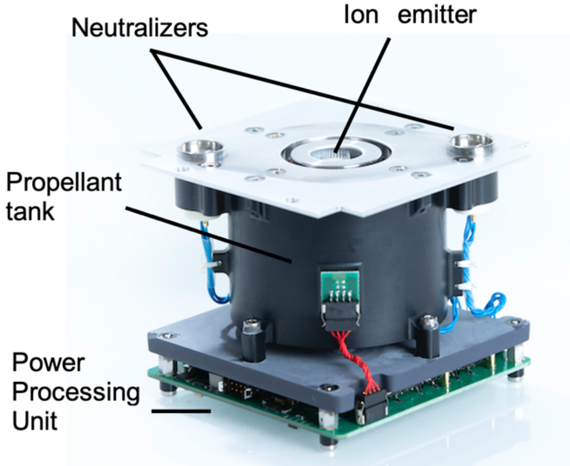

Figure 1: ENPULSION NANO propulsion system (formerly: IFM Nano Thruster) with key components identified

The ENPULSION NANO is a 40W system power propulsion unit generating 0.33mN of thrust with specific impulses ranging from 1500s to above 5000s and a total impulse capability above 5000Ns. The higher ENPULSION MICRO is based on the same propulsive principle but using 4 ion emitters in parallel and an increased propellant loading, generating 1mN of thrust and can be operated at variable specific impulse ranging from 1500s to 4500s.

Figure 2: Next generation R^3 propulsion systems ENPULSION MICRO R^3 with space heritage

To date, two propulsion systems based on the proprietary FEEP technology have achieved flight heritage: the ENPULSION NANO, shown in Figure 1, and the higher power ENPULSION MICRO R^3 (Figure 2)[1,13,14] The ENPULSION NANO AR^3, a successor of the heritage ENPULSION NANO with added thrust vectoring capability[15], was recently launched.

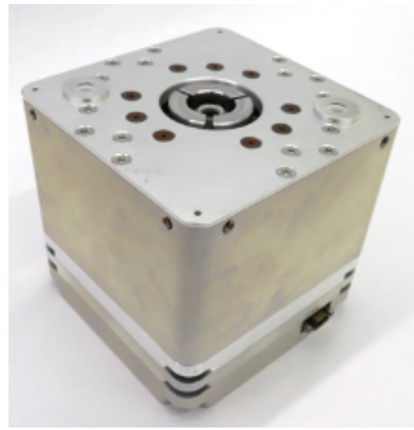

Figure 3: Next generation R^3 propulsion systems launched recently: ENPULSION NANO AR^3

Direct thrust measurements have been performed on the ENPULSION NANO, the ENPULSION NANO R^3 and the ENPULSION MICRO R^3, confirming the established FEEP thrust relation. Several independent thrust campaigns have been conducted on the ENPULSION NANO, at facilities including two agencies, two customer facilities and at FOTEC. The ENPULSION NANO R^3 and ENPULSION MICRO R^3 have both been tested on FOTEC's direct thrust measurement facility.[17]

IN ORBIT DEMONSTRATION OF THE ENPULSION NANO

The first IOD of the ENPULSION NANO propulsion system, which also represents the first propulsive operation of a FEEP thruster in space has been previously reported[1,2]. This IOD was conducted on a 3U Cubesat launched in 2018, and included an independent thrust verification by comparing the s/c altitude change expected from propulsion system telemetry, to the altitude change determined by GPS measurements before and after at 15 min and a 30 min thrusting maneuver. A comparison of expected (from propulsion system telemetry) to observed (GPS) altitude change showed good agreement, with the expected altitude change within the measurement accuracy of the orbital dertermination.[1] Later stages of the IOD included verification of the controllability of the propulsion system to perform precise thrust steps, as well as thrust repeatability after several idle days.[1] Later publications showed telemetry of an early commercial application[3], as well as telemetry covering larger orbit change maneuvers.[15]

IN ORBIT APPLICATION OF THE ENPULSION NANO

Due to the large numbers of propulsion systems launched and the modular nature of the system, the ENPULSION NANO has been used for of different mission applications. A non-exhaustive list of applications that have used the ENPULSION NANO is given hereafter.

- bring into target orbit, in conjunction with ride share
- formation and cluster initiation
- maintenance of precise orbits to improve ground track
- constellation rollout
- deorbiting

Figure 4, plotting the semi-major axis evolution of two spacecraft carrying ENPULSION NANO systems shows a combining of some of the above. The semi-major axis plotted for the two spacecraft shows the natural decay of both spacecraft before commissioning of the propulsion systems, followed by a propulsive transfer to the target orbit. After reaching the target orbit, in this case a repeat ground track orbit, the propulsion units were frequently used to maintain a precise target orbit, in this example to improve the ground track for an earth observation instrument. The data shows two spacecraft that were launched from a shared launch vehicle, including in-plane separation achieved by staggered orbit acquisition maneuvers.

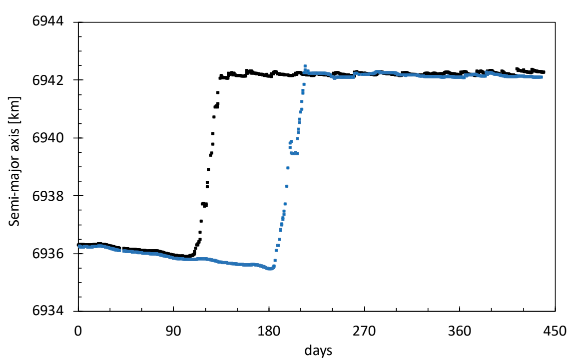

Figure 4: Average semi-major axis evolution of two spacecraft using multiple ENPULSION NANO systems for orbit transfer each, arbitrary relative time in days: natural decay before thruster usage, followed by orbit acquisition, followed by precise orbit keeping during operational mission. Both spacecraft were launched on the same rideshare, data shows drifting separation. Data taken from Ref 18.

ON-ORBIT STATISTICS

Launch statistics

To date, hundreds of propulsion systems have been delivered to customers for integration. All delivered systems have been subjected to at least the standard acceptance test procedure, consisting of emitter characterization firing, vibration and ambient thermal cycling testing, followed by a standardized functional acceptance firing, in which the thruster system performance and ion emission parameters are determined. In total, 138 propulsion systems have been launched, on a total of 63 different spacecraft.

Table 1 summarizes the number of propulsion systems currently on orbit and the number of spacecraft the thrusters are distributed, ranging from 1 propulsion system on a 3U Cubesat, to a cluster of 7 systems on a >100 kg class spacecraft.

Table 1: Summary of ENPULSION propulsion systems in space

Margin	NANO	NANO AR³	MICRO R³
Number of s/c	61	1	1
Number of Thruster	136	1	1
Thrusters on Cubesats	22	1	0
Thrusters on ESPA class s/c	114	0	1
Different launches	19	1	1

Figure 5 plots the launch history of the ENPULSION NANO over four years since the IOD in 2018. Several launches with multiple spacecraft carrying ENPULSION NANO can be identified by corresponding stepwise increase in number.

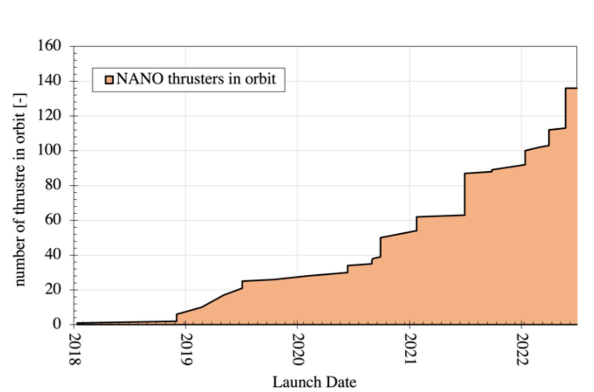

Figure 5: Launch history of the ENPULSION NANO system.

On-orbit telemetry data availability

Since most of the missions employing ENPULSION propulsion systems are of commercial nature, data availability becomes the premier issue for statistical analysis. Nevertheless, we are continuously able to receive significant amounts of telemetry, creating a valuable basis for statistical analysis of onorbit propulsion performance and behavior.

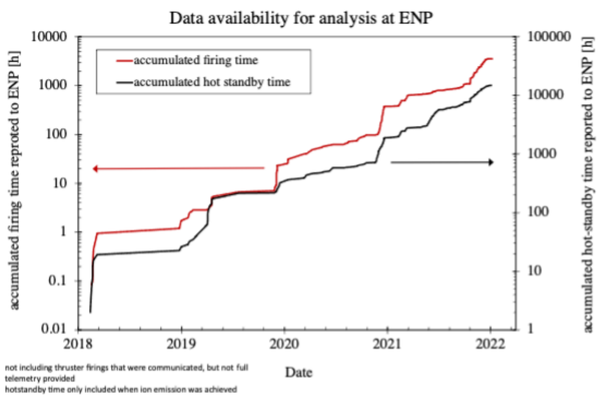

Figure 6: ENPULSION NANO propulsion system data availability for analysis at ENPULSION: Accumulated firing time and hot standby time for which full telemetry was made available to ENPULSION. The scaling of hot standby time with firing time indicates that the data shown is limited by data visibility, and accordingly represents minimum accumulated times, with true on-orbit times likely higher, based on customer communication.[15]

Figure 6 plots the data availability of accumulated onorbit telemetry times for the heritage ENPULSION NANO systems currently in space that ENPULSION has received full telemetry on. From Figure 6 it would appear as if hot standby times scale with accumulated thrusting time. However, from operations support it is known that propulsion systems are frequently kept in hot standby for weeks or even months between thrusting maneuvers, which would make us expect hot standby times accumulating even in times of little thrusting operation. The fact that this is not the case in Figure 6 indicates that the data shown is not the actual accumulated onorbit times, but only the portion that is made available to ENPULSION in the course of review and support. The data made available is often skewed around specific customers and operational constraints (eg. when support is provided during a change of thruster operation). In addition, repetitive thrusting maneuvers and hot standby durations are less frequently reported to ENP to minimize customer effort. Only data where the telemetry provided to ENP was included in the data shown, while firing and hot standby durations reported by the customer qualitatively without telemetry is not included. It can therefore be concluded that the data repository at ENPULSION is limited by the visibility we have. This means that the true accumulated firing time and hot standby times on orbit are likely to be higher, and the data shown in Figure 6 corresponds to the lower bound of accumulated durations. With only one ENPULSION MICRO R^3 and ENPULSION NANO AR^3 system onorbit at time of writing it is not possible to present data without allowing to infer on customer and mission profile.

The data underlying the high-level parameters shown in Figure 6 represents an exhaustive source for analyzing propulsion onorbit performance over a large number of different missions, usages and customers. As of Feb 2022, the accumulated orbit life for all operational propulsion systems where ENPULSION has visibility on thrust generation accumulates to 58.3 years. This number however includes time accumulated between the last telemetry was made available to ENPULSION and Feb 2022, assuming that during normal operations, any anomaly would be reported to ENPULSION. The accumulated orbit life for all operational systems between launch and last telemetry of thrust maneuver made available to ENPULSION accumulates to 22.0 years. As several customers provide telemetry after commissioning only intermittently to ENP, the two values are considered a lower and upper bound for accumulated times. Also note that propulsion systems not yet commissioned are not accounted in these numbers. The longest accumulated firing time on a single propulsion system (launched in June 2021) is more than 650 hours of thrusting.

LESSONS LEARNT FROM THE ENPULSION NANO SYSTEM

Based on the significant heritage and data available on the ENPULSION NANO, several lessons learnt, and issues observed can be derived[15]. This section gives a brief discussion of aspects encountered and mitigated.

Propellant solidification cycling and thruster resets

When high voltage is applied to the ion emitter after launch for the first time, a thin oxidation layer has to be overcome and therefore voltages to initiate the emission are higher, increasing the likelihood of sparks between the emitter and the extractor. The high voltage sections of the PPUs are designed to be resilient against such sparking events, which occur primarily during the early startup of ion emission from the emitter needles, but internal interferences in the HV and LV sections of the heritage PPU of the ENPULSION NANO have been found to be capable of triggering electronics resets that can cause the propulsion system electronics to reboot into idle state. Since the PPU is also used to control the propellant temperature to maintain the propellant in liquified state during ion emission, such resets can lead to propellant solidification, if not acted upon within several minutes of the reset by the OBC by commanding temperature control mode. It has been found that especially during early thruster life, solidification cycles can bear the risk of thruster degradation, if repeated solidification cycles are performed without properly conditioning the ion emitter by achieving sustained ion emission first. Most customers have been able to implement the recommended FDIR measures to identify such resets and command the propulsion system back to liquefication mode within several minutes. However, relying on an external FDIR implementation is considered a certain risk, especially given the combination of increased occurrence of sparking events at early commissioning, in combination with the higher risk of degradation by repeated solidification cycles which is also amplified during early commissioning stages. Both aspects of the early commissioning stage, during which the thruster-system interaction is typically less well understood, can lead to failure in systems that are unable to successfully detect such events. To refrain from relying on the external FDIR implementation on OBC side, resilience of the PPU against sparking to maintain propellant liquification throughout commissioning, was a design driver on the upgraded propulsion system development of the ENPULSION NANO R^3 series and ENPULSION MICRO R^3.

Volatile contamination during storage, AIT and launch

Exposure of the ion emitter to a contaminating material that features more favorable wetting properties on Tungsten than Indium, was found as a root cause for decreased propellant availability at the emission sites, which can ultimately result in a loss of ion emission. Examples of such materials include silicone oils, hydrocarbon lubricants or volatiles of certain epoxies. This effect can be augmented by the fact that the ENPULSION NANO design (contrary to the new R^3 generation design) features large internal venting paths that form, in many cases, the largest venting path of the spacecraft. This leads to a situation in testing and deployment in space, in which a significant proportion of the internal volume of the spacecraft and therefore volatiles from non-space compliant materials, could be vented through the ENPULSION NANO ion emitter. Exhaustive compatibility studies of commonly used materials, including exposing samples during curing, have been investigated based on material lists provided by a range of customers.

OBC commanding forbidden states

Instances have been encountered during which forbidden command states, eg forbidden high voltage settings during thruster operation in manual mode, or violation of the startup sequence of auxiliaries, such as the neutralizer prior to ion emission when operated in manual mode, were commanded. In the ENPULSION NANO, commanding such forbidden states can lead to damage, or loss, of the propulsion system. Three main causes leading to these events are highlighted:

a. In an instance observed, an anomaly was caused by sending overlapping command sequences, eg following a trigger of an FDIR while executing a command script, which was remedied by a manual reset of the propulsion system, but without aborting the continuing command script. After manual system initialization, the propulsion system therefore received command segments from the OBC from the inadvertently continuing earlier script.
b. Starting from an undefined state due to a previous, not fully executed, or incorrectly finished script: While the ENPULSION NANO preforms a full initialization when power cycled, no initialization of the command registers is performed between thrust maneuvers. This bears the risk of an undefined propulsion system state after a thrust maneuver was commanded, if not properly commanded to initial state. It has been observed that in subsequent activation of subsections of the PPU, the thruster was then effectively commanded to control to the previously setpoints, which can lead to issues in case of time sensitive startup sequences, such as the required start of the neutralizer before ion emitter activation to guarantee neutralization through all stages of the operation.
c. Due to insufficient ground verification of commanding scripts: Errors in commanding sequence scripts sent by the OBC have been encountered, which may have been avoided with increased effort and time spent in ground verification. However, this is amplified by the strong time pressure in a majority of the missions, and the typically stringent facility requirements necessary to perform an EP propulsion end-to-end verification after integration. The latter capability is in many cases beyond the capability of most Smallsat customers, and necessitates assistance by the propulsion provider to assist such joint testing in the propulsion manufacturer facilities.

Value of flexibility to change on-orbit command software

A significant benefit of the large number of parallel onorbit commissionings and operations is the opportunity to improve operation across different missions. The large amount of data, operation time accumulated and learnings from multiple propulsion systems operated in different architectures and operation modes, allows for continuing learning of system behavior onorbit and improvement of propulsion system operation, including optimized commissioning strategies or identification of new FDIR conditions. This can create significant benefit as learnings can be shared across missions and customers by infusing findings into new revisions of the user manual, without violating mission confidentiality. However, to fully leverage this potential, operators are required to have the flexibility to change their onorbit command sequences and command structures to implement new findings. As this can cause additional implementation and validation efforts, it is observed that operators may tend to neglect or significantly delay implementation of such newer findings. The outcome of such lack of timely implementation of new findings has been observed to range from continuing to perform unnecessary extra tests, to omitting the implementation of a new FDIR condition that was found in another customer mission, which in the worst case, could lead to failure.

Beam interaction with metallic structures (Baffle/Facility)

Due to the neutral droplets ejected from the FEEP emission site during ion emission that can condense on surfaces that have a direct view path to the emission site, baffles to shield sensitive equipment have been sometimes employed when placing sensitive equipment within the view of the emission site could not be avoided. Such a baffle is however not only blocking the unwanted droplet trajectories, but is also exposed to the high angle portions of the high energy ion plume, which in turn leads to backsputtering of the baffle surface material to the emitter. This leads in turn to a situation in which the ion emitter is exposed to a – usually metal – surface which experiences ion impingement of different energies, depending on distance and angle at which the baffle is introduced into the field of view of the thruster. Similarly, when operating a FEEP in a vacuum chamber, such as in a verification campaign, the chamber walls are hit by high energy ions and can lead to secondary species emission and significant backflow during ground test campaign.[19]

Depending on geometry, material choice and operation modes, it has been observed that metal backflow from features implemented by the customer to shield sensitive equipment that would violate the defined plume stayout zones can lead to degradation effects of the ion emitter over extended duration operation. The same degradation mechanism has been reported during ground test campaigns. The degree of such degradation is dependent on the specific materials employed, geometries such as view angle and distance of the obstruction, and operation mode, eg emission current level, of the thruster. For example, the presence of metal backflow condensing on the emitter, if soluble in the propellant, can lead to locally changed physical properties of the propellant, if the ratio of backflow to reemitted flow is large, as can be the case when introducing a significantly large metal surface into the stayout zones which then comes in contact with the ion plume.

The interaction when introducing an obstruction into the ion beam of any EP system is a complex topic and is highly depending on the specific geometry and materials, as well as the system operating parameters, typically requiring dedicated experimental characterization of each specific configuration. In the course of customer integration support, we have performed a significant number of in-depth investigations of specific customer integrations and operation points, as well as material compatibility studies, complemented by establishing significant understanding of the ion beam properties at ENPULSION and FOTEC.[20,21,22]

Due to this interaction of the ion emitter with material backflow either from baffle obstructions or facility walls, testing FEEPs in new environments on ground remains a difficult endeavor that typically requires several iterations to minimize facility impact on the ion emitter, a prerequisite to allow testing emitters for extended durations of time.

Space environment interaction effects

Certain aspects of the orbital environment are complex to simulate in ground testing, but remain relevant to the onorbit performance of the propulsion system

a. ATOX in combination with lower orbits and hot standby facing in Ram direction

We have noticed a potential correlation showing degradation of performance for specific lower orbits in combination with extended hot standby operation, with the spacecraft pointing the propulsion system with liquified propellant in Ram direction, in combination with not performing any thrusting operation (ion emission). During hot standby, the metal propellant is held in liquified state at increased temperature, facilitating oxidation buildup in combination with ATOX in lower earth orbits when facing Ram direction for extended durations. While oxides can be removed to some extent by ion emission when thrusting, oxide buildup during extended idle times when kept in hot standby and facing Ram direction could lead to potential emitter degradation. While this is currently in investigation including onorbit verification, this effect can be mitigated by means of implementing a stayout orientation for lower orbits when propellant is liquified and no thrust maneuvers are performed.

b. Operator negligence of local environment during operation, eg. high geomagnetic activity

While the PPU of the heritage ENPULSION NANO has been matured through testing, it remains a COTS component based high voltage electronics. Given the lack of EEE part lot control, and therefore limited applicability of radiation testing results across different production lots, usage in orbit commends certain safety precautions, which may include safety precautions like suspension of high voltage operation during significant geomagnetic activity. Two measures have been implemented to remedy such failure case:

- Increase awareness at customers, especially customers with strong focus on Newspace business cases of potential risk and limitations.
- New generation ENPULSION NANO R^3 and ENPULSION MICRO R^3 propulsion systems that are developed with a focus on PPU resilience, including part lot control.

Propellant accumulation on extractor

The accumulation of propellant droplets accumulating at the inward facing circumference of the extractor ring during long duration operation has been previously reported.[23,24]. If not counteracted, this can lead to changes in the electrical field geometry and ultimately establish a physical, and therefore electrical bridge between the emitter and the extractor. So far, this effect has not been encountered in space. As this is a deposition mechanism and not an erosion effect, it is reversible by melting the deposited Indium. This so-called cleaning has recently been verified successfully during an endurance test campaign. Recent tests however have indicated a stronger dependency of the rate of clogging with respect to the emitter mass flow, which can lead to higher clogging rates than previously reported.[23,24] A model of the clogging process which provides good agreement with experimental data is described in Ref. 26, and a method of removing such propellant accumulation by changing the operational parameters of the thruster before a short can occur has been experimentally verified on ground. This method can be executed after accumulating a certain period of operation to remove and redistribute the propellant at the extractor without additional means required and can be implemented on orbit if telemetry would indicate the need for such a "cleaning" procedure.

EXPANDING CAPABILITIES: THE NEW GENERATION R^3 PROPULSION SYSTEMS

Design philosophy

Incorporating lessons learnt as described in the previous section, the development of new products and product updates has focused on:

- Improved operations by increasing propulsion system autonomy and resilience in terms of software and resets
- Increased electronics resilience, including EEE part lot control
- Increased agnostic against system integration issues, eg by minimizing satellite internal outgassing impacting sensitive propulsion components
- Improved firmware including fully automatic thruster operation.
- Added capabilities: AR^3 beam steering while maintaining entirely passive system

A new generation of fully integrated propulsion systems has been developed since 2018. This new generation is using many of the core elements of the heritage product, but features several distinct improvements on the PPU that allow the overall system to meet commercially relevant lifetime requirements in a broad range of applications. This includes a redesign of the PPU targeting increased radiation resilience with the support from agencies, lot-controlled testing and a new firmware that allows full automatic propulsion system operation and recovery. The R^3 design also avoids several failure modes on user-side by protecting sensitive parts from handling-issues during AIT and features extended protection against errors during operations.[25,26] The new ENPULSION NANO R^3 product family also includes the addition of new capabilities to the FEEP propulsion systems, such as the thrust vector steering capability of the ENPULSION NANO AR^3. This propulsion system, which shares the major propulsion system modules with the ENPULSION NANO R^3 has the added capability to steer the net emitted ion beam by spatially distributed differential throttling of the ion emission sites. This is accomplished using multiple extractor electrodes, and does not require moving parts.[27,28]

Status and testing

The QM models of the ENPULSION NANO R^3 and ENPULSION MICRO R^3 propulsion systems are currently undergoing qualification testing.[25] This qualification campaign includes, for each propulsion system among other, indirect and direct thrust measurements, vibration, shock, thermal vacuum, endurance, TID, EMC and SEE testing.

Figure 7: ENPULSION NANO R^3 propulsion system mounted to the FOTEC direct thrust test stand[25]

Figure 7 and Figure 8 show the ENPULSION NANO R^3 mounted during direct thrust measurements and the resulting measured thrust compared to the thrust reported by the onboard thruster telemetry.

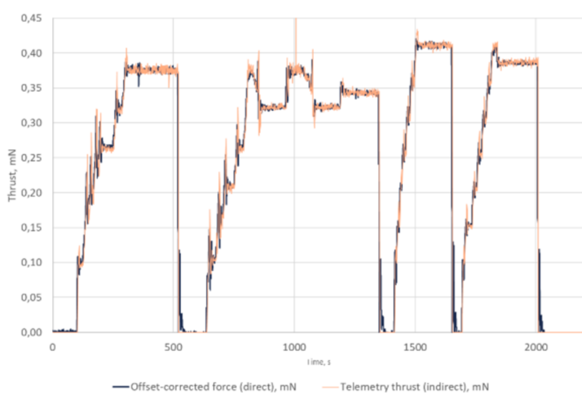

Figure 8: ENPULSION NANO R^3 direct thrust measurement compared to thruster telemetry at FOTEC direct thrust test stand[17,25]

Figure 9 shows the ENPULSION NANO R^3 PPU during EMC testing according to ECSS-E-ST-20-07C, Rev.1 at the EMC test laboratory of Seibersdorf Laboratories.[25]

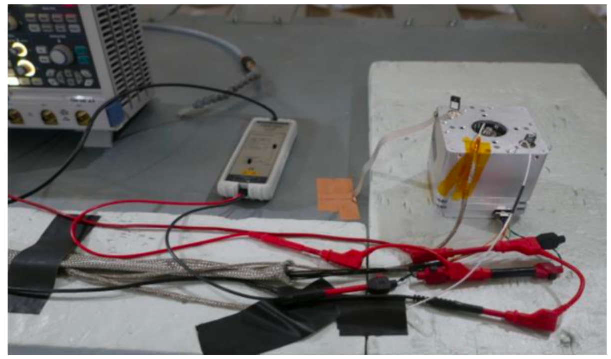

Figure 9: ENPULSION NANO R^3 during EMC testing[25]

Figure 10 shows the ENPULSION MICRO R^3 propulsion module during the full system indirect thrust test campaign. The four dedicated ion emitters (appearing in blue) can be distinguished from the bright thermionic neutralizer on top.

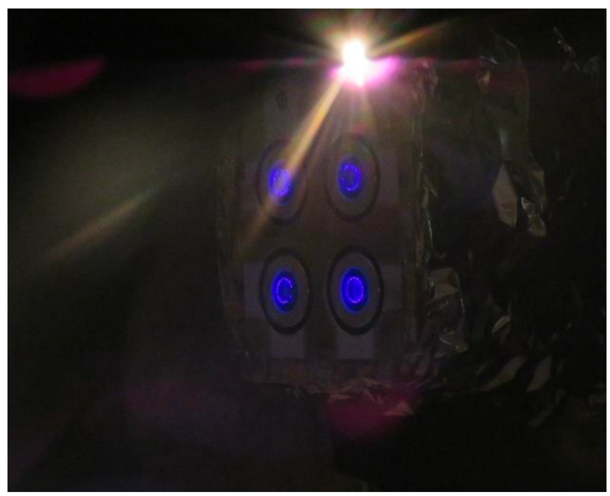

Figure 10: ENPULSION MICRO R^3 propulsion system firing with neutralizer activated[25]

The ENPULSION NANO AR^3, a version of the ENPULSION NANO R^3 with included thrust vectoring capability based on spatially selective beam throttling, has undergone direct beam diagnostic verifying the beam steering capability without moving parts in two different external facilities at FOTEC[27] and ESA.[28] Figure 11 shows a collection of optical images taken of the AR^3 emitter crown during different stages of thrust vectoring. Increased ion emission is associated with increased brightness, the center image corresponds to a thrust vector aligned with the center thrust axis, that is uniform emission over the entire ion emitter crown.

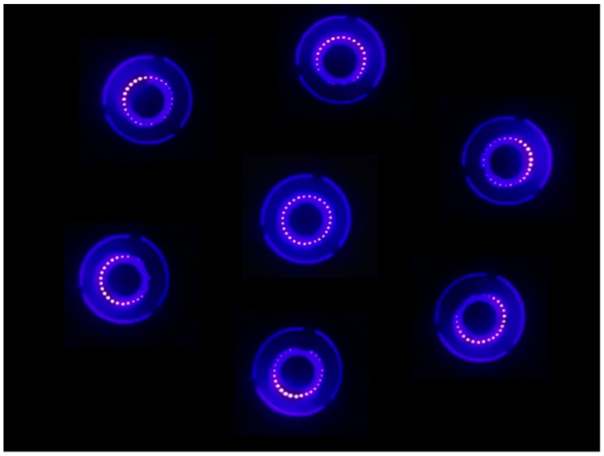

Figure 11: NANO AR^3 differential throttling: Assembly of images taken of the ion emitter during thrust vector operation (center image corresponds to minimum thrust vector angle) and resulting thrust as a function of off axis thrust angle

CONCLUSION

This paper presents the on-orbit statistics of the ENPULSION NANO, ENPULSION NANO AR^3 and ENPULSION MICRO R^3 propulsion systems, with a total of 138 propulsion systems launched to date on 63 different spacecraft. Through the significant number of propulsion systems launched, as well as the standardization of the ENPULSION NANO, we explore the opportunity to gather a statistical view of onorbit data, as well as on integration in a large variety of missions and integrator capabilities. We discuss data availability regarding a large number of ENPULSION NANO systems and based on this present high level statistical ENPULSION NANO data including the data availability regarding total firing and hot standby durations, and report an accumulated firing duration of >650 hours on orbit for an ENPULSION NANO module. We discuss a variety of lessons learnt based on on-orbit operation, integration, and customer side ground test campaigns, which have been incorporated in the next generation ENPULSION R^3 propulsion products.

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