| Category | | | |
|---|---|---|---|
| Baseline (Configured) | 1 **A** – Customer **A**pproval (Configured) | |
| | 1 **R** – Customer Acceptance (**R**eview) | |
| | 1 **I** – Other (**I**nformation Only) | |
| Not Baseline (Unconfigured) | 2 **A** – Customer **A**pproval (Not Configured) | |
| | 2 **R** – Customer Acceptance (**R**eview) | X |
| | 2 **I** – Other (**I**nformation Only) | |

| Classification | |
|---|---|
| Secret | |
| Confidential – On-Site Only | |
| Confidential | X |
| Restricted | |
| Public | |

**DDL No.: ESR**
**WP: 1**
**MS: 3**

# Executive Summary Report

## ENPULSION NANO AR$^3$

**24.02.2023**



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| Signature: | Signature: | Signature: | Date: - |
| Name: T. Schönherr | Name: T. Vogel | Name: A. Buhl | |

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**CONTENTS**

# 1 INTRODUCTION AND SCOPE

This document summarizes the results of the TDE Contract No. 4000130766/20/NL/RA between the European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), the Netherlands, and ENPULSION GmbH, Austria. The product subjected to this project is the ENPULSION NANO $AR^3$, a field-emission electric propulsion (FEEP) system. The main trait is an active thrust vector control (TVC) without any mechanisms or moving parts allowing to steer the ejected ion beam off axis up to 12.5°.

## 2 APPLICABLE AND REFERENCE DOCUMENTS

Throughout this document, applicable and reference documents are referred to as [AD-*x*].

### 2.1 Applicable Documents

Unless specified otherwise, the following documents in their latest revision shall be considered as integral part of this document.

| Ref. | Number | Title |
|---|---|---|
| [AD-1] | ESA-TRP-TECMPE-SOW-015295 | Statement of Work<br>ESA Express Procurement Plus - EXPRO+<br>Innovative Propulsion Systems for CubeSATs and MicroSATs |
| [AD-2] | ENP2023-003 | ENPULSION NANO AR³ - TDE Final Report |

**Table 2-1: Applicable Documents**

### 2.2 Reference Documents

The following documents are referenced in the scope of this document and shall be considered as informational only:–

| Ref. | Number | Title |
|---|---|---|
| [RD-1] | ECSS-S-ST-00-01C | ECSS System – Glossary of Terms |

**Table 2-2: Reference Documents**

## 3 TERMS, DEFINITIONS AND ABBREVIATED TERMS

In the scope of this document, the following abbreviated terms are defined and used:–

| | |
| --- | --- |
| AD | Applicable Document |
| DUT | Device Under Testing |
| ECSS | European Cooperation on Space Standardization |
| EM | Engineering Model |
| EPL | ESA Propulsion Laboratory |
| ESA | European Space Agency |
| FEEP | Field-Emission Electric Propulsion |
| PPU | Power Processing Unit |
| RD | Reference Document |
| SPF | Small Plasma Facility |
| TVC | Thrust Vector Control |

## 4 CONTEXT AND OBJECTIVES

Commercially available spacecraft propulsion is in high demand as more and more satellite manufacturers emerge and the realization of constellations for various commercial and scientific aspects result in increasing propulsion requirements. Field-emission electric propulsion (FEEPs) as part of the electrostatic propulsion family are low-thrust, high-Isp subsystems suitable for various mission applications on satellites ranging from Cubesats over constellations to larger satellites and can be easily clustered to fulfil mission requirements. Existing products like the ENPULSION NANO have been successful in providing a solution to the market and have gathered substantial flight heritage.

The main objective of the ENPULSION NANO $AR^3$ is to extend the functionality of small-scale propulsion even further by including a non-mechanical thrust vector control to allow beam steering up to 12.5° off axis. This allows for Customers to outline mission profiles that would otherwise require complex hardware (e.g., gimbals) or invoke a substantial mass penalty (e.g., cold gas thruster propellant for AOCS). The feasibility to control the vector had been demonstrated on BBM level, so the objective for the first task within this project was to merge the elements and design aspects necessary for the thrust vector control with the existing and flight-proven designs of the ENPULSION NANO and the parallel development of the ENPULSION NANO $R^3$ thrusters. The first task concluded with a definition of the system requirements and the overall product design. Subsequently, in the second task, an engineering model suitable for testing was built and assembled. In the third task, the NANO $AR^3$ EM was subjected to test activities at both ENPULSION and the ESA Propulsion Laboratory (EPL) to verify primarily the functionality of thrust vector control alongside general performance and an interlaboratory comparison. Based on the outcome of the test activities, further development and verification needs were defined and outlined.

## 5 SOLUTION OVERVIEW AND RATIONALE

The ENPULSION NANO $AR^3$, shown in Figure 1, is the resulting design of the propulsion system including a thrust vector capability by dividing the extractor ring (negative electrode used for extraction and acceleration of ions) into 3 segments with high differential potentials to influence the ion beam. The design started as an evolution based on the heritage ENPULSION NANO with adding the two more high-voltage sections required to drive the extractor segments. With the parallel design efforts for the ENPULSION NANO $R^3$, synergetic trade-offs were included in the NANO $AR^3$ design:

- Encasing of the electronics boards in aluminum frames mainly for better protection against EMC and ionizing radiation
- Pathing of mechanical loads via the external frame and decoupling of the central reservoir from the electronics
- Increase of thermal interface contact surface
- Selectable mechanical interface
- Improved neutralizer design

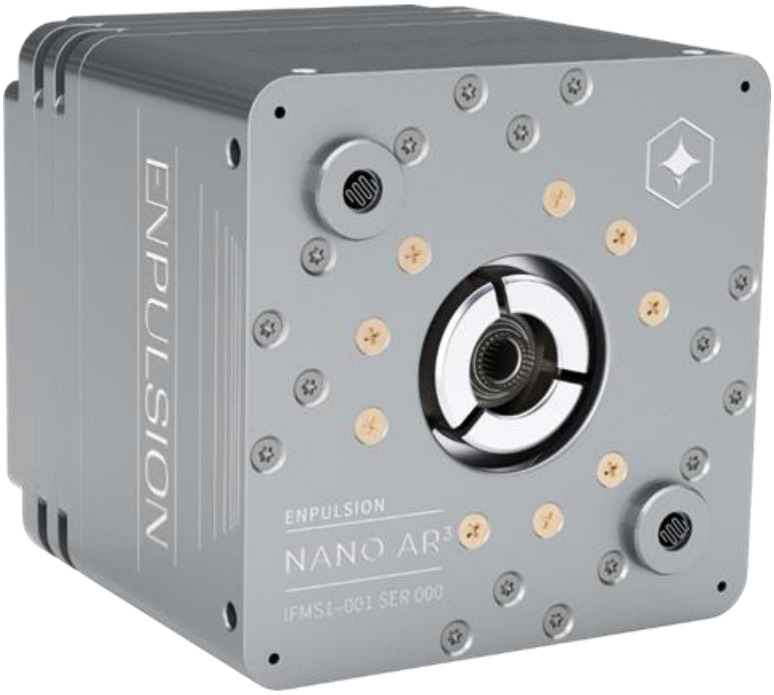


**Figure 1 - ENPULSION NANO AR³**

As part of the development activity with ESA, the overall thruster design based on the breadboard level and the PPU development was converged into a design suitable for further verification testing of the TVC concept on EM unit level. A review of the system requirements and the design resulted in a refined design state and a first EM was commissioned to production.

Following successful acceptance testing at ENPULSION, the NANO AR³ EM was installed in the Small Plasma Facility (SPF) in the ESA Propulsion Laboratory at ESTEC, NL. The test setup included 12 Faraday cups mounted on a rotary arm to evaluate the ion beam current density at various operational setpoints to verify the TVC feasibility. It was also the first time that a large vacuum chamber at EPL was used to operate and test a thruster based on indium propellant. The main objective of the test campaign was to verify the TVC, but also to show that the thruster can operate stably with an inclined thrust vector for an extended firing duration. To do so, following the initial characterizations the thruster was operated for 200 hours at 10 degrees of inclination (i.e., angle between thruster normal vector and thrust vector).

To further study the long-term behavior of the thruster unit, another 250 hours of continuous firing were conducted in an engineering vacuum facility at ENPULSION, while introducing some design changes for firmware and thermal concept. The main objective was to demonstrate the same stability in performance as part of an interlaboratory comparison, but also to further use diagnostic means to verify that the thruster design is adequate to conduct firing operations to reach its lifetime goals. While a full lifetime test was out of scope of the ESA activity, tendencies in terms of, e.g., electrical parameters of the subsystems were analyzed to derive further improvements necessary.

# 6 MAIN ACHIEVEMENTS

The results of the test campaign at ESA confirmed that for the three thrust levels investigated (350, 300, 250 µN), TVC was feasible up to 14° of inclination (higher the lower the thrust level). However, due to some challenges in the data acquisition affecting the accuracy of the measurements, only a qualitative comparison with the calibrated telemetry from the thruster was feasible. Similarly, a comparison of an ESA-internal probe to the Faraday cups developed by FOTEC specifically for indium thrusters was inconclusive due to acquisition challenges.
Subsequently, the propulsion system was operated successfully for about 200 hours at ESA. Due to thermal constraints of the thruster, a sub-nominal thrust point of 250 µN was chosen, and the EM fired continuously without signs of degradation in thrust, neutralizer performance, PPU efficiency, or thrust vector stability. Comparison of the test data with expectations from electrical and thermal testing revealed further design improvement potential that will be incorporated into the product design as well as observations with regard to the firmware behavior and functionalities.

The subsequent test campaign at ENPULSION incorporated some of the design improvements already in the EM, but most of the identified needs are yet to be implemented in a dedicated follow-up activity. The NANO AR³ EM was operated for another 250 hours without incident. Success criteria were met within diagnostic accuracies, and further development activities outlined including the need for PPU delta development.

In parallel, structural and thermal modeling were conducted to justify the design choices, and to compare with the experimental data.

# 7 CONCLUSIONS

The ENPULSION NANO AR³ was configured, manufactured, and successfully tested on EM level within the vacuum facilities of ESA and ENPULSION for extended firing times demonstrating the feasibility for active thrust vector control to more than 12° of inclination. The control function was qualitatively verified by plume diagnostics at ESA for different thrust levels and different commanded directions. Design aspects to further improve the design to be better suited for the commercial market were identified and are to be implemented in the subsequent design increment.

**END OF DOCUMENT**