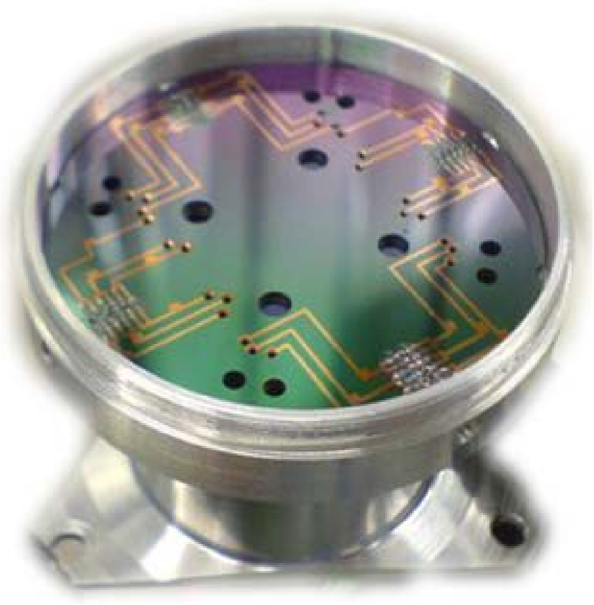
NanoSpace

# FINAL REPORT

## METHODOLOGY FOR COMPLEX MICROPROPULSION SYSTEMS SPACE VALIDATION



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Swedish Space Corporation Group


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# 1 Abstract

All space missions have different sets of requirements and specifications, but there is still a common methodology to assess space qualification for all the incorporated components and subsystems on the spacecraft. The manufacturing of Micro Electro Mechanical Systems (MEMS) differs a lot from conventional fabrication and hence the standard methodology to achieve space qualified products can not be used and therefore there is a need for a modified methodology custom designed for MEMS.

The main objective of the project Methodology for Complex Micro Propulsion Systems Space Validation, Contract no. 20720/06/NL/SFe was to identify and perform the preparatory activities required for future qualification of a MEMS-based micro propulsion system.

The work logic was to begin with a micropropulsion technology assessment and present a comparison of different micropropulsion technologies, understand the requirements and discuss reliability issues and failure modes. A preliminary generic requirement specification was also established early in the project. The justification of this generic requirement specification was made by considering/reviewing two relevant missions, i.e. Prisma and Proba-3.

Second, a thorough documentation of the already developed micropropulsion system was made. The documentation includes configuration documents, specification documents, and MEMS specific documents. The latter are Process Identification Documents (PID), Lot Travellers (LT), MEMS Definition Sheets, and MEMS Flow Charts.

It is in the nature of MEMS that the manufacturing procedure is not from structure via component to system as the case is in conventional manufacturing. The high level of integration makes it difficult to perform in-line functional measurements on MEMS components for example; the full functionality is only complete in the last manufacturing step when several wafers are bonded together. This requires that qualification methodologies for MEMS must rely on process qualification rather than product qualification. The major part of the work has been to develop this quality analysis methodology where definition and manufacturing of test structures, followed by validation of the same has been performed.

Wafer level tests make it possible to start the testing and sample screening early in the manufacturing process. These tests are meant to control characteristics of device structures and materials, and manufacturing processes. They provide reliability and performance data at various stages in the manufacturing process. Wafer level tests are included in all process packages in the manufacturing of the micropropulsion system. Most of the tests can be performed on actual micropropulsion system wafers and structures, precluding the need for specially designed process control monitoring (PCM) structures or PCM wafers. The wafer level tests performed in this work are presented together with an evaluation of the efficiency of the test structures and test methods. Most of the tests are made to control standard processes used by the MEMS community all over the world, other processes are used specifically for the subject complex micro propulsion system.

In conclusion several preliminary steps towards a process qualification methodology for a novel MEMS micropropulsion systems space validation have been taken. The development of quality analysis structures to monitor and control the in-line manufacturing of the micropropulsion system and an associated quality analysis methodology was described and validated during the project.

All gathered information throughout the project was finally considered in the last part of the work i.e. the writing of a qualification test plan.

# 2 Reference Documents

/RD 1/ Micropropulsioin Cold Gas Thrusters, Phase 3 & 4, Summary Report of ESA contract no. 18592/04/NL/HE

/RD 2/ Methodology for complex micropropulsion systems space validation, ESA Contract no. 20720/06/NL/SFe

/RD 3/ Requirement Specification – MEMS Thruster Module, SPN0700-S12 v2

/RD 4/ FF propulsion technology development status, maturity and backup, P3H-S62 v4

/RD 5/ ESA CDF Study Report, Proba 3, Formation Flight Technology Demonstrator and Coronagraph Mission, SSS33-S26

/RD 6/ Summary of Proba 3 Phase A work on Micropropulsion, Document No. SSS30-S40

/RD 7/ Space Engineering, Testing, ECSS-E-10-03A, 15 February 2002

/RD 8/ Ariane 5 User's Manual, Issue 3, Revision 0

/RD 9/ Soyus User's Manual, Issue 3, Revision 0 April 2001

/RD 10/ Vega User's Manual, Issue 3 Revision 0, March 2006

/RD 11/ Rockot User's Guide, Issue 3, Revision 1, 2001

/RD 12/ Dnepr User Manual, Issue 2, November 2001

/RD 13/ Cyclone 2K User's Manual Issued 2002

/RD 14/ H-IIA User's Manual, Second Edition, NASDA-HDBK-1007B, Rev.2c

/RD 15/ PSLV User's Manual Issue 4 December 1999

/RD 16/ Total Dose Steady State Irradiation Test Method, ESA/SCC Basic Specification no 22900

/RD 17/ MEMS Reliability Assurance Guidelines for Space Applications, Brian Stark, Jet Propulsion Laboratory, Pasadea, California, 1999

/RD 18/ Statement of Work: Methodology for Complex Micropropulsion Systems Space Validation, TEC-QCT/2006SoW01/FF-LM

/RD 19/ SV14, http://www.marotta.co.uk/pages/prsolenoid2.htm

/RD 20/ Proportional microthruster data sheet, www.bradford-space.com

/RD 21/ Micropropulsion system, www.nanospace.se

# 3 Abbreviation List

| | |
|---|---|
| ESA | European Space Agency |
| MEMS | Micro Electro Mechanical System |
| PID | Process Identification Document |
| LT | Lot Traveller |
| FF | Formation Flying |
| PCM | Process Control Monitoring |
| PDR | Preliminary Design Review |
| CDR | Critical Design Review |
| MST | Micro System technology |
| MNT | Micro Nano Technology |
| TRL | Technology Readiness Level |
| SSC | Swedish Space Corporation |
| R&D | Research and Development |
| IPR | Intellectual Property Rights |
| SoW | Statement of Work |
| TN | Technical Note |
| QM | Qualification Model |
| ECSS | European Cooperation for Space |
| WP | Work Package |
| WPD | Work Package Description |
| WBS | Work Breakdown Structure |
| SPC | Statistic Process Control |
| MIV | MEMS Isolation Valve |
| PRV | Pressure Release Valve |
| CAD | Computer Aided Design |
| PCV | Process Control Vehicle |
| SRS | Shock Response Spectrum |
| GNC | Guidance, Navigation and Control |
| QM | Qualification Model |
| MEOP | Maximum Expected Operating Pressure |
| PSD | Power Spectral Density |
| TID | Total Ionising Dose |
| FM | Flight Model |
| PFM | Proto Flight Model |

| | |
|---|---|
| FMECA | Failure Mode Criticality Analysis |

# 4 Background and Introduction

This document is the final report of NanoSpace work on the ESA contract no. 20720/06/NL/SFe, "Methodology for complex micro-propulsion systems space validation" in an answer to ESA ITT AO/1-5294/07/NL/SFe.

The main objective of the performed work was to establish strategies and methods to validate a novel micropropulsion system for space applications. This work will propose a methodology to be utilized in following efforts that will qualify these kinds of complex micro-systems for specific space missions. The overall objective is to ensure quality and reliability of an emerging category of products for space –namely Micro Electro Mechanical Systems (MEMS).

NanoSpace has prior to this activity developed a complex micro-propulsion system under an ESA-funded contract (ESTEC Contract no. 18592/04/NL/HE) which was successfully completed and reported in February 2007.

In another and currently ongoing activity, the first flight opportunity for the developed micropropulsion system is assessed. The subject satellite project is Prisma - a technology demonstration mission with focus on rendezvous and formation flying (FF). The objective is to flight demonstrate the micropropulsion system on Prisma in 2009.

This final report describes the activities deemed necessary to prepare for a future space qualification, e.g. targeted towards Proba-3, and built on the previous and ongoing work in parallel projects.

The work logic was to begin with a micropropulsion technology assessment and present it in a technical note.

Secondly, a thorough documentation of the already developed micropropulsion system was planned and performed. The documentation includes a set of new MEMS specific documents. Documents that are suggested to be added to the ESA standard PDR/CDR document list.

Thereafter a quality analysis methodology was developed where definition and manufacturing of test structures, followed by validation of the same was made.

Finally a qualification test plan usable for future space qualification has been proposed.

It is in the nature of MEMS that the procedure is not from structure via component to system as the case is in conventional manufacturing. In MEMS the system is finalized in the last manufacturing step since it is governed by compatibility issues and has to be processed in this order. This implies a new technical approach to achieve reliability, where process qualification becomes more critical than usual and where most of the effort has to be put.

## 4.1 Definitions and Terminology

An important background is a common ground of definitions and terminology used throughout this work.

### 4.1.1 MEMS Reliability

In space applications the reliability assurance is very important. However, there are no standards for MEMS reliability established at the moment. An important challenge is not only to qualify the device itself, but also to examine the entire process surrounding the part, from conception to finish including the, for MEMS, critical packaging step. This implies the logic of process qualification, followed by product qualification, and last product acceptance.

### 4.1.2 Micropropulsion

The definition of micropropulsion can vary in literature. One definition by Micci and Ketsdever is “any propulsion system that is applicable to a microspacecraft (mass less than 100 kg) mission”. Here, the term micropropulsion will be used to denote propulsion with thrust levels in the order of microNewtons (μN) up to several milliNewtons (mN) i.e. not connected to the size of the spacecraft the propulsion system is used on. A micropropulsion system can hence be suitable, not only for micro- or nanospacecraft, but also for larger spacecraft with stringent requirements on precision and stability e.g. formation flying missions such interferometer missions, where a number of spacecraft fly in precise formation.

### 4.1.3 Micropropulsion Technologies

There are mainly two approaches to develop micropropulsion system, by miniaturization of conventional systems or by using micro electro mechanical system (MEMS) technology and develop new propulsion systems. Both approaches are currently ongoing in both Europe and in the U.S.

There are a number of micropropulsion technologies: cold gas microthrusters, field emission electric propulsion (FEEP), colloid thrusters, ion engines, Hall-effect thrusters, solid propellant microthrusters, conventional resistojets, free molecule micro-resistojets, vaporizing liquid microthrusters, low-power arcjets, pulsed plasma thrusters, magnetoplasmadynamic thrusters, and maybe more. All are not commented in this technical note.

### 4.1.4 MEMS, MST, and MNT

There are several synonyms to describe the same microfabrication technology as we here refer to as Micro System Technology (MST) or Micro-Electro-Mechanical Systems (MEMS). Another synonym used in the space segment is Micro Nano Technology (MNT).

### 4.1.5 MEMS Basics

The MEMS (or MST) manufacturing technology has evolved from the planar technology used in microelectronics or integrated circuit (IC) industry. A third dimension has been added by exaggerating the micromachining processes that selectively etch away parts of the substrate or adds new structural layers in order to integrate micro mechanical elements onto the substrate, which commonly is a semiconducting silicon wafer. In this way MEMS, micro electro mechanical systems, with integrated mechanical structures, sensors, actuators, and electronics can be realised on micrometer to centimetre scale. The manufacturing is ideally suited for mass production but has to be performed in a clean room environment. There are mainly two types of fabrication processes in MEMS; surface micromachining and bulk micromachining. Other important key words in MEMS are lithography, batch processing, and process compatibility.

### 4.1.6 Technology Readiness Levels

Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The TRL levels used in this report refers to the definition in /RD 4/. The Technology Readiness Levels can be summarized as follows:

| | |
|---|---|
| TRL 1 | Basic principles observed and reported |
| TRL 2 | Technology concept and/or application formulated |
| TRL 3 | Analytical and experimental critical function and/or characteristic proof-of concept |
| TRL 4 | Component and/or breadboard validation in laboratory environment |
| TRL 5 | Component and/or breadboard validation in relevant environment |
| TRL 6 | System/subsystem model or prototype demonstration in a relevant environment (ground or space) |
| TRL 7 | System prototype demonstration in a space environment |
| TRL 8 | Actual system completed and “flight qualified” through test and demonstration (ground or space) |
| TRL 9 | Actual system “flight proven” through successful mission operations |

## 4.2 Road Map for Micropropulsion

Propulsion systems with the capability to deliver accurate micro- to milli-Newton thrust levels has been identified as mission critical for many advanced space systems such as Darwin, Gaia, LISA and Microscope, to mention a few, currently under development. Different technologies are being pursued, and one of the promising concepts is based on micro electro mechanical system (MEMS) technology.

MEMS is an enabling technology that will have a general impact in several space applications, especially on component and subsystem levels. Although cold gas systems is not the obvious choice for micropropulsion for many it is very suitable to merge with MEMS, a technology which itself is a result of successful technology merging.

### 4.2.1 MEMS – An Enabling Technology

The approach to use MEMS technology for micropropulsion system offers the largest potential to take technology steps in several areas. The first advantage is of course the great miniaturisation i.e. manufacturing of feature sizes down to micrometer range. Micrometer structures opens for microforces i.e. really low thrust applications in e.g. accurate attitude control missions.

The second advantage to merge mechanical structures and electrical components into a small physically sized system enables enhanced complexity and greater performance in terms of lower power consumption, lower noise, etc..

### 4.2.2 MEMS-Based Cold Gas Micropropulsion Systems

A cold gas suffers in general of a low specific impulse, however by incorporating electronic heaters by means of MEMS technology and run the system in hot gas mode improves the performance drastically. Recent results indicate an advantage for cold gas micropropulsion technology based on MEMS technology /RD 1/.

The logical way of pursuing this development of high performance MEMS propulsion is to gradually increase the complexity by going from:

Cold gas → hot gas → combustion (monopropellant) → combustion (bipropellant) From a chemical propulsion point of view the strategy would be to start with MEMS-based cold gas system, increase performance by applying resisto-jet technology i.e. where the propellant could be thermally exhausted through the nozzle. To learn and adapt to scaling laws prior to the next step which should be catalytic decomposition (monopropellant) and to be able in the long run to go to more advanced miniaturized bipropellant systems.

The work previously performed under ESA contracts /RD 1/ and the ongoing parallel activities with PRISMA are excellent prerequisites for the next suggested step, i.e. Proba-3. Furthermore, the current project is a parallel work with focus on validation methodology of MEMS-based micropropulsion /RD 2/. This effort is an important activity to bridge the gap between a proto flight system on Prisma and a formal on-ground qualification, which is required before the system is deemed mature enough to be a mission critical system onboard an ESA mission.

The relations and logical couplings between the previous and the ongoing work, and future work, is shown in the roadmap in Figure 1. A formal qualification of the micropropulsion system for Proba-3 is a step in this direction.

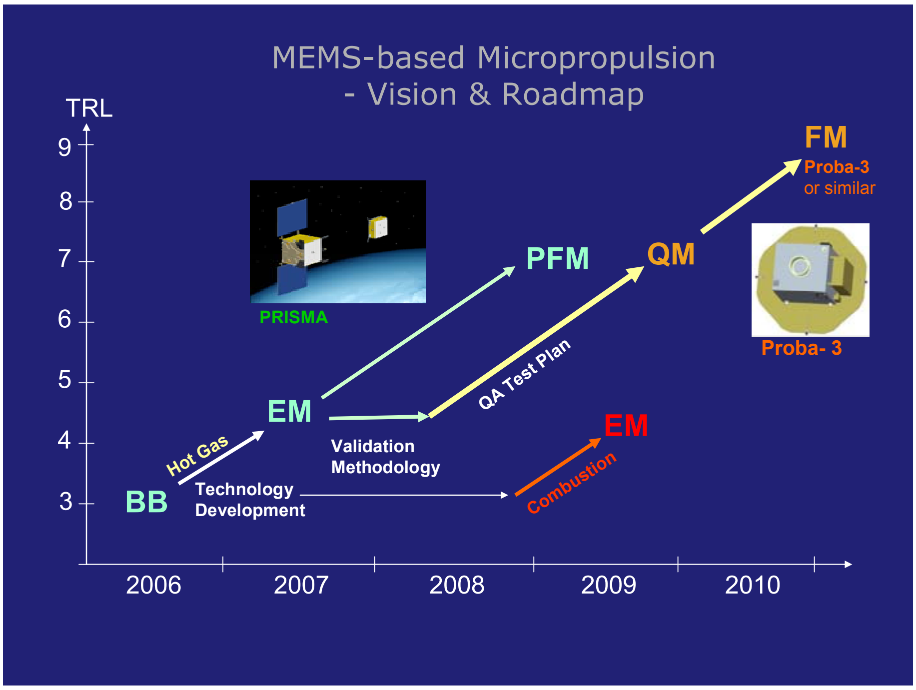



*Figure 1. Vision and roadmap for the MEMS-based micropropulsion system.*

## 4.3 NanoSpace Profile

NanoSpace AB is a subsidiary to Swedish Space Corporation (SSC) with the overall objective to develop and provide commercial products for the space industry based on MEMS technology.

NanoSpace started its operation in 2005 by taking over two ongoing ESA contracts at the time held by ACR Electronics and being carried out at the Ångström Space Technology Centre (ÅSTC) in Uppsala, Sweden. At the same time, NanoSpace procured all the intellectual property rights associated to these and other projects. Since the start, NanoSpace has built up the own organization as the activities in ACR and ÅSTC has diminished.

NanoSpace is mainly a R&D company with a number of products under development. Our main product lines are:

- A miniaturized cold gas propulsion system for satellites
- A miniaturized xenon feed system for Ion engines
- A miniaturized propellant gauging system for spacecraft

In addition to these major products, a number of discrete components such as valves, sensors and filters for space applications are developed to stand-alone products.

Overall, NanoSpace's vision is to become a component and subsystem supplier with a number of commercial products –based on own development and secured by own IPR. NanoSpace future customers are companies and institutes that integrate and provide space systems

Presently, NanoSpace occupies approximately 10 people and Mr. Tor-Arne Grönland has been the company's president since the start in 2005.

NanoSpace has currently about 10 patents (granted and pending) in its portfolio.

## 4.4 Relevant Facilities

Apart from basic electronics and test laboratories at NanoSpace premises in Uppsala, the main portion of NanoSpace R&D work is carried out using the Ångström laboratory in Uppsala. In the Ångström laboratory all MEMS process development and manufacturing is done.

In addition to the Ångström laboratory, NanoSpace does also have access to SSCs facilities in Solna. These facilities are shortly described hereafter.

### 4.4.1 The Ångström Laboratory

The Ångström clean room facility has a total area of 2,000 m$^2$ including over 30 lab rooms with service corridors. The major part of the clean room is classified as 10,000 (particles > 0.5 $\mu$m per cubic foot air). 150 m$^2$ is constructed as a class 100 clean room with unidirectional airflow from the ceiling to the floor. It is, of course, possible to create smaller areas with an even higher degree of cleanliness such as class 10 or class 1. The temperature is stable within +/-1°C. The relative humidity is held constant at 43+/-3 % in one third of the clean room. The vibration-free foundation has a unique construction, classed ad BBN-E.


The clean room is subdivided in 2 sections, the first part being mainly occupied by characterization equipment, the second part dedicated to processing. The laboratory is very well equipped with up-to-date characterization systems such as high-resolution TEM, electron microscopes, STM/AFM instruments, ESCA, etc. the process laboratory, for micro fabrication, includes equipment like a pattern generator and an ion implanter. The clean room is equipped for processes such as dry-etch, wet chemical, high temperature, and PVD metallization.

### 4.4.2 SSC facilities

NanoSpace, as part of the Swedish Space Corporation Group, has access to the premises in Solna which includes:

- 800 $m^2$ of electronic laboratories for design, manufacturing and test for the development work. A 100 $m^2$ 100 000 class clean room is available with 2*20 $m^2$ 10000 class clean areas inside.
- Integration rooms with handling equipment.
- Mechanical workshop with NC milling, turning, drilling, grinding and welding machines.
- Environmental test facilities such as tanks for thermal vacuum and thermal cycling.

# 5 Description of Space Validation Work

The main objective of the performed space validation work is, in accordance to the SoW, to identify and perform the preparatory activities required for a future qualification of a MEMS-based micropropulsion system. In the SoW this objective is threefold, but an amendment of an extra technical note (TN) was suggested in the proposal dividing the objectives into four separate tasks.

First, a micropropulsion technology assessment for comparison of different micropropulsion technologies is made and presented in a technical note. This task includes:

- Applications and missions for micropropulsion systems
- Evaluation of, and trade-off between, different micropropulsion technologies
- Understanding of requirements and presentation of a preliminary requirement specification
- List of relevant missions, consideration and agreement upon a typical spacecraft/mission
- Discussion of known or expected reliability issues, e.g. failure modes

Second, a thorough documentation of the already developed micropropulsion system is made. This task includes:

- Configuration documents
- Specification documents
- MEMS specific documents

The latter includes Process Identification Documents (PIDs), Lot Travellers (LTs), MEMS Definition Sheets, and MEMS Flow Charts.

Third, definition and manufacturing of test structures and a subsequent validation of them is made. This task includes:

- Definition of Process Control Monitoring (PCM) structures
- Description of the quality analysis methodology with details on test methods and test procedures
- Definition of pass/fail criteria
- Manufacturing of test structures
- Characterization and tests to help validating the efficiency of the test structures.

In the last task, a qualification test plan is prepared. A preliminary test plan is prepared early in the project in order to get early feedback and arrive at a useful and realistic test plan at the end of the project.

## 5.1 Technical Approach

NanoSpace will adopt and implement the methodology for product qualification used in commercial MEMS products where applicable and use a concurrent design, also referred to as design-for-reliability, to improve system reliability.

The specific conditions for space application, especially during launch and in orbit will of course need a customized approach; moreover, the space specific requirements such as thermal and mechanical shock as well as radiation are seldom dealt with in commercial MEMS. The high-reliability MEMS products available on earth are manufactured in millions using SPC (statistical process control) and allows for more statistical studies to be performed in comparison to the more limited number of devices to be produced for space. A methodology to space qualify conventional manufactured parts already exist and will be adopted as much as possible.

The manufacturing and development strategy is partially adopted from industrial MEMS experiences. It is based on process steps that have been developed and verified through manufactured test structures or components, and that are implemented in the process library. The process library is kept under configuration control; new or improved manufacturing process steps are implemented during revisions and new releases. The manufacturing and development strategy is as follows:

- Selection of materials and process steps to establish a compatible manufacturing sequence
- Identification of critical steps and manufacturing of feasible structures and components
- Iteration of structures and components towards a simplified functional system
- A gradual increase in complexity when a functional system exists.

## 5.2 Microcpropulsion Technology Assessment

In the SoW the objective was threefold, but an amendment of an extra technical note (TN) suggested dividing the objectives into four separate tasks.

The suggestion was to amend a micropropulsion technology assessment for comparison of different micropropulsion technologies is made and presented in a technical note. This task includes:

- Applications and missions for micropropulsion systems
- Evaluation of, and trade-off between, different micropropulsion technologies
- Understanding of requirements and presentation of a preliminary requirement specification
- List of relevant missions, consideration and agreement upon a typical spacecraft/mission
- Discussion of known or expected reliability issues, e.g. failure modes

## 5.3 Documentation of Micropropulsion system

NanoSpace documents the manufacturing processes and the manufactured components by using PIDs and LTs. The entire process flow down to each individual process step is controlled. The corner stone is the Process Library in combination with the MEMS Manufacturing Procedure. All documentation is made electronically for improved traceability. Each process step is signed off by the process engineer. The sections below describe the manufacturing and development strategy including the MEMS specific documents required.

There is an ESA standard list of documents for Preliminary and Critical Design Reviews (PDR/CDR). NanoSpace has a corresponding list of documents with an amendment of MEMS specific documents. As an example, the manufacturing, inspection, and assembly of MEMS batches/components is handled separately in MEMS Flow Charts which is a part of the Definition Sheet for the MEMS components. The MEMS Flow Chart is important since it presents the complex manufacturing sequence of how different batches and structures fall into place and result in a multi wafer microsystem in the end.

## 5.4 Quality Analysis Methodology

Product qualification is a very important issue for space applications. There is no standard qualification methodology for MEMS products established at the moment, however. The manufacturing differs a lot from conventional manufacturing so only a limited part of the conventional methodology can be used. It is difficult to perform direct in-line measurements on MEMS components for example. Since the manufacturing sequence is governed by compatibility issues, the full functionality of MEMS components is only complete in the last manufacturing steps when several wafers are bonded together.

Due to the high level of integration, a qualification methodology for MEMS products and components must to a larger extent than usual rely on the process qualification instead of product qualification. Process qualification is also important due to the exceptional sensitivity and complexity of many MEMS manufacturing processes. It must be understood, however, that MEMS technology is still constantly evolving and that the phrase “freezing of a manufacturing process” does not apply.

A general approach in the proposed quality analysis methodology is to focus on product qualification in terms of performance validation, environmental tests, and accelerated lifetime tests on the completed microsystem. The in-line process control suggested consists of different kinds of process control monitoring steps.

## 5.5 Qualification Test Plan

The strategy and goal of the last and most relevant work to be done is the preparation of a test plan. The strategy is to begin as early as possible with this work by select and chose a baseline mission and corresponding preliminary requirements during the first work package. Use this initial information to prepare a preliminary qualification test plan including a review of existing requirements for a conventional propulsion system and make preliminary definitions of the Qualificaiton Model (QM) and preliminary definition of qualification to be able to get feedback from ESA already at midterm review. The starting point will of course be the documents found in European Coordination for Space Standardisation (ECSS).

All gathered information throughout the project will finally be included in the last work i.e. the qualification test plan. The test plan will cover worst case requirements, both non-flight and flight critical cases. To determine the reliability of the complex system a test plan which reveals the critical failure modes first by applying driving conditions in representative environment to accelerate failure modes is planned.

## 5.6 Work Logic

The proposed work consists of six groups of Work Packages (WP) where WP3000 Documentation of Micropropulsion System, WP4000 Quality Analysis Methodology, and WP5000 Qualification Test Plan are the core of the whole project. The first and the last work packages are the standard Management and Final Delivery packages.

WP2000 is not included in the SoW but is added in order to give an assessment of existing micropropulsion technologies. It is summarised in an additional technical note referred to as TN0 in the Work Package Description (WPD).

Another suggested modification of the work logic also not stated in the SoW is to prepare a Preliminary Qualification Test Plan prior to a mid term review in order to be able to get early feedback from ESA and to be able to conclude the project within the given time frame.

The work breakdown structure (WBS) for the proposed space validation work is shown in Figure 2 below.

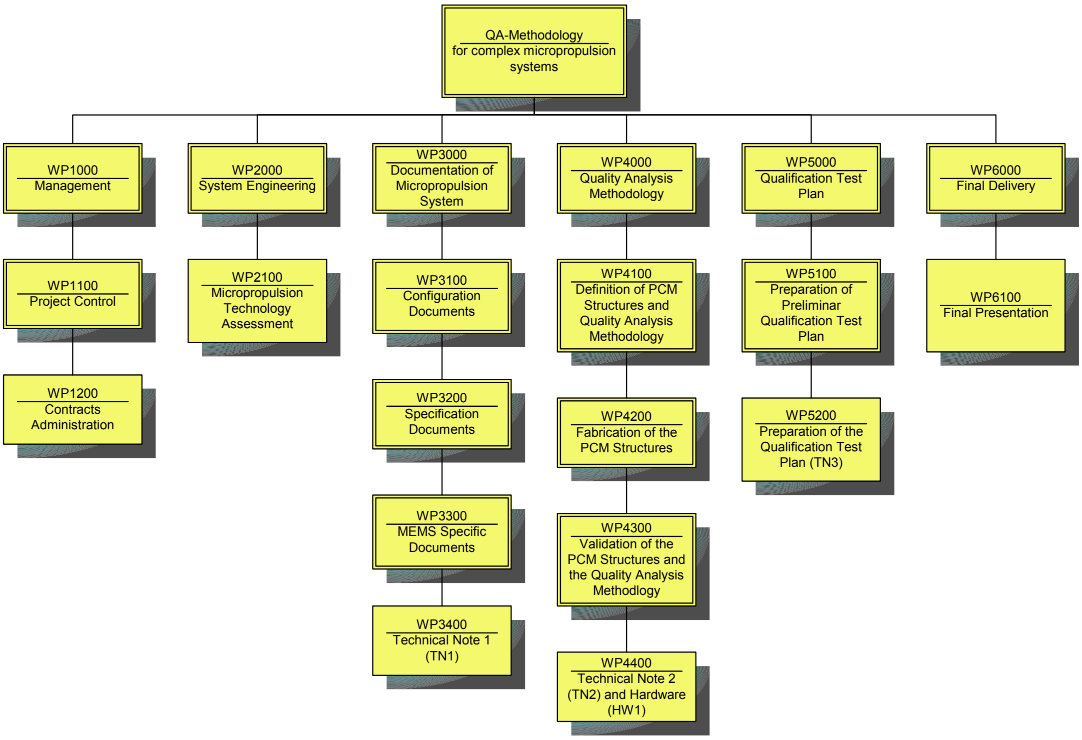



*Figure 2. Work breakdown structure of the proposed work.*

## 5.7 Time Schedule and Meetings

The planning was made for 12 month project duration.

Standard ESA rules for progress reports, milestones and meetings have been applied throughtout the project.

## 5.8 Study Logic

The study logic of the proposed work is shown the following flow chart. Green colour indicates reviews or approval by ESA.

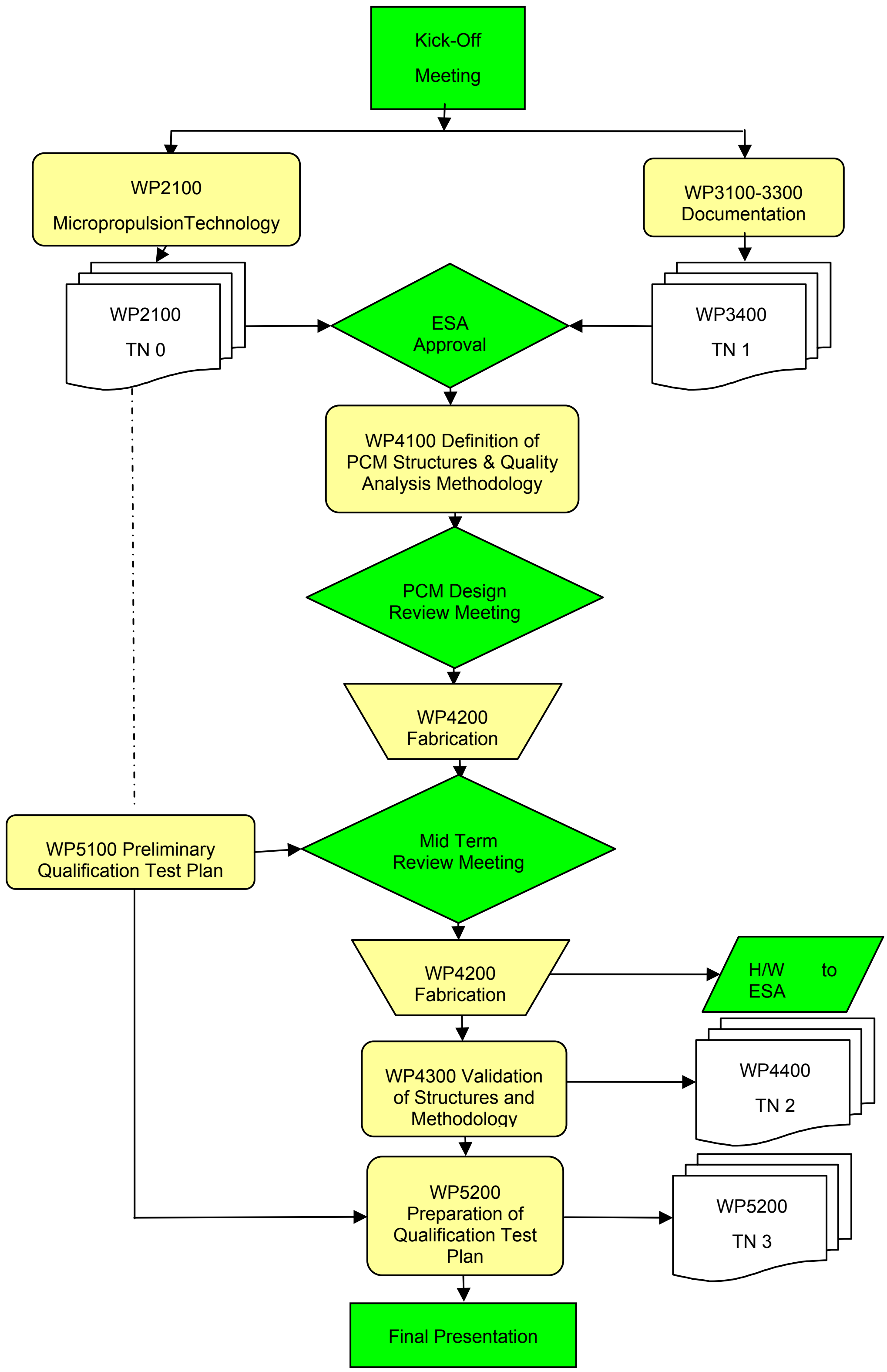



*Figure 3. Study logic flow chart of the proposed work.*

## 5.9 List of Deliverables

The deliveries within the project are not only documents, but also hardware deliveries in terms of samples of fabricated test structures.

### 5.9.1 Documents

Documents to be delivered according to /RD 18/ Statement of Work with an additional technical note, i.e. the Micropropulsion Technology Assessment, referred to as TN0 below.

| **Doc. Ident.** | **TN no.** | **Title** |
|---|---|---|
| D1 | | *Web Summary* |
| D2 | TN0 | Micropropulsion Technology Assessment |
| D3 | TN1 | Documentation of the Micropropulsion System |
| D4 | TN2 | Quality analysis methodology of the micropropulsion system |
| D5 | TN3 | Qualification test plan of the micropropulsion system |
| D6 | | Final Report |
| D7 | | Abstract |

### 5.9.2 Hardware

Nanospace shall provide ESA with hardware according to /RD 18/ after finishing WP4400. At least one test structure of each kind shall be delivered.

| **Item. Ident.** | **Description** |
|---|---|
| HW1 | Samples of fabricated test structures. |

# 6 Activities Performed

## 6.1 Micropropulsion Technology Assessment

The purpose of the first part of the work was to make a micropropulsion technology assessment including application and missions, evaluate and make trade-off between different technologies. Another purpose was further to get an understanding of requirements and to select a base line mission as model mission for the project. The result of this work is presented below.

### 6.1.1 Applications & Missions for Micropropulsions Systems

#### 6.1.1.1 Propulsion Overview

A satellite needs propulsion for various reasons. First the satellite has to find its correct orbit when it leaves the launcher (carrier rocket). The orbit injection maneuver is a velocity increase, Delta-v, and the magnitude of the required Delta-v is strongly dependent of launcher and final orbit.

Station keeping is another need for propulsion i.e. to compensate for the velocity loss and consequent altitude loss in low earth orbits (600-2000 km).

Orbit change is a very costly maneuver, in terms of Delta v, during a satellite mission.

Inclination change only requires a velocity change perpendicular to the orbit velocity and might be solved using a micropropulsion system. Also pointing operations could be solved using micropropulsion, where only a small angular velocity is needed. Especially stabilisation methods require a high accuracy and small delivered force to reach a high pointing precision.

#### 6.1.1.2 Chemical Propulsion

There is a wide spectrum of different chemical propulsion systems. The common denominator is the expel of material in one direction to achieve a force in the opposite. The propellant can be stored either in solid, liquid or gas phase. The simplest chemical propulsion systems do not involve a chemical reaction and the gas is just expelled through a nozzle such as in the cold gas system.

#### 6.1.1.3 Electric Propulsion

Electric propulsion is the collective name for system which obtain their thrust through expel of positively charged ions. Example of electric propulsion systems are plasma thrusters.

### 6.1.2 Selecting Propulsion System

Once the total Delta-v, i.e. the sum of all individual Delta-v:s, of a mission is estimated the propulsion system can be selected. Also the maximum and minimum force must be known.

Chemical propulsion systems generally have a lower Isp but can deliver high forces. They do not require large amounts of power, but still large propellant tanks due to the low Isp.

Electric propulsion system utilizes high acceleration voltages and has a rather high power consumption.

### 6.1.3 Applications for Micropropulsion

Every application where there is a need for low thrust levels and small impulse bits a micropropulsion system is needed. Beside potential pico- or nanospacecraft missions, which have an obvious need for micropropulsion, even the other end in size might need micro forces an example could be large inflatable craft, required to off-set small but continuous solar pressure disturbance torques. However the main application area would be microspacecraft mission there are a number of different missions where formation flying in one or another way is needed. Constellation flying missions where interferometry is included is an example of high precision formation flying. Inspection missions are other examples.

### 6.1.4 List of Relevant Micropropulsion Missions

Propulsion systems with the capability to deliver accurate micro- to milli-Newton thrust levels has been identified as mission critical for quite a few advanced space systems such as Darwin, Gaia, LISA, Xeus, Max, Simbol-X, Proba-3, and Microscope. Different technologies are being pursued, and one of the promising concepts is based on MEMS technology.

#### 6.1.4.1 Prisma

The concept of MEMS-based micropropulsion needs to be demonstrated in space before this new technology will be accepted on a broader base. The achievements under the ESA-funded micropropulsion contract developed in Uppsala since late 90:ies paved the way for an effort where a prototype of the MEMS-based micropropulsion system will be flight tested onboard the Prisma satellite in 2009. The Prisma programme represents a unique opportunity to flight demonstrate the MEMS-based micro-propulsion system and thus take a significant step to enable greater satellite functionality, while significantly reducing cost and weight.

#### 6.1.4.2 Proba-3

The next interesting mission is Proba-3. The proba-3 mission will be the first ESA formation flying mission, and will be the test bench for the new technologies necessary for future missions such as LISA and Darwin.

### 6.1.5 Proba-3 Propulsion Requirements

Proba-3 is intended to be a “low cost” Formation Flying test bed for enabling technologies for precision formation flying missions like XEUS, Darwin, and Simbol-X.

The total spacecraft mass shall be in the 200 kg range with a total solar array power production of up to 200-300W, with a total satellite power requirement of ~172W for the Occulter and 143W for the Coronagraph.

Launch should be around 2011.

#### 6.1.5.1 Micropropulsion Requirements

The micropropulsion requirements concerns the formation flying (FF) part of the mission are mainly related to small, accurate and predictable impulses. Small, accurate and predictable impulses generally implies a propulsion system with low thrust levels.

For the Proba-3 mission, a thrust level of 40-44 mN is required by the thrusters /RD 5/. However, recent analysis done by Alcatel has shown that only 10-20 mN is required for the fine FF manoeuvring, with a total mission $\Delta V$ of ~61 m/s. With a positioning accuracy on the order of mm between the two satellites, the difference between thrust level increments should be as small as possible and the response time should be should be minimized.

Moreover, if the Proba-3 mission shall be a relevant precursor for more advanced formation flying missions, e.g. DARWIN, even lower thrust levels (and hence better formation accuracy) would be relevant. In extreme cases thrust levels down to $\mu$N could be required.

Another relevant aspect for the Proba-3 mission is contamination. Although little or no information is available at this point, a general concern for spacecrafts that carry optical sensors is contamination by expelled mass from propulsion system(s).

### 6.1.5.2 Selection of Model Mission

Based on the text above the best choice of model mission is to use Proba-3 requirements as base line mission. The timing and basic requirements are suitable and a “proper” mission is better than a “theoretical/academic/paper” mission.

## 6.1.6 Trade-Off of Micropropulsion Technologies

To achieve small thrust levels (order of mN or less) and correspondingly small impulse bits (typically $10^{-4}$ Ns or less), a number of possible propulsion concepts could be foreseen although the technical maturity for most of these concepts are modest compared to commonly used chemical propulsion or cold gas systems. Table 1 shows the possible chemical propulsion options. As compared to the electrical propulsion options in Table 2, the TRL level of the chemical propulsion systems is generally higher.

*Table 1. Chemical propulsion candidates for Proba 3 FF.*

| Description | Company | TRL | Thrust (mN) | Isp (s) | Propellant | Specific power (W/mN) | Power req. for nominal (W) | Mass (kg) |
|---|---|---|---|---|---|---|---|---|
| $N_2$ cold gas | AASI-F | 5 | 0-1 | 55-78 | $N_2$ | | | <0.13 |
| Proportional Micro Thruster | Bradford | 5/6 | 0-2 | 65-76 | He, Xe, $N_2$, dry air | 2.25 | <4.5 | <0.175 |
| Cold gas | Marotta | 8 | >50 | | $N_2$ | 0.02 | <1 | 0.07 |
| SV14 Cold gas | Marotta UK | 8 | 10/40 | 70 | $N_2$, Xe | 0.0875 | <3.5 (pull in) <0.7 (holding) | <0.075 |
| Cold gas, MEMS design | NanoSpace | 5 | 0.01-1 | >50- >100 | $N_2$ | 1 | <5/pod(4 thrusters | 0.1/pod (4 thrusters) |
| $N_2O$ resistojet | SSTL | 9 | 125 | 127 | $N_2O$ | | 100-600 | 1.24 |
| Cold gas, Butane thruster | SSTL | 9 | 45-120 | 60 | Butane | 0.72 | | 0.422 |
| Low power resistojet | SSTL | 9 | 10-75 | 48-99.4 | $N_2$, butane, Xe | 3 | 30W for Xe, up to 50W possible | 0.16 |

*Table 2. Electric propulsion candidates for Proba 3.*

| Description | Company | TRL | Thrust (mN) | Isp (s) | Propellant | Specific power (W/mN) | Power req. for nominal (W) | Mass (kg) |
|---|---|---|---|---|---|---|---|---|
| PPS-101, Pulsed Plasma thruster | Aerojet | 6 | 1.24-2.5 | 1350 | Teflon | 80 | 99.2 | 4.74 incl. PPU |
| HT-100, 100W class mini Hall Effect Thruster | Alta S.p.A. | 5 | 0.5-1, 2-10 | 1000-1300 | Xe | 25 | 10-50, thermionic, 50-250 hollow cathode | 4.6 (excluding tank), 0.9 only thruster |
| FEEP | Alta S.p.A. | 4/5 | 0.001-2 | 6000-10000 | In/Cs | 58 | 116 | 3 |
| Tandem-200, Hall effect thruster | Busek | 6 | 4-17 | 1200-1600 | Xe | | 200 | 0.9 |
| MOA, Magnetic field Oscillating Amplified thruster | CERN | 2/3 | 8.09 | 1042 | Xe | 51.1 | 398 | |
| RIT-10, 10cm gridded ion thruster | EADS-ST | 8/9 | 2.25-20.25 | 3300 | Xe | 38 | 570 | 1.8 |
| Arcjet | IRS (Stuttgart University) | 4 | 115 | 480 | NH3 | | 750 | 0.48 |
| MiXi, Miniature gridded ion truster | NASA | 4 | 0.5-3 | 3100 | Xe | | <100 | |
| T5,10 cm gridded ion thruster | Qinetiq | 8/9 | 1-20 | 3300 | Xe | 29 | 435 | 2 |
| Hollow cathode thruster | Qinetiq | 8 | ≤1 | 500 | Xe | 30 | 30 | 0.1 |
| Colloid thruster | RAL | 5 | 0.005-1 | 500-1500 | Glycerol | 10 | 10 | |

## 6.1.7 Analysis of Propulsion Options

### 6.1.7.1 Cold Gas

Due to the low power demand and mass of the chemical propulsion systems, the thrust range will be the basis for down selecting the applicable systems. Thus it should be below 44mN and possibly with a maximum thrust level of 20mN. As such the Bradford Proportional Micro Thruser, Marotta UK SV14 cold gas thruster, SSTL low power resistojet and the NanoSpace cold gas thruster are possible candidates. The SSTL resistojet does however require a power of 30-50W, at least 10x higher than the other options and therefore the other options would be more appropriate. The mass of these thruster are below 175g and as low as 70g for the NanoSpace thruster. The NanoSpace Pod does however incorporate 4 thrusters in one unit, thus reducing the overall thruster mass by a factor 4 over other systems. However there is no single thruster that is capable of covering both the high thrust regime, 10-20mN, for the basic Solor Coronagraph formation flying mission and the low thrust regime of ~10 to 25 µN required for demonstrating the full envelope of future precision formation flying missions. As such, a combination of “high” thrust and low thrust thrusters should be found. This will optimally be done if the two systems have a common propellant storage and feed system.

### 6.1.7.2 Cold Gas Propellants

Numerous propellants have been considered for the cold gas option and a trade-off is made. The trade-off is based on an assumed spacecraft mass of 200 kg and a total mission $\Delta V$ of 61m/s. The following table lists the considered propellants with their theoretical vacuum specific impulse at a propellant temperature of $0^{o}C$. The table also shows the resulting propellant mass that is required as well as the required volume to store the propellant at a pressure of 250 bar. This is used to determine the appropriate propellant tank.

*Table 3. Cold Gas Propellants.*

| Name | Gas | Isp [s] | Prop. Mass [kg] | Prop. Vol [dm3] |
|---|---|---|---|---|
| Hydrogen | H2 | 284.8 | 4.4 | 218.3 |
| Helium | He | 172.2 | 7.2 | 180.5 |
| Neon | Ne | 75.9 | 16.4 | 86.2 |
| Nitrogen | N2 | 76.8 | 16.2 | 57.8 |
| Argon | Ar | 54.2 | 22.9 | 52.1 |
| Xenon | Xe | 29.6 | 42.1 | 15.3 |
| Methane | CH4 | 113.0 | 11.0 | 57.9 |
| Ammonia | NH3 | 108.3 | 11.5 | 11.3 |
| Nitrous Oxide | N2O | 68.2 | 18.2 | 15.2 |
| Carbon Dioxide | CO2 | 68.2 | 18.2 | 17.7 |
| Propane | C3H8 | 70.5 | 17.6 | 34.6 |
| Butane | C4H10 | 99.2 | 12.5 | 21.6 |

The following conclusions can be drawn from this analysis:

- Ammonia is theoretically best as it has a high specific impulse, comparatively low required propellant mass and requires the smallest propellant tank. However, issues with safety, handling, material compatibility with available thrusters is less attractive.
- Nitrious oxide and carbon dioxide are attractive due to their low tank size requirement and ease of use. They could be considered for further investigations.
- Propane and butane have a higher specific impulse than nitrous oxide and carbon dioxide but with low vapour pressure and handling becomes an issue due to flammability.

- Hydrogen and Helium have very attractive specific impulses and low mass requirements, but they, as well as Neon require too much tank volume at a MEOP of 250bar to be feasible.
- The trade between Nitrogen and Argon on one hand and Xenon on the other hand is a trade between available mass and volume on the spacecraft. Xenon requires more mass but small volume and vice versa. Propellant heritage and cold gas thruster heritage does however favour Nitrogen. A combined feed system with an EP using Xenon would favour the Xenon. Likewise a combination of different cold gas systems using Nitrogen favours this.

### 6.1.7.3 Electric Propulsion

As for the electric propulsion options are much more power demanding and as such the first selection criteria for Proba-3 is power. Assuming an available power of 100-150 W (solar panel production - stand-by mode [1]), this limits the EP options to 4 possible. With regards to the thrust level, the only option that remains is the Alta HT-100 thruster. The thrust level is on the border line of being acceptable, even for the high power Ht-100 option, which can produce 10mN at a power level of 250W. This unit, including PPU and other peripheral equipment has a mass on the order of 4.65 kg, with a single thruster mass of 900g. For the basic solar coronagraph formation flying phases, with a thrust requirement of 10-20 mN and an assumed available power of 100-150W, EP can only be used in combination with a higher thrust cold gas system, where the EP will be responsible for the very fine thrust manoeuvres. This option would result in the mass budget becoming a primary driver.

For the µN thrust regime required for demonstrating relevant performance for the most demanding future missions, six possible thrusters technologies exist, all requiring less than 150W to operate. However as only ESA/EU member state thrusters should be considered, the remaining four thrusters are:

- HT-100
- FEEP
- colloid thrusters
- Qinetiq hollow cathode thruster

FEEP and Colloid thrusters have demonstrated thrust levels as low as 1 µN. The minimum thrust level for this phase, as well as the propellant type will thus determine the optimal system.

## 6.1.8 Trade-Off Conclusion

The use of a single propulsion system will be able to satisfy the basic formation flying requirements of the mission but will not add the technological advantage of becoming a precursor mission for more advanced formation missions such as Xeus and DARWIN where µN thrust levels may be required. Combining high and low thrust systems on one spacecraft will thus be required to add high scientific and technological value to the mission. The power budget imposes severe constraints on the use of electric propulsion, for the required thrust levels, and is thus almost all are removed from being viable options for Proba-3 FF operations. A possible solution would be to have a high thrust cold gas system on both spacecrafts in order to fulfil the nominal formation flying requirement, and then to add a low thrust cold gas system, using the same propellant type, to the Coronagraph and an EP system to the Occulter in order to demonstrate µN thrust levels for future advanced formation flying. This will add the greatest amount of value to the mission, will not imply a significant mass or power penalty and improve the overall reliability and redundancy.

The TRL levels of the short listed chemical propulsion options are higher than the possible EP options, apart from the Qinetiq hollow cathode thruster, and will thus be more acceptable, with respect to a launch date in mid 2010. The Bradford thruster TRL may be improved by then, but it is developed for the GAIA programme and has not flown. The NanoSpace thruster will increase its TRL to 9 in 2009 when it will be flown on Prisma. The TRL increase of the appropriate EP systems is however more uncertain.

The possible propulsion options for Proba-3 are summarized in Table 4 below.

*Table 4. Possible propulsion options for PROBA-3.*

| Type | Description | Company | TRL | Thrust (mN) | Isp (s) | Propellant | Specific power (W/mN) | Power req. for nominal (W) | Mass (kg) |
|---|---|---|---|---|---|---|---|---|---|
| **Solar Coronagraph & Basic FF needs** | | | | | | | | | |
| Cold gas | SV14 Cold gas | Marotta UK | 8 | 10-40 | 70 | $N_2$, Xe | 0.0875 | <3.5 (pull in) <0.7 (holding) | <0.075 |
| Cold gas | Low power resistojet | SSTL | 9 | 10-75 | 48-99.4 | $N_2$, butane, Xe | 3 | 30W for Xe, up to 50W possible | 0.16 |
| **Advanced FF** | | | | | | | | | |
| Cold gas | N2 cold gas | AASI-F | 5 | 0-1 | 55-78 | $N_2$ | | | <0.13g |
| Cold gas | Proportional Micro Thruster | Bradford | 5/6 | 0-2 | 65-76 | He, Xe, $N_2$, dry air | 2.25 | <4.5 | <0.175 |
| Cold gas | Cold gas, MEMS design | NanoSpace | 5 | 0.01-1 | >50->100 | N2 | 1 | <5/pod(4 thrusters | 0.1/pod (4 thrusters) |
| EP | HT-100, 100W class mini Hall Effect Thruster | Alta S.p.A. | 5 | 0.5-1, 2-10 | 1000-1300 | Xe | 25 | 10-50, thermionic, 50-250 hollow cathode | 4.6 (excluding tank), 0.9 only thruster |
| EP | FEEP | Alta S.p.A. | 4/5 | 0.001-2 | 6000-10000 | In/Cs | 58 | 116 | 3 |
| EP | Hollow cathode thruster | Qinetiq | 8 | ≤1 | 500 | Xe | 30 | 30 | 0.1 |
| EP | Colloid thruster | RAL | 5 | 0.005-1 | 500-1500 | Glycerol | 10 | 10 | |

### 6.1.9 Proposed Micropropulsion Subsystem Mass Budget

Shown in Table 5 is a breakdown of the proposed mass budget for the cold gas micropropulsion subsystem of the combined Coronagraph propulsion system. It also incorporates tanks and propellant for both the high and low thrust thrusters over the whole mission, i.e. 61m/s. The result is that the mass difference between the pod and PMT option is on the order of 180 g, where the PMT option is 180 g heavier. The analysis assumes that the subsystem of the Pod version and the PMT version remain virtually the same with the exception of different thrusters. This is done as the operating pressures and mass flow rates are similar between the two systems. With four Pods, the Pod version will have a total of 4x4 thrusters, thereby giving increased manoeuvrability in and rotation around more axes than otherwise possible, i.e. the longitudinal axis.

*Table 5. Cold gas mass budget.*

| **UNITS** | **No.** | **Mass (kg) per unit** | **Total Mass (kg)** | **Margin (%)** | **Margin (kg)** | **Mass with margin** | **Notes** |
|---|---|---|---|---|---|---|---|
| NanoSpace Pod | 4 | 0.115 | 0.46 | 20% | 0.092 | 0.552 | 2x redundant |
| Bradford PMT | 4 | 0.175 | 0.7 | 5% | 0.035 | 0.735 | 2x redundant |
| Propellant Tank | 2 | 10.6 | 21.2 | 5% | 1.06 | 22.26 | For both propulsion systems |
| Tubing and fittings | 1 | 0.600 | 0.6 | 20% | 0.12 | 0.72 | 6 m tubing |
| Filter | 1 | 0.024 | 0.024 | 5% | 0.0012 | 0.025 | VACCO high pres. Miniature |
| Isolation valve | 2 | 0.080 | 0.16 | 20% | 0.032 | 0.192 | NanoSpace |
| Pressure relief valve | 1 | 0.100 | 0.1 | 20% | 0.02 | 0.12 | NanoSpace |
| Pressure transducer | 2 | 0.080 | 0.16 | 20% | 0.032 | 0.192 | Presens |
| Pressure regulator | 1 | 0.250 | 0.25 | 20% | 0.05 | 0.3 | Marotta |
| Service Valve | 1 | 0.178 | 0.178 | 5% | 0.0089 | 0.187 | Marotta |
| Brackets, supports and fasteners | 1 | 0.600 | 0.6 | 20% | 0.12 | 0.72 | |
| **Total dry mass Pod** | | | **23.73** | | **1.54** | **25.27** | |
| **Total dry mass PMT** | | | **23.97** | | **1.48** | **25.45** | |
| Propellant | 1 | 16.20 | 16.2 | 20% | 3.24 | 19.44 | GN2 for both propulsion systems |
| **Total wet mass Pod** | | | **39.93** | | **4.78** | **44.71** | |
| **Total wet mass PMT** | | | **40.17** | | **4.72** | **44.89** | |

Table 6 shows a breakdown of the proposed mass budget for the electric propulsion micropropulsion subsystem of the combined Occulter propulsion system. It also incorporates tanks and propellant for both the high and low thrust thrusters over the whole mission, i.e. 61m/s. The result shows the HCT option with a dry mass of 18.37kg, being 3.17kg lighter than the HT-100 option. This analysis assumes that apart from the thruster, the subsystem remains the same. This configuration will have the thrust axis along the longitudinal axis.

*Table 6. Electric propulsion mass budget.*

| UNITS | No. | Mass (kg) per unit | Total Mass (kg) | Margin (%) | Margin (kg) | Mass with margin | Notes |
|---|---|---|---|---|---|---|---|
| HT-100 thruster | 4 | 0.90 | 3.6 | 10% | 0.36 | 3.96 | 2x redundant |
| HCT (hollow cathode thruster) | 4 | 0.1 | 0.4 | 110% | 0.44 | 0.84 | 2x redundant |
| Multifunction valve | 2 | 0.40 | 0.8 | 20% | 0.16 | 0.96 | |
| High pressure transducer | 1 | 0.05 | 0.05 | 20% | 0.01 | 0.06 | |
| High pressure filter | 1 | 0.05 | 0.05 | 20% | 0.01 | 0.06 | |
| Fill & drain valve | 1 | 0.024 | 0.024 | 20% | 0.0048 | 0.0288 | |
| Tubing and fittings | 1 | 0.35 | 0.35 | 20% | 0.07 | 0.42 | 3.5m tubing |
| Cathode neutralizer assembly | 1 | 0.045 | 0.045 | 10% | 0.0045 | 0.0495 | Not in HCT version |
| PPCU | 2 | 1.5 | 3 | 20% | 0.6 | 3.6 | 2x redundant. Assumes same type can be used for either thruster |
| Harness | 1 | 0.25 | 0.25 | 20% | 0.05 | 0.3 | |
| Tank | 2 | 5.5 | 11 | 10% | 1.1 | 12.1 | For both propulsion systems |
| **Total dry mass HT-100** | | | **19.17** | | **2.37** | **21.54** | |
| **Total dry mass HCT** | | | **15.92** | | **2.44** | **18.37** | |
| Propellant | 1 | 42.1 | 42.1 | 20% | 8.42 | 50.52 | GXe for both propulsion systems (<<2 kg for EP) |
| **Total wet mass HT-100** | | | **61.27** | | **10.79** | **72.06** | |
| **Total wet mass HCT** | | | **58.02** | | **10.86** | **68.89** | |

### 6.1.10 Proposed Micropropulsion Subsystem Power Budget

In Table 7 one can see a breakdown of the proposed power budget for the cold gas micropropulsion subsystem of the combined Coronagraph propulsion system. It should be noted that the Pod power usage is per pod, i.e. per four thrusters.

*Table 7. Cold gas power budget.*

| Unit | No. | On | Nominal power/unit (W) | Nominal power (W) | Contingency margin % | Normal Power/Unit (W) |
|---|---|---|---|---|---|---|
| NanoSpace Pod | 4 | 2 | 4 | 8 | 10% | 8.8 |
| Bradford PMT | 4 | 1 | 4.5 | 4.5 | 10% | 4.95 |
| RTU | 1 | 1 | 8.8 | 8.8 | 10% | 9.68 |
| Heater | 4 | 2 | 1 | 2 | 10% | 2.2 |
| **Total Pod** | | | | | | **20.68** |
| **Total PMT** | | | | | | **16.83** |

Table 8 shows the power budget for the electric propulsion subsystem of the Occulter propulsion system. It assumes a similar PPCU and heater can be used for either thruster.

*Table 8. EP power budget.*

| Unit | No. | On | Nominal power/unit (W) | Nominal power (W) | Contingency margin % | Normal Power/Unit (W) |
|---|---|---|---|---|---|---|
| HT-100 | 2 | 1 | 50 | 50 | 10% | 55 |
| HCT | 2 | 1 | 30 | 30 | 10% | 33 |
| PPCU | 2 | 1 | 5 | 5 | 10% | 5.5 |
| Heater | 2 | 1 | 1 | 1 | 10% | 1.1 |
| **Total HT-100** | | | | | | **61.6** |
| **Total HCT** | | | | | | **39.6** |

## 6.1.11 Additional Thruster Data

Following is a detailed presentation of three of the interesting cold gas alternatives: Marotta SV14 /RD 19/, the Bradford PMT /RD 20/, and the NanoSpace MEMS thruster module /RD 21/.

### 6.1.11.1 Marotta SV14

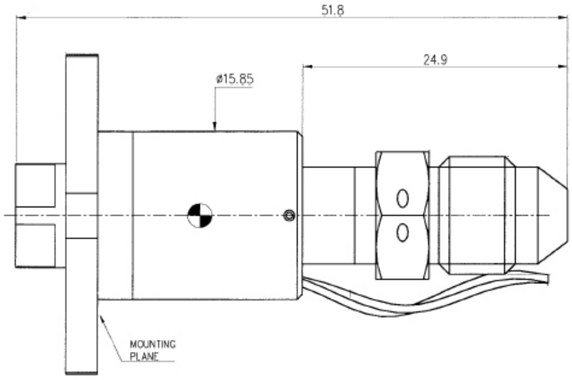
#### 6.1.11.1.1 Performance

The SV14 has a nominal vacuum thrust of either 10 or 40 mN ±5% at an operating pressure at 1.5 bar inlet pressure. With the use of an electronic pressure regulator the inlet pressure can be varied, thus proportionally varying the thrust level. However, using pulsed operations the thrust level can be lowered. With a maximum thrust of 40 mN the SV14 has a mass efficiency of 0.53 mN/g. The nominal specific impulse depends on the selected propellant, however for nitrogen it is typically 70 s.

The power requirement varies from <0.7 W to <3.5 W, depending on the operating state.

### 6.1.11.1.2 Accommodation Constraints

The SV14 mass is on the order of 75g, thereby imposing a minimal mass increases per thruster. The maximum length is 51.8mm with a main body diameter of 15.85mm. The thrusters shall be accommodated on the spacecraft such that each thruster has essentially “free sight” along the thrust axis.




### 6.1.11.1.3 Development Plan and Current Status

The SV14 Cold Gas thruster was designed and qualified for the CryoSat mission and with the use of gaseous nitrogen as a propellant, but they have also be qualified for xenon.

Due to the failure of the CryoSat launch, the TRL of the SV14 is still at 8, but it should be considered as a mature technology. The thruster has a design life of 2000000 cycles.

### 6.1.11.1.4 Ground Test Facilities

The Marotta Assembly and Test Department is responsible for total assembly and in-process testing of components and systems.

Special hardware assembled at Marotta occurs in the 1,000 square foot class 10,000 Clean Room. This Clean Room is monitored and controlled in accordance with FED-STD 209.

The majority of components/systems produced by Marotta are "active control products" requiring 100 percent final acceptance testing. To achieve that requirement, Marotta maintains a complete on-site high performance test capability including:

- Pneumatic up to 15,000 psig, and up to 20,000 SCFM @ 6,000 psig
- Hydraulic up to 10,000 psig, and up to 250 GPM @ 3,000 psig
- Hydrostatic up to 40,000 psig
- Vacuum down to 1 x 10-2 TORR
- Environmental - vibration, contamination, thermal, shock, explosion, humidity, sub-sea, salt spray, life cycle & more

### 6.1.11.1.5 Compatibility with PROBA 3

To reduce complexity, the propulsion system will use the same propellant tank for the high and low thrust thrusters and as such the thrusters must be compatible with the propellant. Being able to operate with either $N_2$ or Xe, the SV14 would be suitable as it could operate with other low thrust cold gas systems using $N_2$ or it could use Xe in combination with an electric propulsion system.

The thrust range is within that which is required by the solar coronagraph and basic formation flying needs.

At <75g each, a redundant system of 8x2 thrusters would have a total thruster mass of ~1.2kg.

## 6.1.11.1.6 Data Sheet

# Cold Gas Thruster Valve

Model No. SV14

MAROTTA
MAROTTA U.K., Ltd.

[ www.marotta.co.uk www.marotta.com ]

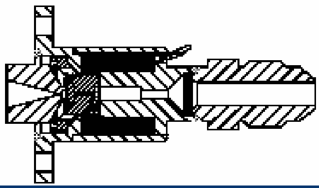
Based on a well-established range of high performance solenoid valves used in high-pressure fluid control applications, the SV14 Cold Gas Thruster uses a flat faced seal to reduce the risk associated with valve internal leakage due to a high cycle life. Variations in thrust level are achieved by use of different sized thruster nozzles.

This valve is a single coil solenoid operated thruster valve comprising of a fixed pole and a suspended moving pole/armature, to which is attached the sealing feature (poppet) of the valve. With increasing supply pressure, the stress on the seal will be increased, but the valve is designed such compression of the seal will be limited by a mechanical stop on the moving pole.

The valves are opened by energising the coil, the resulting force generated by the induced magnetic flux, causes the armature to move towards the 'fixed pole' so retracting the poppet from its seat. The valve is closed by de-energising the coil, collapsing the magnetic field. The armature moves the poppet to the closed position under the influence of the helical spring and remains closed under the combined influence of the spring and forces of the working fluid.

### Performance Characteristics

| | | |
|---|---|---|
| Operational Temperature | -35°C to +65°C | |
| Operating Pressure | 2.5 bar | |
| Vacuum Thrust | 10 mN (± 5%) to 40 mN (± 5%) | |
| Coil Resistance | 105 - 115 Ω @ 20°C | |
| Power Consumption | < 3.5 W (Pull-in) | < 0.7 W (Holding) |
| Response Time | < 4.0 ms (Opening & Closing) | |
| Mass | < 75 g | |
| Maximum O/D | 15.85 mm | |
| Cycle Life | 2,000,000 | |
| External Leakage | 1 x 10-6 scc/sec GHe max. @ 1.5 bar | |
| Internal Leakage | 2.7 x 10-4 scc/sec GHe max. @ 1.5 bar | |
| Construction | Body & Magnetic Components | Stainless Steel 304L/Radiometal 4550 |
| | Seal | Silicone Rubber |
| Mechanical Interface | Inlet | 7/16-20 UNJF-3A 37° STD Flare - Male |
| | Mounting | 4 off M3 holes on 23 mm PCD |
| Maximum Length | 52 mm | |
| Operating Fluid | GN2, Xe | |



**PRODUCT HISTORY**

The SV14 Cold Gas Thrusters have been designed for use gaseous Nitrogen and qualified for the CryoSat Earth Explorer Satellite. The SV14-001 has a thrust level of 40 mN and the SV14-002 is rated at 10 mN. The SV14 has also been used as an in-line valve for the qualification of the ROS 2000 Xenon Flow Control Unit.

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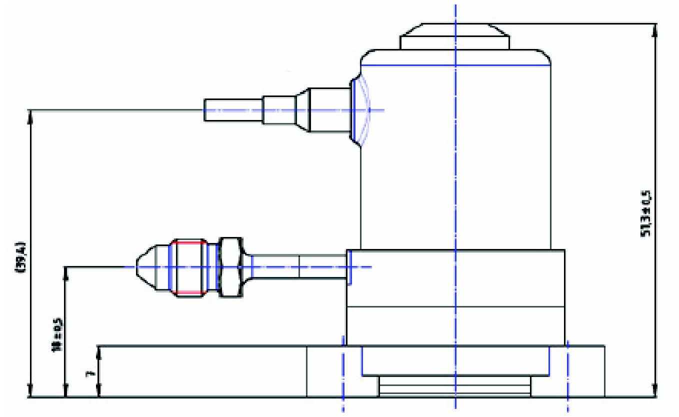
*Figure 4. Marotta SV14 cold gas thruster data sheet.*

### 6.1.11.2 Bradford PMT

#### 6.1.11.2.1 Performance

The PMT thrust range of 0-2 mN with a step increment of <1 µN makes it a good option for the advanced formation flying needs. With a maximum thrust of 2 mN, the mass efficiency will be 0.0114 mN/g. The power requirement is <4.5 W.



The specific impulse varies with the thrust from ~65 s at <50 µN to ~76 s above 300 µN.

#### 6.1.11.2.2 Accommodation Constraints

The PMT mass is on the order of <175 g, thereby imposing a low mass increases per thruster, or 2.8 kg for 2x8 redundant thrusters. The dimensions of the thruster are approximately 51.3 mm x 41 mm.

#### 6.1.11.2.3 Development Plan and Current Status

The PMT cold gas thruster was developed for the GAIA programme and as such could be considered to have a TRL of 5/6 but could be increased for the use in Proba3.

#### 6.1.11.2.4 Ground Test Facilities

Final assembly can take place inside a class 100,000 cleanroom, if required. A special section inside the cleanroom even provides for a class 10,000 for assembling extremely sensitive hardware. All the space products are cleaned and assembly inside the cleanroom. Packing the deliverables inside dedicated storage and transport containers ensures that the final customer receives the product in a perfect state at the required cleanliness

Verification tests and inspection activities are carried out at Bradford or at the location of selected subcontractors and test houses.

The following tests can be performed at Bradford:

- functionality tests (general operation, electrical check-out)
- mass properties test
- leakage test
- pressure test
- thermal vacuum cycling

- hydraulic performance
- life duration tests
- pressure and flow sensor calibration

For most environmental tests (mechanical vibration, electromagnetic compatibility tests) the facilities provided by subcontractors are used

### 6.1.11.2.5 Compatibility with PROBA 3

To reduce complexity, the low thrust propulsion system will use the same propellant tank as the high thrust thrusters and as such the thrusters must be compatible with the propellant. Being able to operate with $N_2$, He, dry air or Xe, the PMT would not put strict requirements on the choice of propellant.

The thrust range, with discreet steps of <1 μN, is within that required by the advanced formation flying needs.

## 6.1.11.2.6 Data Sheet

SPACE SYSTEMS &
COMPONENTS DIVISION

BRADFORD
engineering

### PROPORTIONAL MICRO THRUSTER

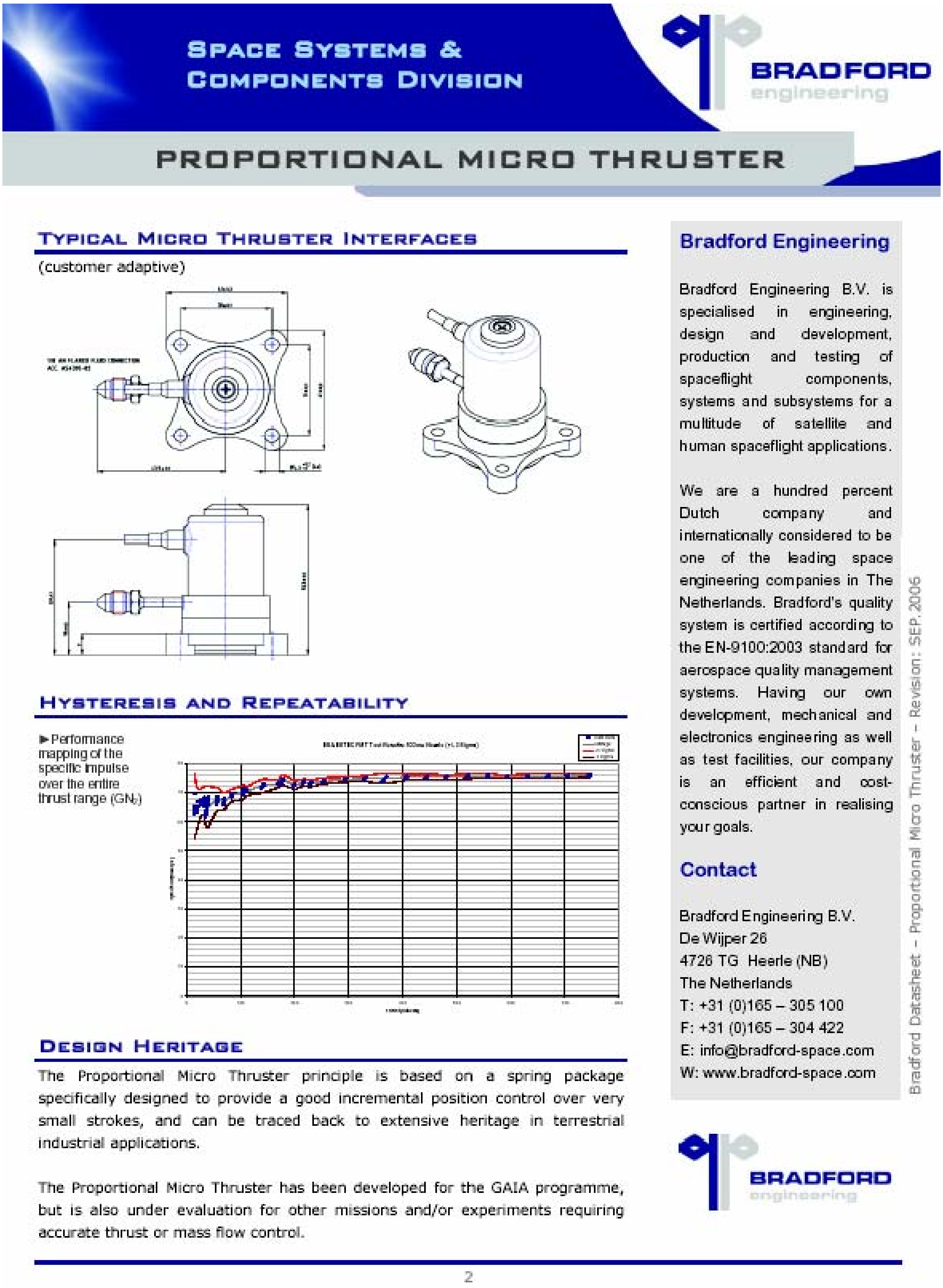
The Bradford Engineering Proportional Micro Thruster (PMT) is a solenoid operated flow control valve for use in cold gas propulsion systems and is specifically optimised to provide proportional control in the thrust range from <1 µN to 2000 µN.

The Proportional Micro Thruster is equipped with an integrated fixed nozzle, which is tuned for the required performance, to deliver the thrust. The PMT can also be outfitted with an fluidic outlet interface, so it can be utilised as a proportional control valve.

The use of a solenoid as actuator allows for a simplified electrical interface (no need for complicated support or driver electronics) and control loop design. By using the Bradford Micro Flow Sensor (MFS), thrust increments of <1 µN have been successfully demonstrated.

#### PERFORMANCE CHARACTERISTICS

| | |
|---|---|
| Medium compatibility | GHe, $GN_2$, GXe, Dry Air |
| Operating pressure range | 0 ... 2.5 barA |
| Mass flow range | 0 ... 2.5 mg/s $GN_2$ (full scale adaptable to customer requirement) |
| Minimum mass flow rate increment | 0.00025 mg/s $GN_2$ (at 1 barA inlet pressure, 12-bit control resolution) |
| Thrust range | 0 ... 2000 µN (depending on required full scale range) |
| Specific Impulse | > 60 s ($GN_2$, over entire thrust mass flow range) |
| Response time | < 13 msec |
| Minimum thrust increment | < 1 µN |
| Proof pressure factor | 8 barA |
| Burst pressure | Up to 16 barA |
| External leakage | < $10^{-6}$ scc/s GHe |
| Internal leakage | < $10^{-5}$ scc/s GHe |
| Power supply voltage | 12 ... 28 Vdc |
| Power consumption | < 4.5 W |
| Mass | < 175 g (Proportional Micro Thruster)<br>< 225 g (Proportional Control Valve) |
| Fluidic interface | Weldable 1/8" tube stub or screwed AS4395 fitting |
| Structural interface | 4 bolts, M3 ... M5 |
| Wetted materials | AISI 316L, VITON |
| Environmental temperature range | -45 ... +70 °C non-operating<br>-30 ... +60 °C operating |
| EMC requirements | According MIL-STD-461E |



SPACE SYSTEMS & COMPONENTS DIVISION

BRADFORD engineering

PROPORTIONAL MICRO THRUSTER

TYPICAL MICRO THRUSTER INTERFACES

(customer adaptive)

HYSTERESIS AND REPEATABILITY

► Performance mapping of the specific impulse over the entire thrust range ($GN_2$)

DESIGN HERITAGE

The Proportional Micro Thruster principle is based on a spring package specifically designed to provide a good incremental position control over very small strokes, and can be traced back to extensive heritage in terrestrial industrial applications.

The Proportional Micro Thruster has been developed for the GAIA programme, but is also under evaluation for other missions and/or experiments requiring accurate thrust or mass flow control.

Bradford Engineering

Bradford Engineering B.V. is specialised in engineering, design and development, production and testing of spaceflight components, systems and subsystems for a multitude of satellite and human spaceflight applications.

We are a hundred percent Dutch company and internationally considered to be one of the leading space engineering companies in The Netherlands. Bradford's quality system is certified according to the EN-9100:2003 standard for aerospace quality management systems. Having our own development, mechanical and electronics engineering as well as test facilities, our company is an efficient and cost-conscious partner in realising your goals.

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BRADFORD engineering

Bradford Datasheet – Proportional Micro Thruster – Revision: SEP. 2006

2

*Figure 5. Bradford PMT cold gas thruster data sheet.*

### 6.1.11.3 NanoSpace MEMS Thruster Module

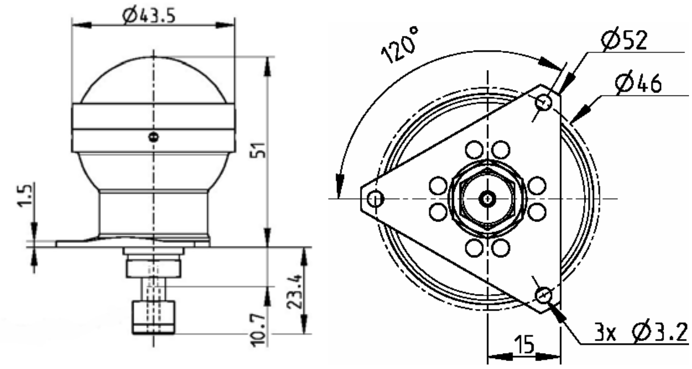
#### 6.1.11.3.1 Performance

The NanoSpace MEMS thrusters have a vacuum thrust range of 10 μN -1 mN at an operating pressure of 4.0 bar. Notably, each thruster module has four identical in-plane orthogonal thrusters in the equatorial plane of the thruster module assembly.

Each individual thruster has redundant internal heaters to improve the specific impulse. Heating of Nitrogen up to 900 deg. C is possible and thus enhancing the specific impulse up to 100 sec. Maximum power consumption for gas heating is 2 watts per thrusters.

Thrusters can also be operated without heating and in that case with a minimum specific impulse of 50 sec over the thrust range.

#### 6.1.11.3.2 Accommodation Constraints




The NanoSpace MEMS thruster module is a golf-ball sized sphere with a maximum diameter of 44 mm and a maximum height from the mounting plane of 51 mm. The propellant feed line and the electrical leads are through centre of the thruster module "foot".

The mass of the thruster module assembly is 115g. Four thruster modules (i.e. in total 16 thrusters) will provide redundant attitude control around three axis as wells as translation control in all directions. The thruster modules shall be accommodated on the spacecraft such that each thruster has essentially "free sight" along the thrust axis. The thruster module's mounting interface shall be in thermal contact with the support structure which shall be within -30 to +40 deg C.

#### 6.1.11.3.3 Development Plan and Current Status

The NanoSpace MEMS thrusters module is currently under development for the PRISMA programme. PRISMA CDR are in January 2007 and delivery of the NanoSpace micropropulsion system shall be during the second half of 2007. Launch is scheduled to 2009.

Current maturity of the MEMS thruster technology is TRL-5 which is based upon experimental verification of MEMS thrusters which has an accumulated test heritage of about 100 hours and 5000 thermal cycles.

Based on the current status and heritage from the PRISMA programme, a detailed development plan of the MEMS-based micropropulsion system towards a flight on Proba-3 in 2011 is provided in a separate document as part of the current study.

#### 6.1.11.3.4 Ground Test Facilities

NanoSpace, as part of the Swedish Space Corporation Group, has access to the premises in Solna which includes:

- 800 $m^2$ of electronic laboratories for design, manufacturing and test for the development work. Two 100 $m^2$ clean room, class 100 000, is available with 2*20 $m^2$ 10 000 class clean areas inside.
- Integration rooms with handling equipment, including He detectors for leakage testing, etc.
- Mechanical workshop with NC milling, turning, drilling, grinding and welding machines.
- An electron-beam welding line and X-ray facilities to handle the complete and space qualified welding of propellant storage and feed systems in stainless steel and titanium. Equipment and personel are SSC in-house.
- Environmental test facilities such table for shock testing, tanks for thermal vacuum and thermal cycling.

In addition to the SSC facilities in Solna, NanoSpace have access to the Ångström clean room facility which has a total area of 2 000 $m^2$ including over 30 lab rooms with service corridors.

- The major part of the clean room is class 10 000, but 150 $m^2$ is constructed as a class 100 clean room with unidirectional airflow from the ceiling to the floor.
- It is possible to create smaller areas with an even higher degree of cleanliness such as class 10 or class 1.
- The temperature is stable within ±1 deg C. The relative humidity is held constant at 43±3 % in one third of the clean room. The vibration-free foundation is classed as BBN-E.
- In this facility, all manufacturing, test and analysis of the MEMS components in NanoSpace propulsion system is carried out.

Facilities for vibration testing is available at various locations in Sweden and NanoSpace partner in Norway provide access to high pressure (1100 bars) proof and burst tests.

### 6.1.11.3.5 Compatibility with PROBA 3

The NanoSpace MEMS thrusters module covers the low thrust regime of the Proba-3 needed to perform advanced formation flying and precision manoeuvring. The lower end thrust level, i.e. down to 10 µN, is strictly not required to carry out the Proba-3 mission (as currently planned) but will still add value to mission as a technology demonstration for following and more demanding mission such as Xeus, Darwin, and Simbol-X.

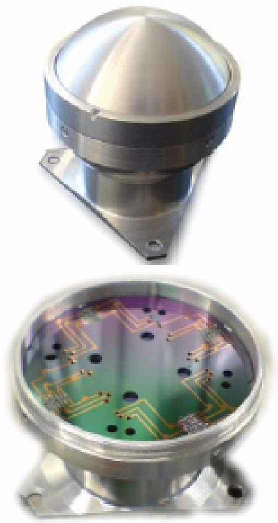
The MEMS thruster module can share a common storage and feed system with the Marotta SV14 thrusters which are needed to provide “high” thrust (20 – 40 mN) along track to perform some of the planned formation flying manoeuvres. Notably, the combination of the SV14 thrusters in the direction needed and the MEMS 4 MEMS thrusters modules to provide redundant control around and along all axis, are by far the most mass efficient solution. 4 MEMS thruster modules provide 16 thrusters with an added mass of 230 g. For comparison16 of the Bradford PMT thrusters adds 2800 grams of mass.

## 6.1.11.3.6 Data Sheet

# MEMS Thruster Module

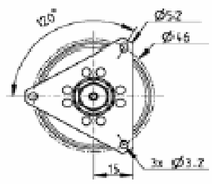
### Product Description

The NanoSpace MEMS Thruster Module contains four individual thrusters capable of delivering proportional thrust in the micro- to milli-Newton range. Each individual thruster has a proportional flow control valve, a filter and internal gas heater inside the chamber to improve the specific impulse. All four thrusters integrated in the same silicon chip which is located in the equatorial plane of the thruster pod assembly. The direction of thrust is in-plane with 90° between each thruster. The thruster pod interfaces a conventional gas storage and feed system with a screwed fitting or a weldable stud to the feed system tubing. Electrically, the thruster pod assembly interface is flying leads. NanoSpace does also provide the complete control electronics which can interface the spacecraft power bus (28 or 50VDC) and databus (CAN or 1553).



| Performance characteristics | | |
|---|---|---|
| Thrust range | 10 µN - 1 mN | Each thruster |
| Specific Impulse | 50 - 100 sec | > 50 with heated $N_2$ |
| Power consumption | 1 Watt per thruster | Nominal |
| | 2 Watt per thruster | Maximum, with heating |
| Operating pressure | 4 bar | Nominal |
| MEOP | 6 bar | |
| Proof/Burst | 9/12 bar | |
| Temperatures | 0 to 50°C | Operating |
| | -10 to 60°C | Non-operating |
| Mass | 115 g | 4 thruster pod assembly |
| Dimension | 44 mm diameter | 4 thruster pod assembly |
| | 51 mm height | |
| External leakage | $1x10^{-6}$ scc/sec | Maximum, GHe @ MEOP |
| Internal leakage | $1x10^{-4}$ scc/sec | Maximum, GHe @ MEOP |

| Interfaces | |
|---|---|
| Structural mounting | 3 bolts, M3 |
| Propellant feed | 1/8 inch weldable stud |
| Electrical | Flying leads |
| Fluid compatibility | N2, He, Xe, Water, IPA |



*Footprint of thruster pod*

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NanoSpace
Swedish Space Corporation Group

*Figure 6. NanoSpace MEMS Thruster Module data sheet.*

## 6.1.12 Reliability Discussion

### 6.1.12.1 Expected Reliability Issues

Reliability is understood as the probability that an item will perform its required task during a given period in time. Reliability is ultimately a measure of the rate at which things fail and can be used to make intelligent predictions about the performance of a system.

The procedure of qualifying a production line (or rather a manufacturing sequence) is called process qualification. Product qualification is the process by which a manufacturer proves that a given device or product meets the requirements, i.e. performs its specific tasks required by the end user.

Reliability and qualification are the crucial issues that are holding back MEMS from playing a larger role in space applications in comparison to the “explosion” of MEMS in terrestrial applications. One reason is the space specific and harsh environment, which needs to be taken into account already during the design phase of MEMS for space applications. Another important difference is that the manufacturing of MEMS differs a lot from conventional fabrication, and hence the standard methodology to achieve space qualified products can not be used. Therefore there is a need for a modified methodology applicable to MEMS for space.

In space applications the reliability assurance is very important. However, there are no standards for MEMS reliability established at the moment. An important challenge is not only to qualify the device itself, but also to examine the entire process surrounding the part, from conception to finish, including the, for MEMS, critical packaging step. This implies the logic of process qualification, followed by product qualification, and last product acceptance.

It is in the nature of MEMS that the procedure is not from structure via component to system as the case is in conventional manufacturing. In MEMS the system is finalized in the last manufacturing step since it is governed by compatibility issues and has to be processed in this order. This implies a new technical approach to achieve reliability, where process qualification becomes more critical than usual and where most of the effort has to be put.

MEMS devices requires a high level of fabrication knowledge in order to create a successful design, but MEMS reliablitiy issues need to be separated from the complexities of the process sequence.

It is difficult, and often impossible, to directly test and verify the functionality of a MEMS component. The level of integration reduces the possibilities of direct measurements. The full functionality is only complete when several wafers are bonded together. This implies that almost all component characterization only can be performed on an assembled system.

A general approach in the selected methodology is therefore to focus on product performance in terms of performance validation, environmental test, and accelerated lifetime tests on the completed microsystem.

As stated above the process qualification is essential for manufacturing of high reliability products. Process qualification is intended to qualify a defined fabrication procedure and product family. However, it must be understood that MEMS technology is still constantly evolving and the phrase “freezing of production process” does not apply in MEMS. The in-line process control suggested consists of different kinds of process control monitoring.

### 6.1.12.2 Failure Mechanisms

To understand the reliability one must understand the failure mechanisms. Since it is sometimes hard to distinguish failure mechanism from failure mode in existing MEMS reliability literature, a distinction between the two concepts is needed. Here, failure mechanism refers to the cause of failure and failure mode to the failure event observed.

In microelectronics the failure mechanisms are more known than they are in MEMS and probably most often caused by device operation. Hence, the failure can be accelerated through standardized life testing. In MEMS the failures are most probably caused by environmentally induced factors such as vibration, shock, temperature cycling, and radiation.

In MEMS there are several expected primary failure mechanisms some of the most severe are listed below.

##### 6.1.12.2.1 Mechanical Fracture

Since most of the MEMS devices are manufactured in monocrystalline silicon, which is a brittle material, a mechanical fracture will lead to a catastrophic failure of the component. In devices manufactured using some kind of bonding, delamination is another kind of severe failure mechanism. This mechanism can for example be identified by the failure mode “leakage” in a fluidic microsystem. The mechanical properties of silicon indicate that fatigue will be a smaller problem, however.

##### 6.1.12.2.2 Stiction

The phenomenon stiction does not occur in the macroscopic world, in the microworld, however, it is an severe obstacle.

##### 6.1.12.2.3 Wear

If the microsystem includes the motion of one surface over another, wear will also be a possible failure mechanism. Since lubricants are almost out of the question, the abrasive wear is the dominant effect. Corrosive wear might also be a failure mechanism in a propulsion system using an aggressive propellant.

##### 6.1.12.2.4 Particle Contamination

The contamination risk and subsequent failure due to sticking of very small particles that prevent flow or cause leakage is a possible failure mechanism. Especially in fluidic applications where the classification of gases do not include particle size less than 0.5 μm in size.

### 6.1.13 Technology Assessment Conclusion

#### 6.1.13.1 Selection of Base Line Mission

Since the current project is aiming for a methodology for complex micropropulsion systems space validation, the first ESA formation flying mission, i.e. Proba-3, is an obvious choice for a model mission. Except for the good timing the requirements and the objectives of the mission suits the micropropulsion developed at NanoSpace. Proba-3 will be a test bench for new technologies necessary for future missions.

#### 6.1.13.2 Trade-Off Conclusion

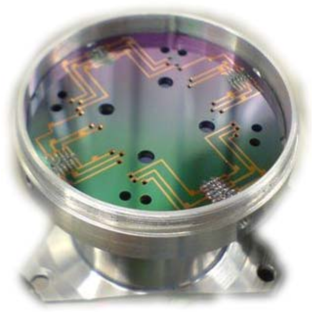
The first selection criterion for Proba-3 is power, which basically disqualifies a number of electric propulsion alternatives. The TRL levels are in general much higher for chemical propulsion systems than EP options and with the Prisma heritage NanoSpace micropropulsion systems will be the strongest option for the advanced formation flying experiment.

Among the chemical propulsion options the cold gas alternative it the most contamination free system, which is attractive in an “optical” mission as Proba-3. Propellant heritage does favour nitrogen, but xenon and nitrious oxide looks interesting.

The NanoSpace MEMS thrusters module covers the low thrust regime of the Proba-3 needed to perform advanced formation flying and precision manoeuvring and might even cover the high thrust levels as well if the requirements will be in the order of 10mN (as currently planned). The lower end thrust level, i.e. down to 10 µN, is strictly not required to carry out the Proba-3 mission, but will still add value to mission as a technology demonstration for following and more demanding mission such as Xeus, Darwin, and Simbol-X.

The most promising concept by all means to save mass by miniaturisation is to miniaturise using MEMS. The NanoSpace cold gas system is full of MEMS components.

## 6.2 Documentation of Micropropulsion System

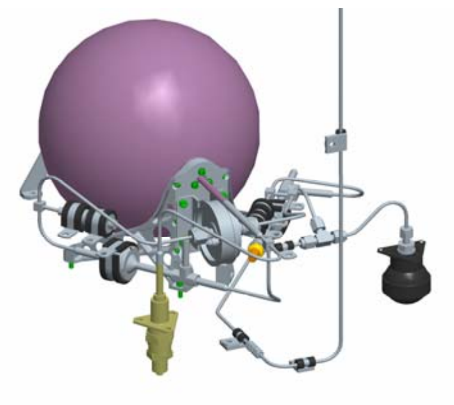


NanoSpace has recently concluded and reported the ESTEC contract: Micro Propulsion Cold Gas Thrusters Phase 3 & 4 /RD 1/. The project started in December 2004 and the final presentation was held at ESTEC the 6th of February 2007.

The overall activity objective was to develop a high precision micropropulsion cold gas thruster based on MEMS technology. The aim in phase 3 and 4 was to develop a self-contained thruster module with four MEMS thrusters in a common housing. The thruster module should undergo a design verification testing and pass a design review. It was, however, not the purpose of this work to perform a formal qualification of the module. The goal was rather to demonstrate the potential capability of a highly integrated MEMS-based microsystem and to bring the technology up to a readiness level where a more formal space qualification or flight validation could follow.

A number of MEMS-based microthrusters were successfully manufactured in different designs and two generations. The last generation was very complex and incorporated a fusion bonded six wafer stack. The microthrusters were evaluated and tested both in atmosphere and in vacuum. Cycling and fire tests were performed both on component and system level. Verification of thrust levels up to several millinewton was made in a thrust balance set-up. Specific impulse measurements in cold gas mode yielded between 50-60 seconds, and more than 20% improvement in hot gas mode by the use of internal gas heaters. Proportional valve behaviour for the gas regulation was also proven. More specific information about the developed micropropulsion system can be found in a separate supporting document included with the proposal.

NanoSpace also performed a Prisma phase B work on a contract from Swedish National Space Board (SNSB) between September 2005 and March 2006. This work included the manufacturing and the testing of a first breadboard (BB) micropropulsion system for Prisma. The phase B work also established the requirements and interfaces to the spacecraft platform.



Following a successful phase B, the C/D phase was started in April 2006 and passed a Critical Design Review (CDR) in February 2007. The phase C work raised the maturity level to the development and testing of an Engineering Model (EM), while the ongoing phase D work is directed towards manufacturing a Proto Flight Model (PFM) of the Prisma micropropulsion system.

Notably, the micropropulsion system onboard Prisma is an experimental payload – and hence not mission critical – which justifies the flight without having undergone a formal on-ground qualification which is the ultimate goal that the proposed space validation work shall lead to.

The MEMS Thruster Module developed under the above mentioned contracts is subject for this methodology work and hence a thorough documentation of the system is needed as platform for the future validation work. The documentation includes configuration documents, specification documents, and MEMS specific documents.

### 6.2.1 Micropropulsion System Description

The micropropulsion system is schematically shown in Figure 7. It consists of the following major components/subassemblies:

- One high pressure propellant tank
- One one-shot isolation valve
- One propellant fill/vent valve
- One system filter
- Two pressure transducers
- One high pressure regulator
- Two thrusters pod subassemblies
- One pressure relief valve

The micropropulsion system also includes tubing to connect all components, mounting structures, heaters, thermostats, and electric wiring required for conducting power and signals to the components. All electrical interfaces are to the micropropulsion remote terminal unit (MPRTU), including heaters and telemetry to the spacecraft. Gaseous $N_2$ is used as propellant.

The MEMS Isolation Valve, the Pressure Relief Valve, the MEMS Thruster Modules that are accommodated in the thruster pods, and the pressure transducers are all MEMS components. The former three are manufactured by NanoSpace and are thus included in both product and process documents described below.

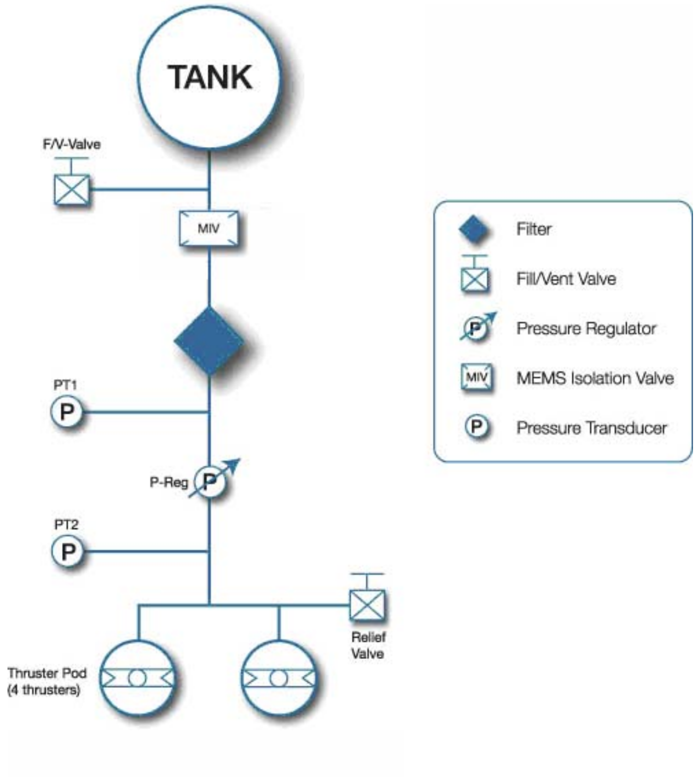



*Figure 7. Schematic system layout of the micropropulsion system.*

### 6.2.2 Micropropulsion System Documentation

Since the micropropulsion system consists of both conventional components and MEMS components, there are both standard ESA CDR/PDR documents and a set of new MEMS specific documents included in the document list. The documents are dynamic and change as the work proceeds; the versions presented in this report are mainly on CDR level. Since the micropropulsion system is developed for, and will be flight tested on, Prisma, many documents are based on Prisma as baseline mission.

There are all in all 24 documents included in the document list. They are divided into three categories; MEMS manufacturing process documents, configuration control documents, and other documents. They consist of both standard documents and a set of new MEMS specific documents that describe the MEMS components and how they are manufactured. The documents are further described in paragraphs 6.2.3-6.2.5 below.

Paragraph 6.2.6 list the documents included in the documentation. Eleven of them are appended to this report, the rest are available for review at NanoSpace premises.

### 6.2.3 MEMS Manufacturing Process Documents

To ensure manufacturing repeatability and a structured work approach, the MEMS manufacturing and documentation work logic follows instructions given in document NS5001. This work logic is schematically illustrated in Figure 8. The different MEMS manufacturing process documents are marked by yellow squares. The manufacturing process design is implemented in the PID using templates, standard processes from the Process Library, and materials defined in the Materials List. Specifications and print outs of the photolithographic masks are included in the PID. Each PID is given a unique batch number that is allocated from the Batch List. The PID must be approved at a design review meeting before manufacturing begins. A log of the manufacturing is implemented in the Log File. Document NS5001 also describes the documentation strategy as a component develops from a single wafer to a multi-wafer stack. A more detailed description of the contents of the different documents is given below.

- The Process Library is a list of standardised MEMS manufacturing processes. Each process is structured into sequential process steps that include detailed information such as machine number, machine parameters, controls, test steps, and inspection stages. New or improved processes are implemented into the library during process design review meetings.
- The Batch List is a list of consecutive wafer or component identification numbers. Batch numbers are allocated for each batch of single or bonded wafers and follow the wafers and the documents throughout the manufacturing process. The wafers are permanently marked with batch numbers in order to be easily identified during manufacturing.
- The Materials List is a detailed inventory list of the raw materials used in the MEMS manufacturing. The list includes material specifications such as wafer thickness and resistivity, metal form and purity; it also specifies the origin of the materials. The materials list is updated when materials are delivered and taken away from stock.
- The CAD Template contains CAD drawings of standard photolithographic mask design structures, such as alignment marks and PCM structures, positioned on their standard locations. It also contains help structures showing for example the area within which the alignment marks must be positioned to be visible in the mask aligner. The CAD template is updated at CAD design review meetings.
- The PID Template sketches out the structure of the PIDs and the Log Files. It is basically a set of empty tables with headings adapted to write down specifications of raw materials and photolithographic masks, the manufacturing process sequence, measurement data, non conformances, etc. The PID template also contains images and brief descriptions of the standard mask design structures. The PID Template is updated at design review meetings.
- The PID is mainly a detailed flow chart of the manufacturing process for a specific batch, put together from the standard processes included in the process library. Manufacturing target values and tolerances are specified for applicable process steps. The PID also contains a detailed list of raw materials and photolithographic masks, and print outs of the masks. The PID must be approved at a design review meeting before manufacturing begins.
- The Lot Traveller, also called Log File, consists of the PID plus a log of the different manufacturing process steps signed off with operator identification and processing date. Measurement data, non conformances, deviations from the process specified in the PID, etc, are logged for applicable process steps. The Log File helps in optimising the manufacturing process and backtracking discrepancies.

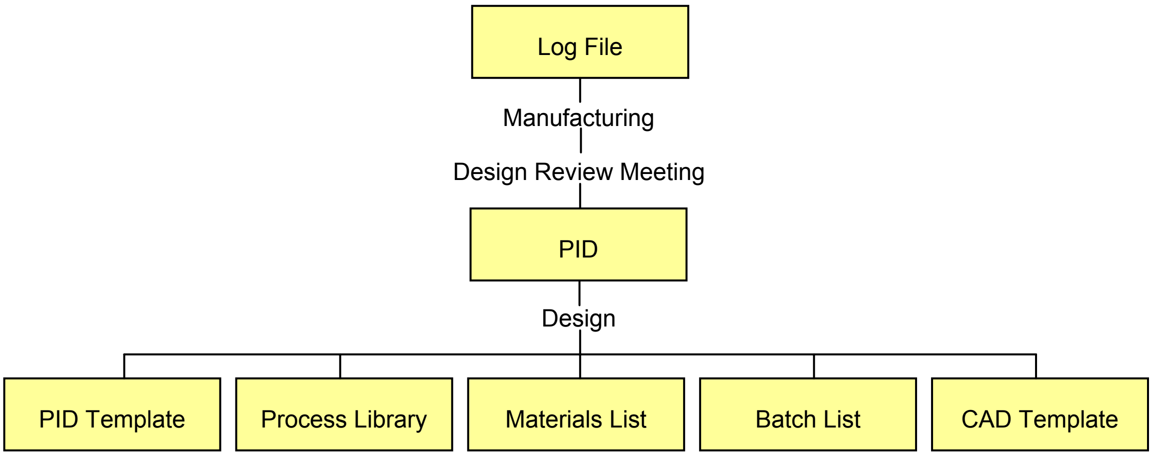



*Figure 8. Schematic illustration of the MEMS manufacturing and documentation work logic.*

### 6.2.4 Configuration Control Documents

The CIDL lists the documents necessary for the configuration control of the micropropulsion system. It also gives the current design status of the system. The documents included consist of both standard ESA CDR/PDR documents and a couple of new documents that describe the MEMS components in the micropropulsion system. Figure 9 schematically illustrates the documentation tree; the contents of the different documents are briefly described in the list below.

- The CIDL lists the steering documents necessary for the configuration control and gives the current design status of the micropropulsion subsystem. There are two CILDs included in the documentation, one for the micropropulsion subsystem and one for the micropropulsion subsystem RTU.
- The DDTP document overviews the development and the implementation of the micropropulsion subsystem on Prisma and ensures that the development logic is coherent with the Prisma programme.
- The micropropulsion system requirement specification establishes the governing set of requirements for the micropropulsion system on Prisma. It also overviews the implementation requirements. The micropropulsion system RTU and RTU FPGA requirement specifications, correspondingly lists the requirements applicable to the RTU and to the FPGA mounted on the RTU circuit board.
- The DVCM gives the compliance status of the micropropulsion system in relation to the requirement specification.
- The Drawing Package document lists the mechanical drawings that cover the micropropulsion subsystem. The list includes drawings of the MEMS components.
- The ICD defines the mechanical, electrical, and thermal interfaces for the micropropulsion subsystem.
- The MEMS Definition Sheet defines the MEMS components of the Prisma micropropulsion subsystem. It briefly describes the function of the components and their physical location in the subsystem, how the functions are implemented into silicon structures, and how the structures are manufactured and assembled into components.
- The MEMS PID describes the manufacturing procedure of the MEMS components. A more detailed description of the PID is given above.

- The DVTP document constitutes test plans and test procedures aimed to verify the design of the MEMS components in the Prisma micropropulsion subsystem.
- The DVTR summarises the tests performed according to the DVTP for the Prisma Micropropulsion System.
- The FMECA establishes a set of failure modes and resulting failure effects, and an analysis to determine the severity of the failure effects.
- The Electronics Schematics is basically a set of electronic drawings of the MPRTU.

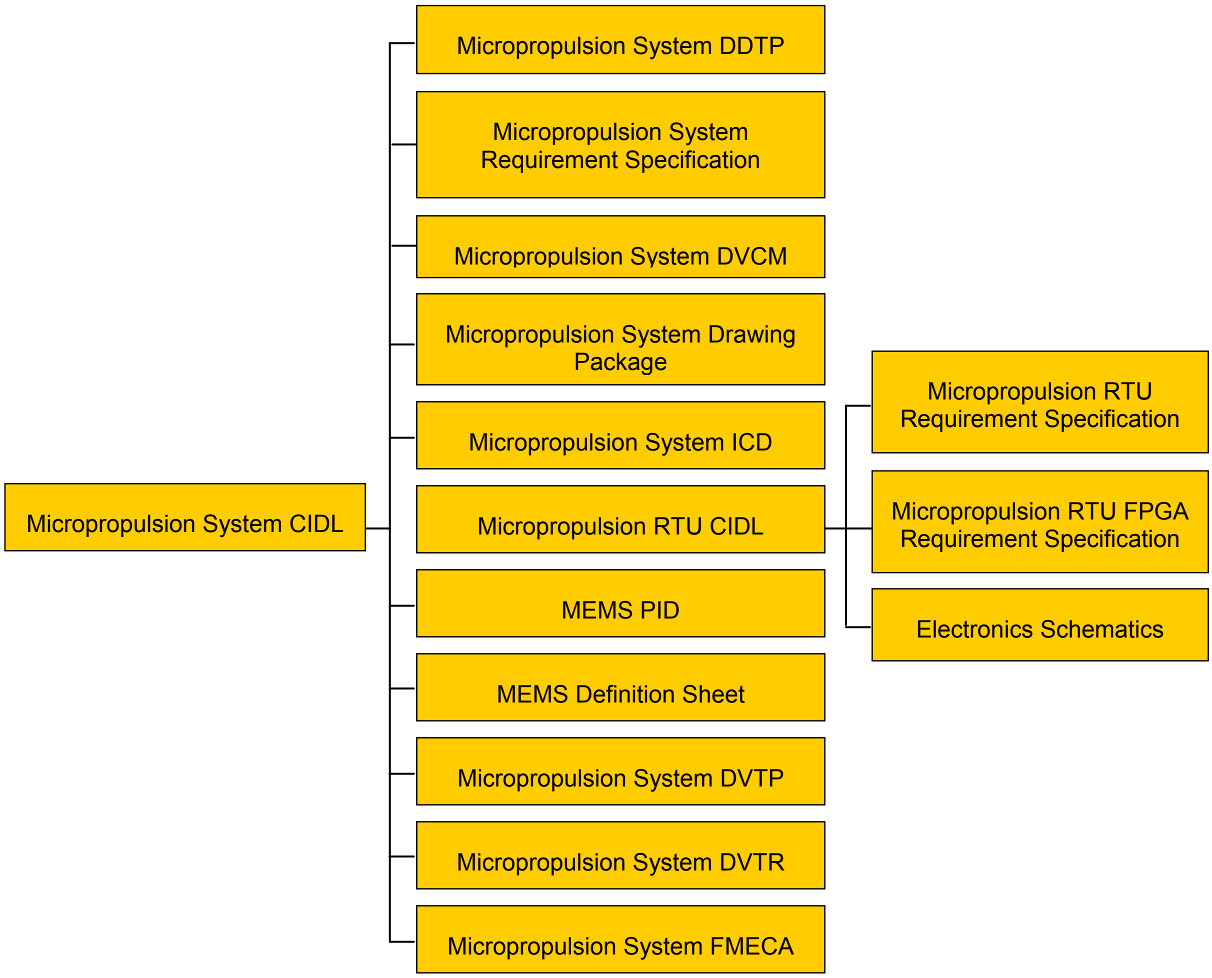



*Figure 9. Illustration of the documentation tree for the configuration control documents of the micropropulsion system.*

### 6.2.5 Other Documents

There are two documents that can not be sorted under the above headings included in the documentation. These are:

- The Product Assurance and Safety Plan for Micropropulsion on Prisma, which states the product-, quality-, and safety assurance activities that shall be performed within the micropropulsion project.
- The Justification File, which justifies the selection of designs and manufacturing procedures for the micropropulsion system, and explains what the selection is based on. The Justification File also contains information on rejected designs and manufacturing procedures, to avoid making the same mistake again.

## 6.2.6 Document List

The documents included in the documentation of the micropropulsion system are listed in Table 9. Eleven of these documents are appended to the technical note. Documents marked with * are available for review at NanoSpace premises.

*Table 9. Prisma micropropulsion system document list.*

| Doc. Number | Version | Document Title | Appendix |
|---|---|---|---|
| SPN0510-S128 | 2 | Prisma Micropropulsion System CIDL | 1 |
| SPN0500-S37 | 2 | Prisma MPRTU CIDL | 2 |
| SPN0500-S85 | 1A | Design Development and Test Plan for Micropropulsion on Prisma | 3 |
| SPN0500-S4 | 2 | Prisma Micropropulsion Subsystem Requirement Specification | 4 |
| SPN0500-S3 | 1B | Prisma Micropropulsion Subsystem Interface Control Document | 5 |
| SPN0500-S34 | 2 | Prisma Micropropulsion RTU Requirements Specification | 6 |
| SPN0500-S35 | 1B | Prisma MPRTU FPGA Specification | 7 |
| SPN0500-S36 | 2 | Electronics Schematics, BOM, and CAM Files | * |
| SPN0500-S96 | 2 | Drawing Package: Prisma Micropropulsion Subsystem | * |
| SPN0510-S184 | 1B | Design Verification Test Plan and Procedures for the Prisma Micropropulsion System | * |
| SPN0510-S185 | 1C | Design Verification Test Report for the Prisma Micropropulsion System | * |
| SPN0510-S186 | 1 | Design Verification and Compliance Matrix for the Prisma Micropropulsion System | 10 |
| SPN0510-S187 | 1 | Prisma Micropropulsion FMECA | 11 |
| SPN0100-S5 | 2 | Definition Sheet: MEMS Components in Prisma Micropropulsion System | * |
| SPN0100-S6 | 2 | Process Identification Documents | * |
| SPN0400-S52 | 2 | Process Library | * |
| SPN0400-S53 | 2 | PID Template | * |
| SPN1000-S6 | 1 | CAD Template | * |
| SPN1000-S5 | 2 | MEMS Manufacturing Materials List | * |
| SPN1000-S4 | 2 | MEMS Manufacturing Batch List | * |
| SPN0100-S7 | 2 | Process Log Files | * |
| NS5001 | 1B | NanoSpace MEMS Manufacturing Process | 9 |
| SPN0500-S86 | 2 | Justification File: Prisma Micropropulsion System | * |
| SPN0500-S1 | 1 | Product Assurance and Safety Plan for Micropropulsion on Prisma | 8 |

### 6.2.7 Documentation Conclusions

The documentation of the micropropulsion system includes both standard documents and a set of new MEMS specific documents. The main purpose of the work has, however, been to define the substance of the new MEMS specific documents and to define how they fall into place in the standard documentation lists.

The MEMS manufacturing process documents included in the documentation are sufficiently detailed to reproduce the manufacturing. However, in order to meet the requirements according to the Statement of Work some details, such as machine number, have been added to the PID template.

## 6.3 Process Qualification Methodology

Reliability and qualification are crucial issues that are holding back MEMS products from playing a larger role in space applications in comparison to the numerous MEMS products found in terrestrial applications. One reason is that the space specific harsh environment needs to be taken into account in designing MEMS products for space. Another reason is that there are no standard qualification methodologies established for MEMS products. The manufacturing differs a lot from conventional manufacturing so methodologies for MEMS will inevitably differ from methodologies for conventional products. The high level of integration makes it difficult to perform in-line functional measurements on MEMS components for example; the full functionality is only complete in the last manufacturing step when several wafers are bonded together. This requires that qualification methodologies for MEMS must rely on process qualification rather than product qualification. It would be too risky to postpone the qualification until the MEMS product is ready-made.

Product qualification deals with performance validation, environmental test, and life-time tests on ready-made products. Process qualification is the procedure of qualifying a production line. It deals with procedures that a manufacturer follows to demonstrate that the design and manufacturing of a product using specific processes is in control.

Statistical process control (SPC) is used for many terrestrial high-reliability MEMS products. These products are manufactured in millions which allows for more statistical studies to be performed in comparison to the more limited number of devices to be produced for space.

Statistics would be desirable for small volume production as well, although the six sigma methodology used by high volume manufacturers would require a number of test devices comparable to the number of real devices. Instead, the process control can rely on 100% inspection, accepting or rejecting the devices depending on how well they meet the specifications.

The purpose of the present work is to set up the preliminary steps towards a process qualification methodology for a novel MEMS micropropulsion system to be used in space applications. The development of quality analysis structures to monitor and control the in-line manufacturing of the micropropulsion system and an associated quality analysis methodology is described and validated below.

The document does not assess a general qualification methodology for MEMS products. The procedure of process qualification depends on the specifics of the manufacturing processes, the materials and the laboratory equipment used, and the structure and device designs, so it is difficult to set up general standards.

### 6.3.1 Quality Analysis Methodology

The quality analysis methodology is schematically illustrated in Figure 10. It addresses all aspects of production. The first step in the methodology is to determine the device to be manufactured and the technology that will be used. Hereafter, the detailed manufacturing procedure is defined and documented together with design and processing procedures. Workmanship and material tracking procedures are documented at the same time.

The next step is to define process control test structures and test methods to characterise the manufacturing procedure, the materials used to manufacture the device, and the device structures and components coming off the line. The test structures are manufactured in the same production run as the device wafers themselves. They can be real device structures or specially designed test structures included on the same wafers as the device, or even structures on separate wafers.

The tests are performed on wafer level and provide reliability and performance data at various stages in the manufacturing process. Testing should start as early as possible to sort out faulty samples early in the process and thus save costs. Components from different wafer lots are tested since the stability of the process is determined as a part of the process qualification. The qualification is successful if the procedures followed assure the quality, the uniformity, and reproducibility of the basic device structures manufactured with the fabrication procedure. It is important to understand that only the process and basic device structures are being qualified and that no reliability information is obtained for a particular MEMS device.

A manufacturing process only needs to be qualified once, although routine monitoring of the production line is standard. It must be recognized, however, that MEMS technology is evolving at an astounding rate, which requires continual updating of manufacturing procedures. Minor changes in the manufacturing process due to incoming materials variations or minor design modifications may also be required. These changes frequently occur and must be permitted. This implies, however, that it may be necessary to qualify a manufacturing process again.

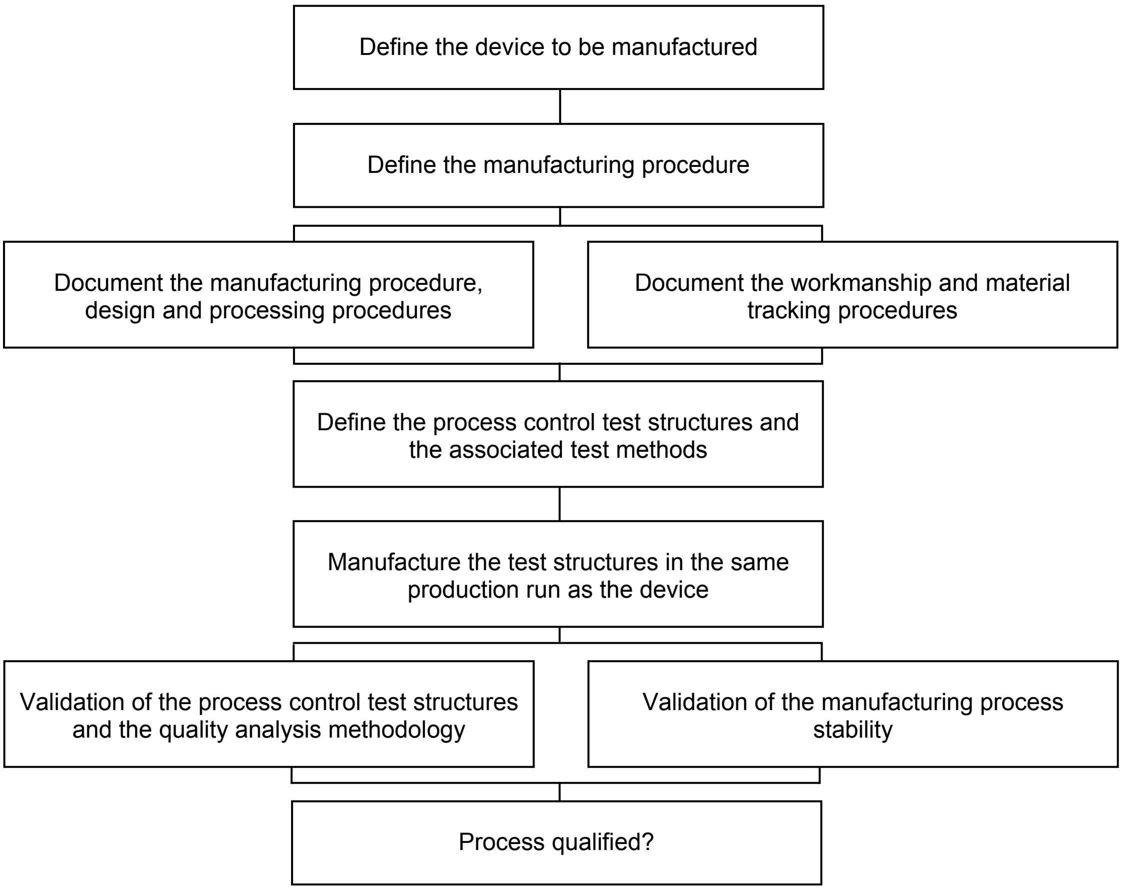



*Figure 10. Schematic illustration of the quality analysis methodology.*

## 6.3.1.1 Device Description

The intent with the quality analysis methodology is to qualify the manufacturing procedure and the basic device structures of both the MEMS thruster chip and two other MEMS components coming off the line.

The MEMS isolation valve (MIV) is a one shot valve working as a leak proof pressure isolation valve until the micropropulsion system is ready to be used. The MEMS pressure relief valve (PRV) acts as an isolation valve during normal operation and as a passive burst diaphragm or active one shot valve if pressure builds up in the system. The MEMS thruster chip has four orthogonal micro- to milli-Newton thrusters, each with a proportional paraffin actuated normally closed valve, and gas heaters to improve the specific impulse.

The three components are all manufactured and assembled from several bulk micromachined silicon wafers using mainly standard oxidation, metallization, lithography, etching, bonding, annealing, dicing, and cleaning procedures. Some of the manufacturing processes are developed and used specifically for the subject devices such as the mounting of ready-made MEMS resistors, the filling and sealing of internal paraffin cavities, and thin film soldering for mechanical fixation and electrical connection purposes.

## 6.3.1.2 Standard Workmanship

To ensure manufacturing reproducibility and a structured work approach, the MEMS manufacturing and documentation work logic follows a procedure given in a steering document. This work logic is schematically illustrated in Figure 11. The yellow squares represent the different documents that are used.

The manufacturing process is defined and implemented in a Process Identification Document (PID) using standard processes from the Process Library. Computer Aided Design (CAD) drawings of the photolithographic masks are made concurrently. Mask layout guidelines and standard process control structures are obtained from the CAD Template. Specifications and print outs of the photolithographic masks are included in the PID. Specifications of the raw materials that are needed are also implemented into the PID. Available raw materials are registered in the Materials List. The PID Template is used to organize the different blocks into a coordinated PID structure. Each PID is given a unique batch number that is allocated from a list of consecutive identification numbers, the Batch List.

The PID must be approved at a design review meeting before manufacturing begins. Hereafter, the contents is copied to a batch traveller or a Log File that follows the batch throughout the manufacturing. The Log File is basically the same as the PID but with a log to sign the different process steps off with date, comments, operator identification, etc.

The subject document also describes the documentation and batch numbering strategy as a component develops from a single wafer to a multi-wafer stack.

The CAD drawings and Development Reports with calculations supporting the design work is electronically stored in the documentation system.

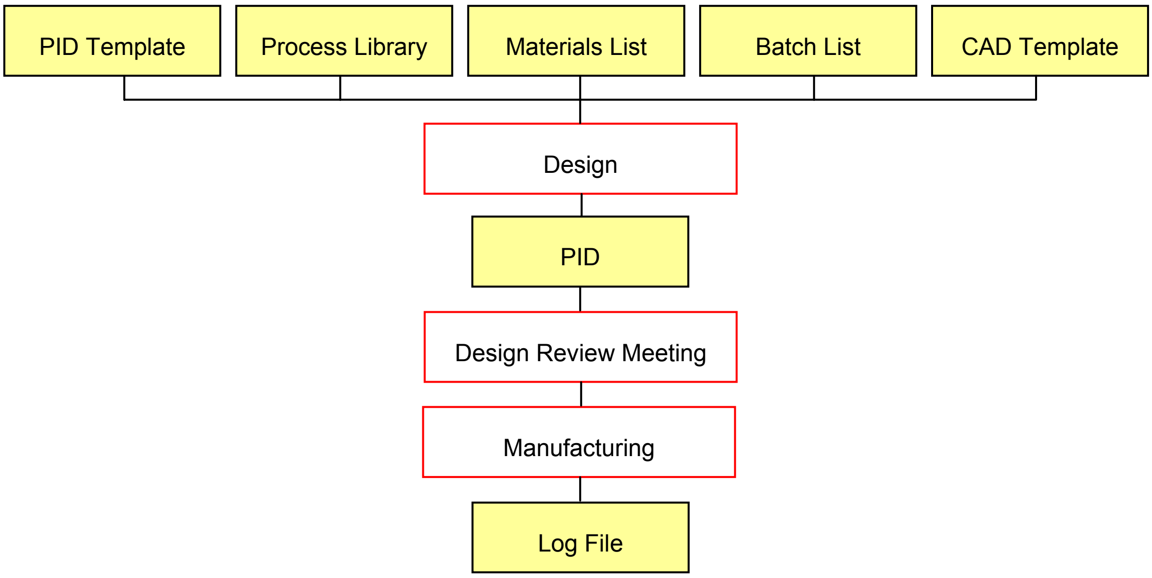



*Figure 11. Schematic illustration of the MEMS manufacturing and documentation work logic.*

## 6.3.1.3 Processing Procedures

The clean room equipment, the chemicals, and the gases used in the manufacturing are an integral part of the clean room and are controlled by the supplier. The Deep Reactive Ion Etch (DRIE) is proprietary to NanoSpace and is controlled by NanoSpace by scheduled service and maintenance work and by means of Process Control Monitoring (PCM) wafers.

The raw materials used in the manufacturing are controlled by the supplier. They are listed in a detailed inventory list. The list includes material specifications such as wafer thickness and resistivity, metal form and purity; it also specifies the origin of the materials. In cases where more accurate specifications are needed, e.g. more accurate wafers thickness measures, these are assessed by the MEMS manufacturer.

The photolithographic masks used in the manufacturing are controlled both by the supplier and the MEMS manufacturer.

The manufacturing processes are put together from standard process packages in the Process Library. A process package is detailed sequence of the different steps involved in performing a single process. Figure 12 shows a dry oxidation process package as an example. Details such as machine numbers and recipes are included in the process steps. Controls such as inspection and measurement steps are included in the sequence.

The standard processes are well-tried and tested to fulfil certain criteria. Any new developed process must be tested and approved at review meeting before it can be implemented into the library.

| ID | Module | Process Step | Process Side | Specification | Machine Number | Programme/Recipe | Parameter |
|---|---|---|---|---|---|---|---|
| 1. Thin Film Deposition | Oxidation Dry | Start | Top Side/ Bottom Side | | | | |
| Thin Film Deposition | Oxidation Dry | Silicon clean RCA 1+2+HF-dip | Top Side/ Bottom Side | | PC03<br>PC04<br>PC13<br>PC14<br>PC28 | RCA 1+2 and HF-dip | Mix and run according to instruction at wet bench |
| Thin Film Deposition | Oxidation Dry | Rinse and dry | Top Side/ Bottom Side | | PC03<br>PC04<br>PC13<br>PC14<br>PC28 | | |
| Thin Film Deposition | Oxidation Dry | Dry oxidation | Top Side/ Bottom Side | ±Å<br>±°C | PD01<br>PD02 | Rec no 17; 1050°C; 1000±100Å<br>Rec no 3; 1050°C; 1000±100Å | |
| Thin Film Deposition | Oxidation Dry | Inspection | Top Side/ Bottom Side | | | | Thickness uniformity |
| Thin Film Deposition | Oxidation Dry | Thickness measurement | Top Side/ Bottom Side | ±Å | PM07 | Si/SiO2 | Number of measurements points/wafer (std: 2 point):<br>Number of wafers to measure (std: 2 wafer): |

*Figure 12. Process package showing the different steps in a dry oxidation process.*

The manufacturing details for every batch of wafers are specified in a PID. It is mainly a detailed flow chart of the manufacturing process put together from the standard processes in the Process Library, but it also contains specifications and print outs of the photolithographic masks used, and specifications of the raw materials that are needed. The PID must be approved at a design review meeting before manufacturing begins.

Once manufacturing begins, the contents of the PID are copied to a batch traveller or a Log File that follows the batch throughout the manufacturing. The Log File is basically the same as the PID but with a log to sign the different process steps off with date, comments, operator identification, etc. The Log File also handles measurement data and non conformances. The Log File helps in optimising the manufacturing process and back tracking discrepancies.

Process Control Vehicles (PCV), real device wafers in an unfinished state, are put aside at critical stages in the manufacturing in order to make it possible to backtrack discrepancies and malfunctions.

### 6.3.1.4 Material Tracking Procedures

Each batch of wafers that is manufactured according to the same process sequence and in the same production run is given a unique batch number. The PID and the Log File associated with the manufacturing have the same batch number. The batch numbers are allocated from a list of consecutive identification numbers. Each wafer in a batch is permanently marked with the batch number and a serial number to differentiate the wafers within a batch from one another.

If wafers from two batches are bonded together, a new batch number is allocated for the bonded pair. When bonded wafers are diced up into chips this traceability is inevitably lost. The wafer marking cannot be done on chip level. Instead, chips are stored in boxes marked with the proper batch and serial number. Individual chips on a wafer can be distinguished from one another; they are marked either by a shallow etch of the surfaces in the initial stage of processing, or by the deposition of a metal layer towards the end of the manufacturing sequence.

Full specifications of the raw materials and photolithographic masks used for a specific batch of wafers are both given in the PID and the Log File.

### 6.3.1.5 Wafer Level Tests

Wafer level tests make it possible to start the testing and sample screening early in the manufacturing process and thus save manufacturing costs. These tests are meant to control characteristics of device structures and materials, and manufacturing processes. They provide reliability and performance data at various stages in the manufacturing process.

Wafer level tests are included in all process packages in the manufacturing of the micropropulsion system. Most of the tests can be performed on actual micropropulsion system wafers and structures, precluding the need for specially designed PCM structures or wafers. Other tests require specially designed PCM structures or PCM wafers. A PCM structure is to be understood as a test structure included on an actual micropropulsion system wafer while a PCM wafer is to be understood as a separate wafer with test structures to control sensitive manufacturing processes.

The wafer level tests performed in this work are presented below together with an evaluation of the efficiency of the test structures and test methods.

Most of the tests are made to control standard processes used by the MEMS community all over the world. Other processes are used specifically for the subject devices.

#### 6.3.1.5.1 Mask Alignment Control

##### 6.3.1.5.1.1 Scope

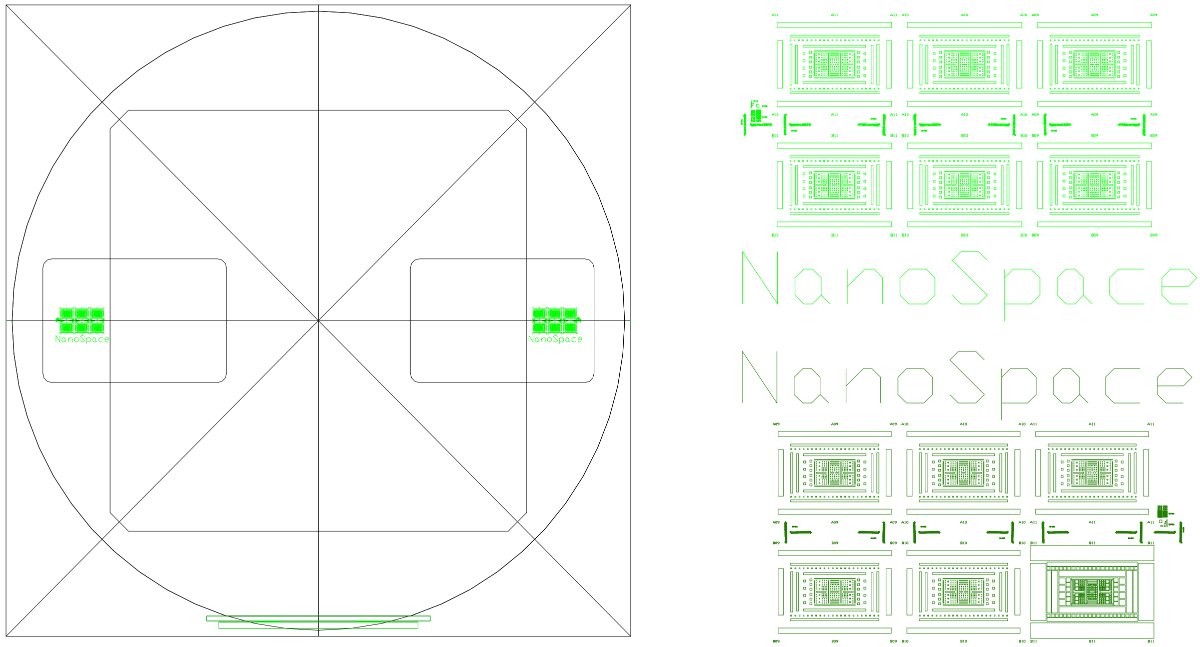
Mask alignment control is needed to control the mask alignment errors in the lithography processes and sort out wafers with misaligned photoresist patterns from further processing. Photolithographic masks are aligned to already existing structures on the micropropulsion system wafers at various stages in the manufacturing process. Two different types of PCM structures are used to control the alignment. One is used to align new masks to existing structures, and the other to measure the resulting alignment error. To avoid escalating alignment errors, all alignments and measurements use reference structures.

##### 6.3.1.5.1.2 PCM Structures

###### 6.3.1.5.1.2.1 Mask Layouts

The reference structures are implemented on two separate photolithographic masks intended for the top and the bottom side of the wafers respectively. There are several pairs of reference structures on each mask. They are located on the right- and the left-hand sides, in areas dedicated for PCM structures, see Figure 13.

Mask alignment structures, to align new masks to the reference structures, and indicating lines, to measure the mask misalignments relative to the reference structures, are included on all other micropropulsion system masks. At least one pair of structures is implemented on each mask. Their design is the same as that of the bottom right dark green structure in Figure 13 b.




(a) (b)

*Figure 13. CAD images of structures on the reference masks. (a) The green structures on the right- and left- hand sides are six pairs of reference structures. The black lines are help lines used in the CAD programme. (b) Close up on six of the reference structures. The light green structures are implemented on the top side reference mask and the dark green structures on the bottom side reference mask.*

### 6.3.1.5.1.2.2 Manufacturing

The reference structures are implemented into the top and the bottom side of the wafers as a preparatory step in the manufacturing of the micropropulsion system. They are wet etched to a shallow depth using standard manufacturing procedures. Care should be taken to etch the structures to a maximum depth of 5 μm.

The mask alignment structures are only used to align the mask to the reference structures on the wafers. They are implemented on the masks but are not developed any further.

The indicating lines are implemented in photoresist in parallel with other structures on the micropropulsion system masks. They are consequently prepared according to standard procedures.

### 6.3.1.5.1.2.3 Handling and Storage

The reference structures go through many further processing steps after being completed. Some of these steps may affect the shape of the structures. Photolithography is the most critical of these processes since poor step coverage of the photoresist will expose the edges of the structures to etching agents. This is not a problem, however, if the structures are sufficiently shallow.

The mask alignment, using the mask alignment structures, should be performed within 24 hours after photoresist coating and soft bake.

Wafers with a developed and hard baked photoresist coating, such as the wafers with indicating lines, can be stored in yellow light or in darkness for six hours without any extra precautions, and up to one week in darkness if they are hard baked prior to resuming the manufacturing process.

The reference structures are handled and stored under class 100-10000 clean room conditions, depending on the particular process that is being executed. Photolithographic masks and wafers with a patterned photoresist coating are handled and stored in a class 100 clean room area. The temperature and the relative humidity are controlled to be within 21±1°C and 43±5% respectively.

### 6.3.1.5.1.2.4 Description

The reference structures consist of reference alignment structures to use as reference when new masks are aligned to existing structures on the wafers, and scales to use as reference when the resulting alignment of the same masks is measured. There are several reference structures on each wafer surface in order to allow the implementation of the required number of new masks.

All photolithographic masks used for the micropropulsion system have mask alignment structures that overlap the reference alignment structures when the alignment is satisfactory. They also have indicating lines that overlap the scales and make it possible to measure the alignment. There is one alignment evaluation structure for each alignment structure.

The alignment and alignment evaluation structures come in pairs. They are implemented on the right- and the left-hand sides of the wafers in order to control the rotation alignment.

*Alignment Structures*

The reference alignment structures consist of differently shaped and sized squares permanently etched into the surfaces of the wafers, see Figure 14. The different pairs have slightly different designs to prevent mix-ups during lithography.

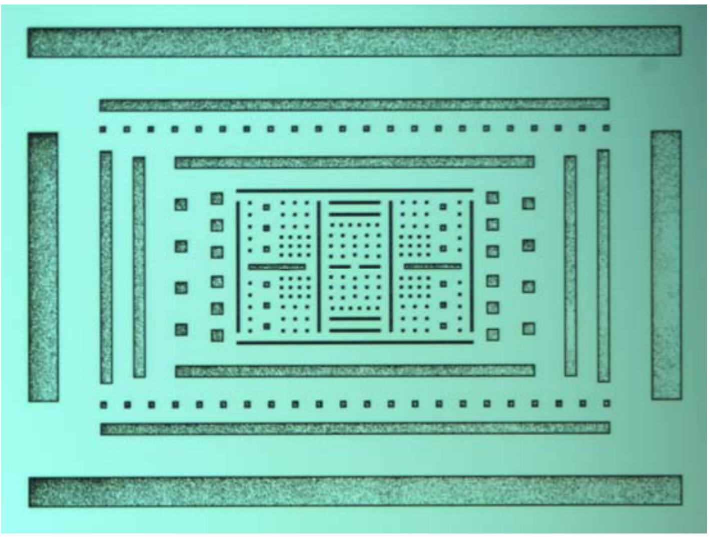


*Figure 14. Reference alignment structure etched into the surface of a wafer.*

The mask alignment structures are geometrically similar, but the squares are larger to encircle the reference alignment structures. When the alignment seen in the mask aligner microscope is satisfactory, the squares of the reference alignment structures should be centred into the larger squares of the mask alignment structures. Figure 15 shows an image taken through the eyepiece of the top mask aligner microscope. The silicon structures (dark) are seen to be encircled by the mask structures (lighter).

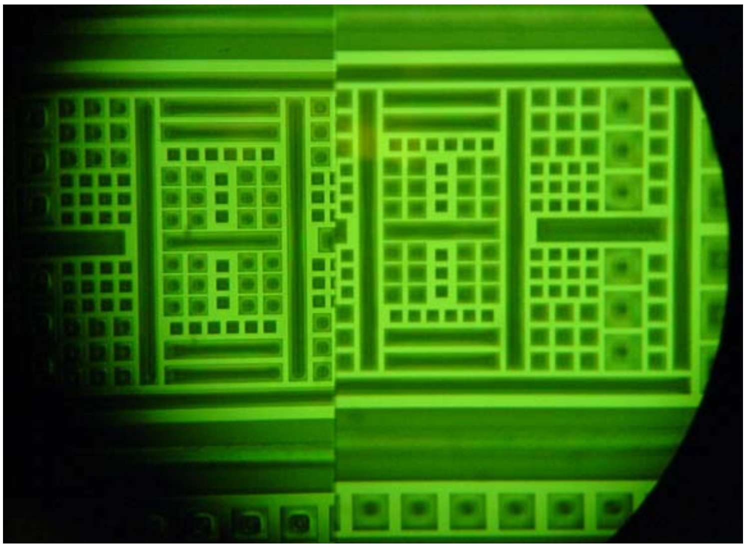


*Figure 15. Image taken through the eyepiece of the mask aligner microscope. Silicon structures (dark) are seen to be encircled by mask structures (lighter).*

The inner squares of the alignment structures are smaller than the outer ones, and are suitable to use for fine alignments. The outer squares are used for coarse alignments. Typical structure sizes are shown in the CAD image in Figure 16. Here, green represents the reference alignment structures and red the mask alignment structures. The dimensions are given in µm.

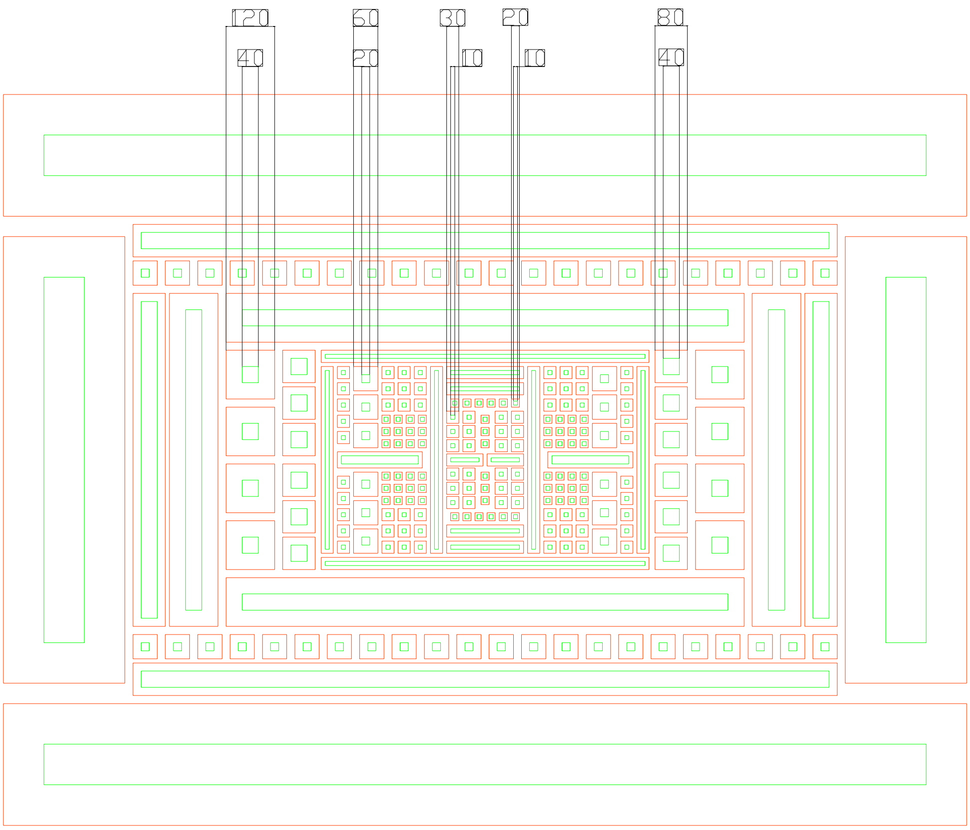



*Figure 16. Typical alignment structure sizes. Green represents the reference alignment structures and red the mask alignment structures. The dimensions are given in µm.*

*Alignment Evaluation Structures*

The scales consist of four parallel rows of squares directed slightly off the x-direction and a similar set of rows directed slightly off the y-direction, see Figure 17.

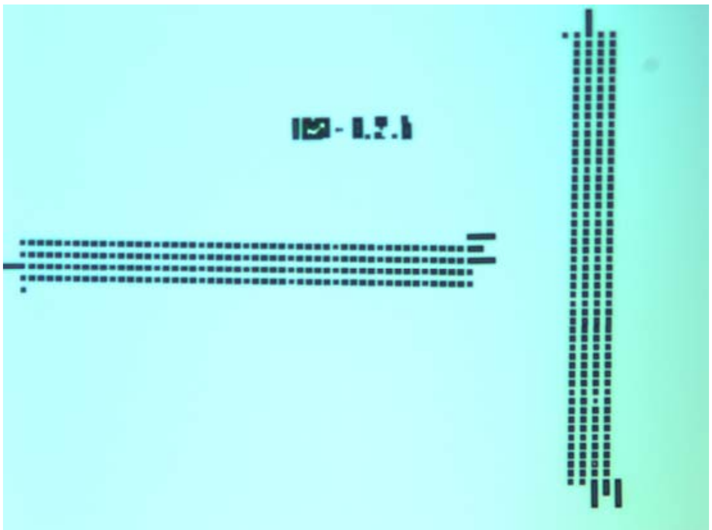


*Figure 17. Scales etched into the surfaces of the wafers.*

The misalignment of a photolithographic mask is obtained from the point of closest alignment between the indicating lines defined in photoresist during the lithography processes and the squares of the scales. Typical alignment evaluation structures are shown in Figure 18 The misalignment can be calculated as a numerical value from the dimensions of the scales. The tilt of the rows is 10 µm while the distance between adjacent squares within a row is 0.2 µm, see Figure 19. The base level is indicated by the protrusions at opposite ends of the second and the third row. The indicating lines are oriented parallel to the x- and the y-directions.

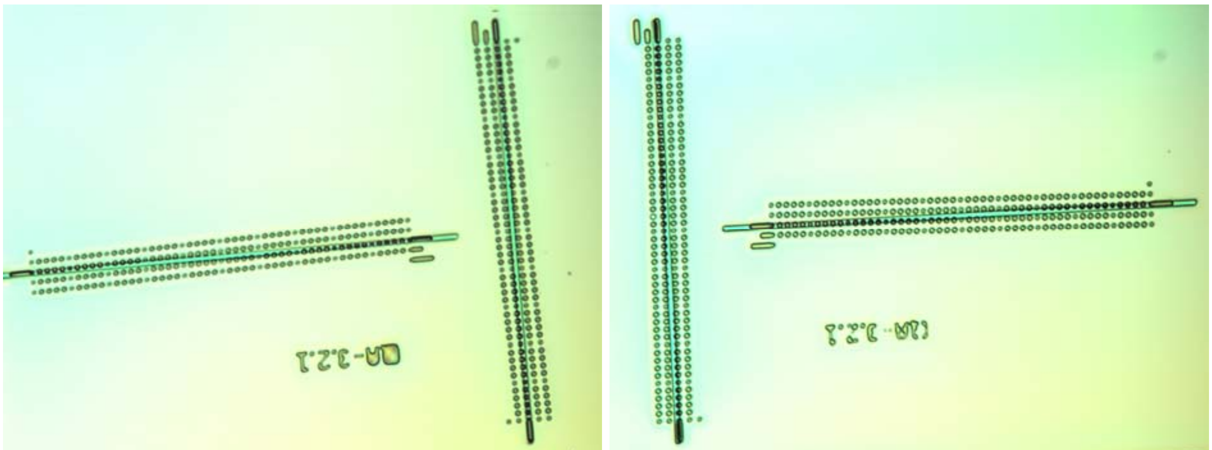


*Figure 18. Images on alignment evaluation structures with indicating lines overlapping the scales.*

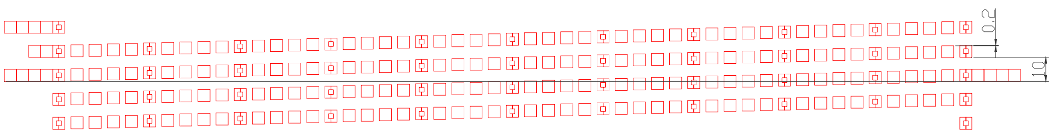



*Figure 19. CAD image showing the critical dimensions of the scales. The dimensions are given in µm.*

For a photolithographic mask that is perfectly aligned in the y-direction, the indicating line would overlap the scale at the base level, as shown in Figure 20. The closest point of alignment is seen to be at the ends of the two rows. Figure 21 illustrates a mask that has been misaligned in the positive y-direction. A close inspection shows a misalignment of 2.2 µm. Misalignments in the x-direction is evaluated similarly.

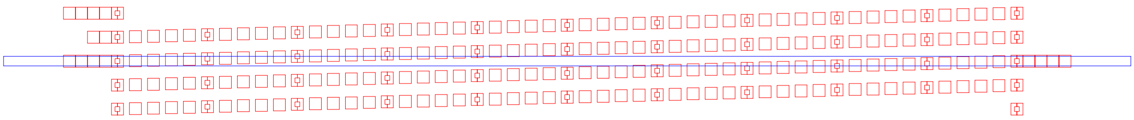


*Figure 20. CAD image illustrating a mask that is perfectly aligned to the scale in the y-direction.*

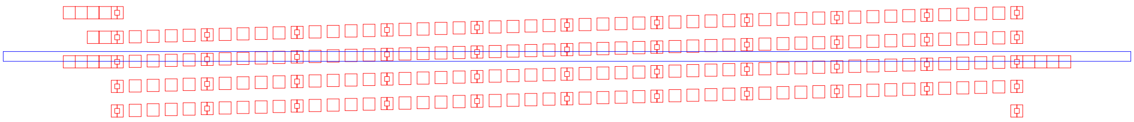


*Figure 21. CAD image illustrating a mask that has been misaligned 2.2 µm in the positive y-direction.*

## 6.3.1.5.1.3 Facilities

The lithography work area should be a clean room of class 100 with yellow light to avoid unintentional exposure of the photoresist during sample processing. The ambient temperature should be controlled to be within 21±1°C and the relative humidity to be within 43±5%.

The reference structures go through subsequent etching and thermal oxidation processes after the lithography. These processes are executed under class 100-10000 conditions.

## 6.3.1.5.1.4 Equipment

*Alignment Procedure*

A high precision mask aligner is needed to control the alignment of the different masks used in the manufacturing. The mask aligner must have top and bottom side alignment possibilities and microscopes with at least x5 magnification.

*Alignment Evaluation Procedures*

A mask aligner with top and bottom side alignment possibilities, and a magnification capability of at least x5, is used to evaluate the alignment between the top and the bottom side reference structures on the wafers. The evaluation could alternatively be done in a double sided microscope with at least x5 magnification and with yellow filters in the illuminator columns.

The alignment of all other micropropulsion system masks is analysed in an optical microscope. The microscope should have at least x50 magnification and a yellow filter in the illuminator column to prevent exposing the photoresist while taking a measurement.

## 6.3.1.5.1.5 Procedure

*Alignment Procedure*

The alignment of photolithographic masks to already existing structures on the wafers is performed within 24 hours after photoresist coating and soft bake, in accordance with the requirements in paragraph 6.3.1.5.1.2.3. The exposure and the development of the photoresist are inherently done immediately thereafter. Both top side and bottom side alignment modes are used for the micropropulsion system wafers. Top side mode is used for all masks except the reference mask with bottom side reference structures.

The alignment procedures of the two modes are very similar. The wafer is moved in the mask aligner so that the reference alignment structures on the right- and left-hand sides are encircled by, and centralised within, the mask alignment structures. The large structures are used for coarse alignments. Squares and rectangles with side lengths of 20-30 µm on the mask are used for fine alignments.

In top side alignment mode, the reference alignment structures etched into the surfaces of the wafers are aligned to the mask. The mask and the reference structures are simultaneously seen in the eyepieces of the mask aligner microscope. The magnification (x10 or x5) is chosen so that the mask and the wafer structures are clearly visible, and so that it is easy to align the structures to one another. Since the focal depth depends on magnification, the gap between the mask and the wafer structures affects the best choice of magnification and structure size. An alignment gap of 20-70 µm is used depending on wafer quality, wafer history, and mask cleanliness considerations.

In bottom side alignment mode, the bottom side of the wafers is patterned by aligning the reference alignment structures defined in photoresist on the top side of the wafers to the alignment structures on the mask. Superimposed images of the reference and mask alignment structures taken from the bottom side mask aligner microscope are seen on a computer screen.

*Alignment Evaluation Procedures*

The mask alignment errors should preferably be evaluated six hours after developing and baking the photoresist, in accordance with the requirements in paragraph 6.3.1.5.1.2.3. The evaluation could be delayed up to one week under circumstances defined in the same paragraph.

The misalignments of masks relative to the reference alignment structures are measured using the alignment evaluation structures. Since the structures include a scale, they can be analysed in an optical microscope. Misalignments are measured in the x- and the y-direction, on the right- and the left-hand sides of the wafers.

The misalignments between the reference alignment structures on the top and the bottom sides of the wafers are evaluated with a mask aligner in bottom and top side modes. The reference alignment structures on one side of the wafer are first aligned to corresponding mask alignment structures using bottom side alignment mode. Hereafter, the alignment between the same mask alignment structure and corresponding reference alignment structure on the top side of the wafer is evaluated in the top side mask aligner microscope. A sufficiently good estimate of the alignment error is obtained using the 20 or 30 µm sized squares on the mask.

### 6.3.1.5.1.6 Acceptance Criteria

Generally, micropropulsion system wafers with photoresist structures that are misaligned by less than ±5 µm relative to the reference structures shall be considered as having passed the examination. For some wafers, the maximum allowed alignment error is ±2 µm.

Wafers that do not pass the examination are sorted out from further processing. Normally, they can be cleaned and patterned again, all according to standard manufacturing procedures.

### 6.3.1.5.1.7 Validation

*Alignment Structures and Procedure*

The alignment structures are easy to use and yield accurate alignments. The photoresist coated squares of the reference structures are clearly visible through the mask alignment structures in the mask aligner microscope, and they are easy to centre. There is no risk mixing the different pairs of alignment structures up since they all look a bit different. The reference alignment structures more or less keep their shape and size throughout subsequent processing steps and can thus be used at the end of the manufacturing process. There are several squares of each size in case some are substandard.

The alignment achieved with the alignment structures is sufficiently accurate. The average absolute alignment error between the masks and the reference structures on the wafers is 0.34±0.58 µm, which is sufficient considering that the requirements are 5 µm or 2 µm. The misalignments were measured using the alignment evaluation structures.

The alignment achieved between the reference alignment structures on the top and the bottom side of the wafers is also sufficiently accurate. From the overlap between the structures in the mask aligner, the average absolute alignment error is evaluated to be 1.64±1.31 µm. The requirement is 5 µm.

*Alignment Evaluation Structures and Procedures*

The structures include a scale which simplifies the evaluation; it can be done in many ordinary optical microscopes. The magnification must be x50 and there is need for yellow filters, but there is no need for graded ocular lenses or digital imaging and measurement software programmes.

The scale has a high resolution of 0.2 µm which facilitates the operator’s judgement and makes the measurement errors smaller. It is, however, often difficult to judge the point of closest alignment between the scales and the indicating lines with such high resolution, see Figure 22. This is not a critical issue for the manufacturing of the micropropulsion system, considering the small alignment errors attained. A larger size difference between the line width and the square size would probably ease the evaluation.

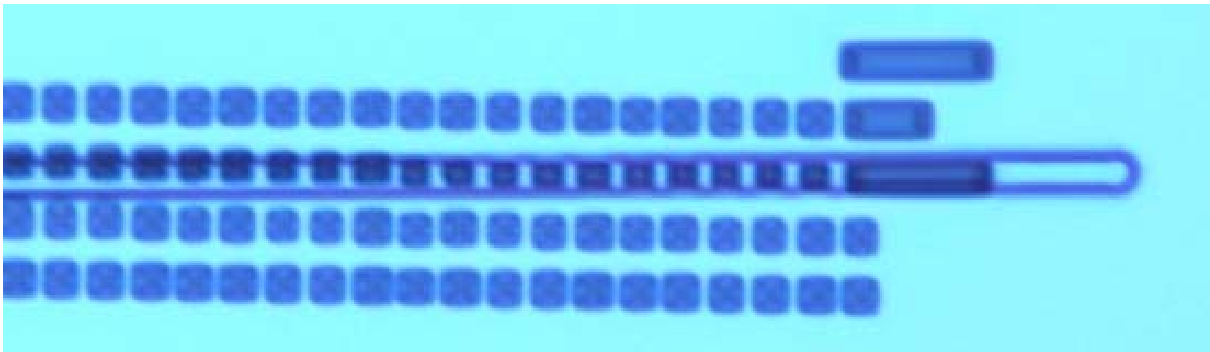


*Figure 22. It is often difficult to judge the point of closest alignment between the scales and the indicating lines with a resolution of 0.2 µm. In this image the misalignment is seen to be between 0.4-1.6 µm.*

The squares and rows of squares of the scales are furthermore positioned too close to one another on the masks and are therefore easily deteriorated during processing. A critical process is photolithography, where poor resist coverage of the structures cause unintentional etching of the structures in subsequent processes, see Figure 23.

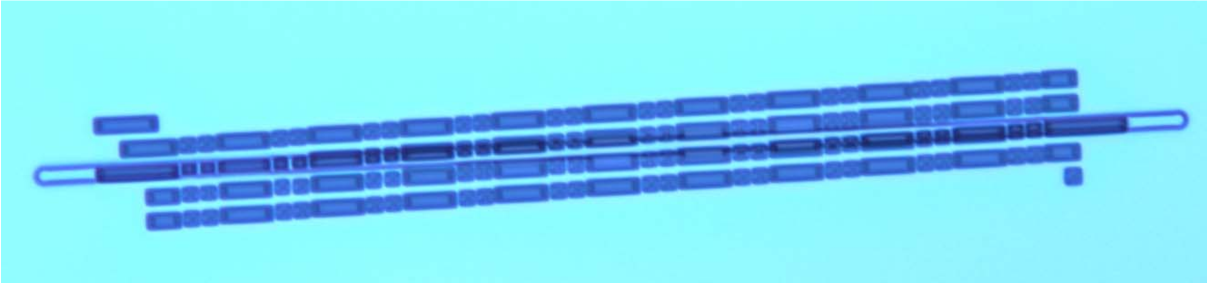


*Figure 23. Alignment evaluation structure with damaged scale.*

Evaluations of the alignment between the top and bottom side reference structures can be made with a resolution better than 5 µm from an inspection of the overlap between the 20 or 30 µm squares on the masks and corresponding structures on the wafers. It would, however, be desirable to have graded structures so that the misalignment can be read as a numerical value. This would also make the evaluation less operator dependent.

## 6.3.1.5.2 Lithographic Resolution Control

### 6.3.1.5.2.1 Scope

Lithographic resolution control is needed to control the resolution of developed photoresist structures in the lithography processes and sort out wafers with inadequately resolved structures from further processing. PCM structures are used to evaluate the lithographic resolution.

### 6.3.1.5.2.2 PCM Structures

#### 6.3.1.5.2.2.1 Mask Layout

Lithographic resolution structures are implemented on all photolithographic masks used in the manufacturing of the micropropulsion system. The structures are located on the right- and the left-hand sides, in areas dedicated for PCM structures. They are found close to the mask alignment structures as can be seen in Figure 24. At least one pair of lithographic resolution structures is implemented on each mask.

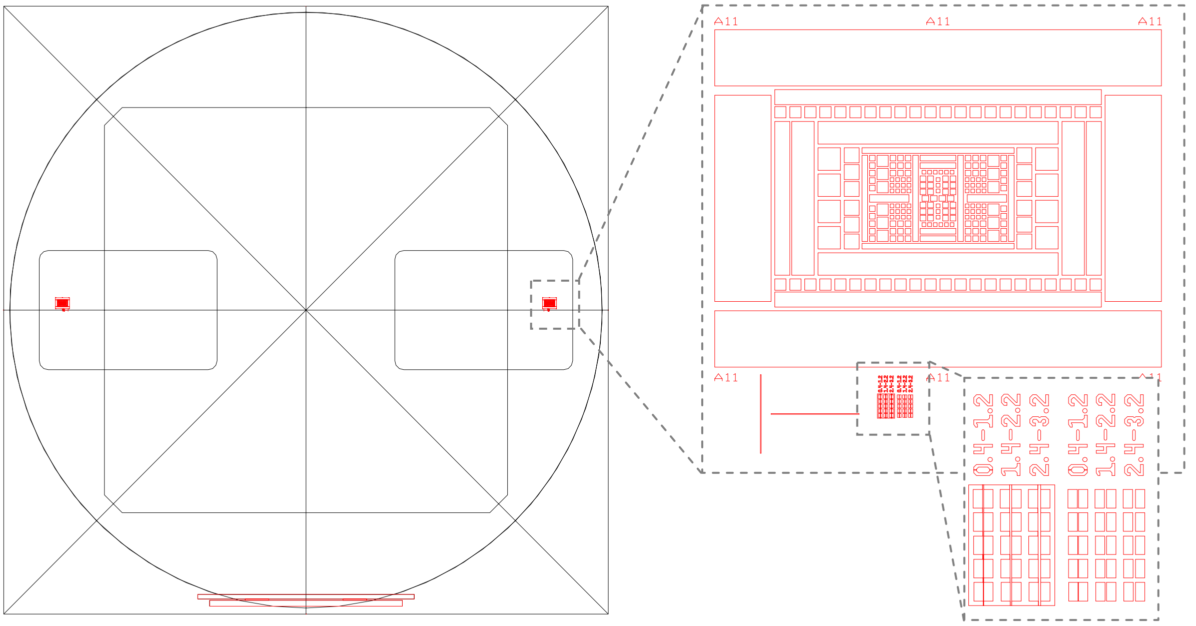



*Figure 24. CAD images showing the location of the lithographic resolution structures on the mask and their position relative to the mask alignment structures and the indicating lines. The black lines in the left image are help lines used in the CAD programme.*

## 6.3.1.5.2.2.2 Manufacturing

The lithographic resolution structures are implemented in photoresist in parallel with other structures on the micropropulsion system masks. They are consequently prepared according to standard procedures.

## 6.3.1.5.2.2.3 Handling and Storage

Wafers with a developed and hard baked photoresist coating can be stored in yellow light or in darkness for six hours without any extra precautions, and up to one week in darkness if they are hard baked prior to resuming the manufacturing process.

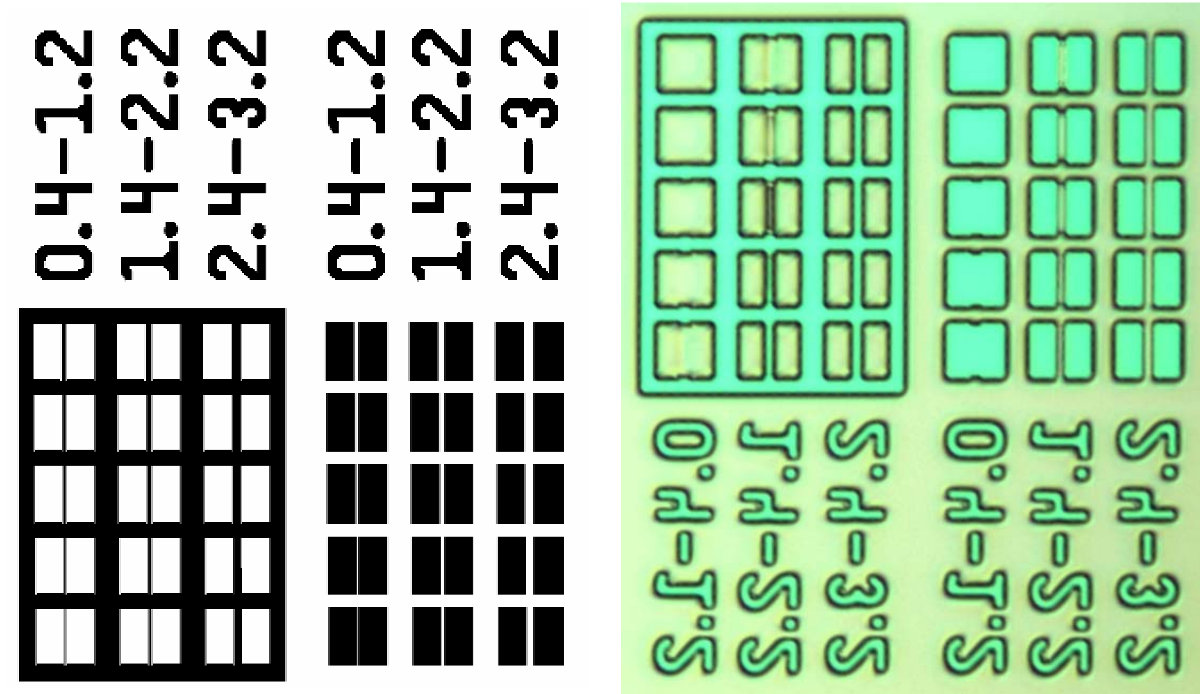
Wafers with patterned photoresist coatings are handled and stored in class 100 clean room areas. The temperature and the relative humidity are controlled to be within 21±1°C and 43±5% respectively.

## 6.3.1.5.2.2.4 Description

All photolithographic masks used in the manufacturing of the micropropulsion system have lithographic resolution structures to control the sizes of the micropropulsion system structures. There is one lithographic resolution structure implemented on the masks for each mask alignment structure in order to evaluate the resolution in all photolithographic processes. The structures are positioned on both the right- and the left-hand sides of the masks to improve the statistics and get an estimate of the lateral variation.

The structures are implemented as 15 differently wide lines of two different types on the photolithographic masks. One type yield narrow channels in photoresist while the other yield narrow ridges. They are defined between squares as illustrated in Figure 25. The figures above the structures indicate the widths of the lines. The narrowest lines are 0.4 µm wide, the second narrowest are 0.6 µm wide, and so on. The widest lines are 3.2 µm.

The resolution obtained in a photolithography process is taken as the narrowest properly resolved lines in photoresist. Channel and ridge structures are interpreted the same way. The narrowest developed structure is obtained from the group of lines to the left in Figure 25 b, and the narrowest coated structure from the group of lines to the right.




(a) (b)

*Figure 25. Images showing lithographic resolution structures. (a) shows the mask layout. White represents chromium coated areas on the mask and black represents open areas. The figures indicate the widths in µm of the lines formed between the squares. (b) shows the same structures defined in photoresist.*

## 6.3.1.5.2.3 Facilities

The lithography work area should be a clean room of class 100 with yellow light to avoid unintentional exposure of the photoresist during sample processing. The ambient temperature should be controlled to be within 21±1°C and the relative humidity to be within 43±5%.

## 6.3.1.5.2.4 Equipment

The lithographic resolution structures are analysed in an optical microscope. The microscope should have at least x50 magnification and a yellow filter in the illuminator column to prevent exposing the photoresist while taking a measurement.

## 6.3.1.5.2.5 Procedure

The lithographic resolution should preferably be evaluated six hours after developing and baking the photoresist, in accordance with the requirements in paragraph 6.3.1.5.2.2.3. The evaluation could be delayed up to one week under circumstances defined in the same paragraph.

The resolution is evaluated using the lithographic resolution structures. Since the structures include a scale, they can be analysed in an optical microscope. Both the smallest developed structure and smallest coated structure should be assessed. The smallest developed structure is used to control the sizes of the microproulsion system structures. The smallest coated structure is mainly used to control the adhesion of the photoresist onto the substrate. Measures should be taken from both the right- and left-hand side of the wafers.

## 6.3.1.5.2.6 Acceptance Criteria

Generally, micropropulsion system wafers that have been examined and where the 3.2 µm lines are properly resolved shall be considered as having passed the examination. For some wafers, the smallest developed line must be 1.6 µm.

Wafers that do not pass the test are sorted out from further processing. Normally, they can be cleaned and patterned again, all according to standard manufacturing procedures.

## 6.3.1.5.2.7 Validation

The structures include a scale which simplifies the evaluation; it can be done in many ordinary optical microscopes. The magnification must be x50 and there is need for yellow filters, but there is no need for graded ocular lenses or digital imaging with measurement software programmes.

The scale has a high resolution of 0.2 µm which facilitates the operator's judgement and makes the measurement errors smaller. It often feels like a random decision which line width to take as properly resolved, since there is no clear boundary between resolved and not resolved, see Figure 26. Reproduced measurements on the same structures indicate, however, that the interpretation errors are small. The reproducibility standard deviation between the measurements is only 1% (for both types of structures). Within each of the data series, the standard deviation is 35% for the smallest developed line and 15% for the smallest coated line.

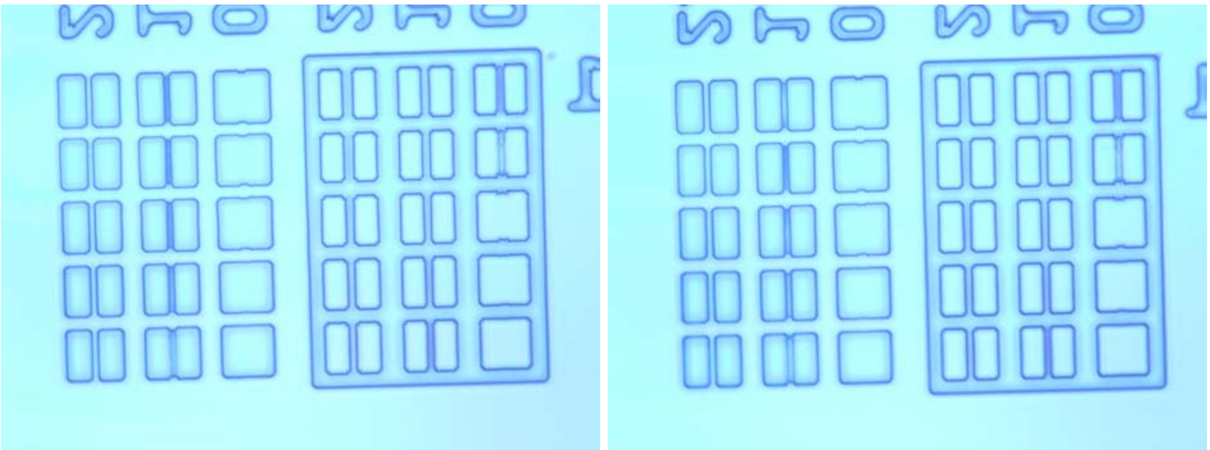


*Figure 26. Lithographic resolution structures defined in photoresist illustrating the indistinct boundary between resolved and not resolved lines.*

The line widths of the lithographic resolution structures should be adjusted to comply better with the requirements for the micropropulsion system. Lines up to 4 µm widths should be included since the acceptance criterion for the smallest developed line is 3.2 µm, which is also the detection limit of the lithographic resolution structures.

It is mainly the smallest developed line structures that are needed to control the lithographic resolution in the manufacturing process. The smallest properly coated structures are mainly used to evaluate whether the adhesion of the resist to the substrate is satisfactory.

## 6.3.1.5.3 Bond Alignment Control

### 6.3.1.5.3.1 Scope

Bond alignment control is needed to control the bond alignment errors in the bonding process and sort out misaligned bonded wafers or chips from further processing. Two different types of PCM structures are used. The reference alignment structures are used when fine bond alignments are required and guide pin holes are used together with guide pins when coarse alignments suffice.

### 6.3.1.5.3.2 PCM Structures

#### 6.3.1.5.3.2.1 Mask Layout

The reference structures are implemented on two slightly different masks; one is used for the top side of the wafers and the other for the bottom side. The structures are used for mask alignments as well, so the masks are further described in section 6.3.1.5.1.2.1.

The guide pin holes are implemented on those masks where it is relevant. There are four holes on each of these the masks, positioned far from one another to minimise the alignment errors. Figure 27 shows the location of the guide pins holes on a mask.

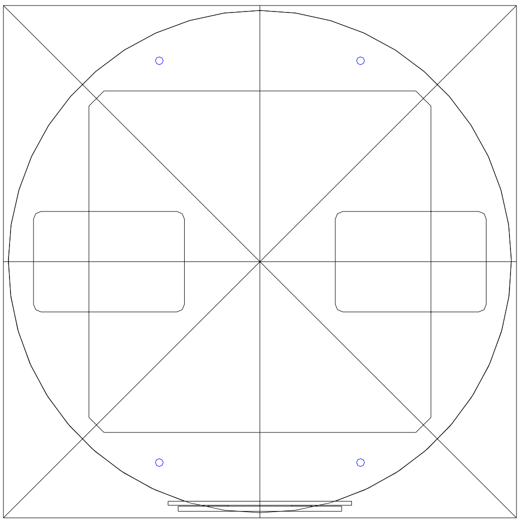


*Figure 27. CAD image showing the location of the guide pin holes (blue) on the masks. The black lines are help lines used in the CAD programme.*

#### 6.3.1.5.3.2.2 Manufacturing

The reference structures are implemented into the top and the bottom side of the wafers as a preparatory step in the manufacturing of the micropropulsion system. They are wet etched to a shallow depth using standard manufacturing procedures. Care should be taken to etch the structures to a maximum depth of 5 µm.

The guide pin holes are etched through the whole thickness of the wafers in parallel with other structures on the micropropulsion system wafers. They are consequently prepared according to standard procedures.

#### 6.3.1.5.3.2.3 Handling and Storage

The reference structures go through many further processing steps after being completed. Some of these steps may affect the shape of the structures. Photolithography is the most critical of these processes since poor step coverage of the photoresist will expose the edges of the structures to etching agents. This is not a problem, however, if the structures are sufficiently shallow.

Wafers with ready-made guide pin holes do go through a few processes before the guide pin aligned bonding, but none of these processes are critical for the structures.

Wafers with reference structures and guide pin holes are handled and stored under class 100-10000 clean room conditions, depending on the particular process that is being executed. The temperature and the relative humidity are controlled to be within 21±1°C and 43±5% respectively.

#### 6.3.1.5.3.2.4 Description

*Fine Alignment Structures*

The reference alignment structures are used to align wafers when fine bond alignments are required. They are used both to achieve alignment and evaluate the resulting alignment. The reference structures are also used for mask alignments, and for the evaluation of misalignment errors between the reference alignment structures implemented on the top and the bottom side of the wafers. A more thorough description of the structures is given in section 6.3.1.5.1.2.4.

*Coarse Alignment Structures*

There are four guide pin holes on each of the wafers that are bonded using guide pin alignment. The holes are positioned far from one another to minimise the alignment errors. The holes are circular and have a diameter of 1550 μm, which is 50 μm larger than the guide pins. This entails that the misalignments between wafers are mechanically restricted to 50 μm.

### 6.3.1.5.3.3 Facilities

The bonding work area should be a clean room of class 100 or better to avoid particle contamination. The ambient temperature should be controlled to be within 21±1°C and the relative humidity to be within 43±5%.

### 6.3.1.5.3.4 Equipment

*Fine Alignment Procedure*

A high precision bond aligner is needed to achieve the fine bond alignments between wafers.

*Coarse Alignment Procedure*

Guide pins, firmly mounted into a fixture are needed for the coarse bond alignments.

*Alignment Evaluation Procedure*

A mask aligner with top and bottom side alignment possibilities, and microscopes with at least x5 magnification, is needed to evaluate the alignment errors. The evaluation could alternatively be done in a double sided microscope with at least x5 magnification.

### 6.3.1.5.3.5 Procedure

Bonding should be performed immediately after surface activation. The alignment is evaluated after pre-bonding but before anneal.

*Fine Alignment Procedure*

The alignment procedure in the bond aligner resembles the bottom side mode mask alignment procedure described in section 6.3.1.5.1.5. Superimposed images of the reference structures on the bottom side of the top wafer and the reference structures on the bottom side of the bottom wafer is shown on a computer screen. The bottom wafer is moved in the bond aligner so that the reference alignment structures overlap. When the alignment is judged to be sufficient, the wafers are pre-bonded. The large squares of the alignment structures are used for coarse alignments. Squares and rectangles with side lengths of 20-30 µm are used for fine alignments.

*Coarse Alignment Procedure*

In guide pin aligned bonding, the guide pin holes on the wafers are aligned to the guide pins on the fixture. The wafers are placed one after the other onto the fixture, and then pre-bonded by a slight pressure with the tweezers on the surface.

*Alignment Evaluation Procedure*

The bond misalignments are evaluated from the overlap seen in the mask aligner, of the reference structures on the top and the bottom sides of the pre-bonded pairs. The same procedure is used to evaluate the alignment between the reference structures on the wafers. For a further description of the procedure see section 6.3.1.5.1.5.

### 6.3.1.5.3.6 Acceptance Criteria

Wafers bonded in the bond aligner with resulting alignment errors smaller than ±10 µm shall be considered as having passed the examination. For samples bonded using guide pin alignment the criterion is ±80 µm.

Samples that do not pass the examination are sorted out from further processing. Since the examination takes place after the pre-bonding but before the annealing, misaligned samples can normally be de-bonded and then bonded again.

### 6.3.1.5.3.7 Validation

*Fine Alignment Structures and Procedure*

The reference alignment structures are just as easy to use for bond alignments as they are for mask alignments, see section 6.3.1.5.1.5. They are clearly visible and have a well defined shape even though the bonding takes place at the end of the microsystem manufacturing process.

The bond alignments achieved are also accurate. The average absolute alignment error between two bonded wafers is evaluated to be 2.7±1.6 µm. The overlap between reference structures in the mask aligner were used to determine the figures. The alignment requirements are 10 µm.

*Coarse Alignment Structure and Procedure*

Guide pin aligned bonding is quick and easy and yield sufficiently good alignment results. The maximum alignment error is mechanically restricted to 50 µm. The average absolute bond misalignments are evaluated to be 16±10 µm from the overlap of reference structures in the mask aligner. The requirements are 80 µm for bonds that are aligned using guide pins.

*Alignment Evaluation Procedure*

The bond alignments can be evaluated with a resolution better than 5 µm, just as was the case for the alignments between reference structures on the top and the bottom side of wafers, see section 6.3.1.5.1.7. The evaluation procedure would, however, be easier and more accurate if the structures were graded. The evaluation procedure is suitable to use when the alignment requirements are smaller than 100 µm.

## 6.3.1.5.4 Dicing Accuracy Control

### 6.3.1.5.4.1 Scope

Dicing accuracy control is needed to control the cutting errors in the dicing process and sort out miscut micropropulsion system chips from further processing. The cutting errors originate from translation and rotation misalignments, and from the discrepancy between the actual saw cut width and the nominal blade width. The alignment of the saw cut relative to the chip structures is controlled and monitored by means of PCM structures. The width of the saw cut is measured directly in the dicing saw; this procedure does not require any PCM structure.

### 6.3.1.5.4.2 PCM Structures

#### 6.3.1.5.4.2.1 Mask Layouts

The dicing alignment structures are implemented on masks that are intended for surfaces that are used for alignments in the dicing machine. Several structures are implemented on the masks for every cut. An example is shown in Figure 28. The saw cut is meant to be in the horizontal direction.

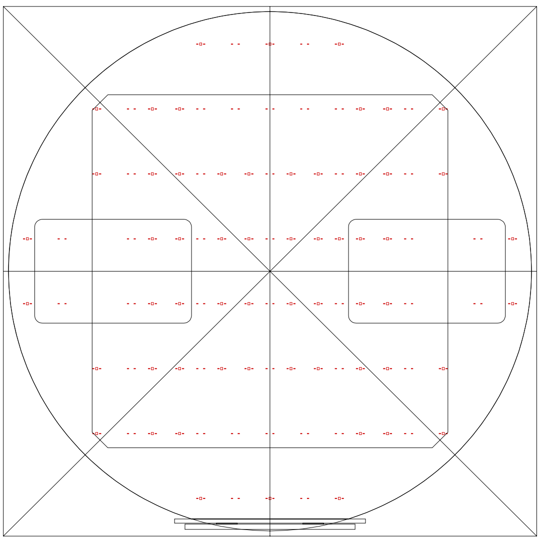


*Figure 28. CAD image showing how dicing alignment structures are typically implemented on a mask. The saw cut is meant to be in the horizontal direction. The black lines are help lines used in the CAD programme.*

#### 6.3.1.5.4.2.2 Manufacturing

The dicing alignment structures are manufactured on the same wafers as the micropropulsion wafers and are consequently prepared according to standard procedures. The structures are implemented together with the reference masks and are wet etched to a shallow depth together with the other reference structures. Care should be taken to etch the structures to a maximum depth of 5 µm.

#### 6.3.1.5.4.2.3 Handling and Storage

The dicing alignment structures go through many further processing steps after being completed. Some of these steps may affect the shape of the structures. Photolithography is the most critical of these process since poor step coverage of the photoresist will expose the edges of the structures to etching agents. This is not a problem, however, if the structures are sufficiently shallow.

The structures are handled and stored under class 100-10000 clean room conditions, depending on the particular process that is being executed. The temperature and the relative humidity in the clean room are controlled to be within 21±1°C and 43±5% respectively.

#### 6.3.1.5.4.2.4 Description

Two geometrically different designs of dicing alignment structures used in the manufacturing of the micropropulsion system. Dimensioned CAD images of the structures are shown in Figure 29 together with microscopic images of real structures. The use of the two is basically the same.

The structures are designed to be cut straight through in the horizontal direction in Figure 29. They consist of narrow squares to facilitate the alignment of the saw blade and wide squares to measure the resulting alignment of the saw cut. The saw cut is confined within the wide squares and the alignment is obtained from the distance between the saw cut edges and the square edges. There are several PCM structures in a row along a saw cut so that the rotational alignment is assessed. This also yields structural redundancy. The narrow squares are centred to the wide squares.

The total cutting error is the sum of the saw cut misalignments and the deviation of the actual saw cut width from the nominal width, so the saw cut width must also be controlled. It is measured from a dummy saw cut on spare area of the wafer which does not require a PCM structure.

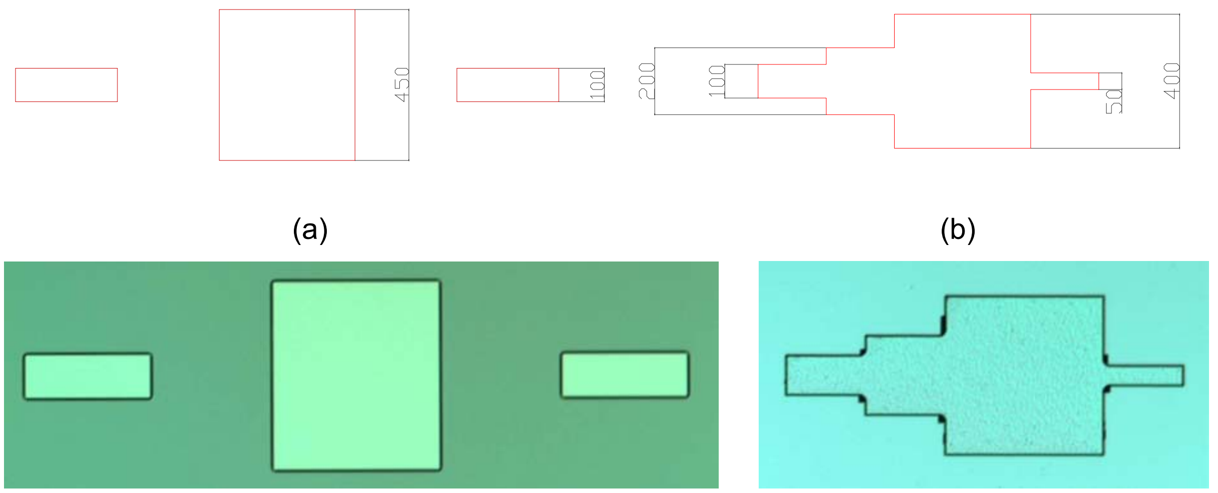



*Figure 29. Dimensioned CAD images ((a) and (b)) and microscopic images ((c) and (d)) of the two different dicing alignment structures. The dimensions are given in µm.*

### 6.3.1.5.4.3 Facilities

The dicing and the dicing alignment evaluation is carried out in a class 100000 clean room where the temperature is held at of 21±1°C.

### 6.3.1.5.4.4 Equipment

A high precision automatic dicing saw, such as Disco DAD 361 or similar, is needed for the dicing and the evaluation of the dicing accuracy.

### 6.3.1.5.4.5 Procedure

Both the alignment of the saw cut relative to the micropropulsion system structures and the evaluation of the cutting errors is done in the dicing saw. The dicing alignment PCM structures are used for both purposes.

The wafers are first aligned so that the rows of dicing alignment structures are oriented parallel to the intended saw cut. The saw cut should be straight through the centre of the dicing alignment structures in the horizontal direction in Figure 29 (a) and (b). The narrow parts of the structures are meant to facilitate the alignment of the saw cut. The two geometrically different designs of structures basically have the same function.

The first saw cut is in a left-over area on the wafer in order to centralise the indicator line on the computer screen to the saw cut, and assess the actual saw cut width. The saw cut width is measured with the dicing saw. If it differs less than 25% from the nominal blade width, a second saw cut along the first row of dicing PCM structures can be made.

The alignment of the saw cut to these PCM structures should be checked before continuing. It is measured relative to the edges of the wide parts of the PCM structures which require that some of the structures remain both above and below the saw cut, see Figure 30. Measures are taken from both the left- and the right-hand sides of the wafer in order to assess the rotational misalignment. If the total cutting error is within specification, the rest of the wafer can be diced up. The cutting errors of the other saw cuts are evaluated by the naked eye and controlled by measurements if judged to be needed.

Separate alignments and alignment checks must be performed for saw cuts in different directions.

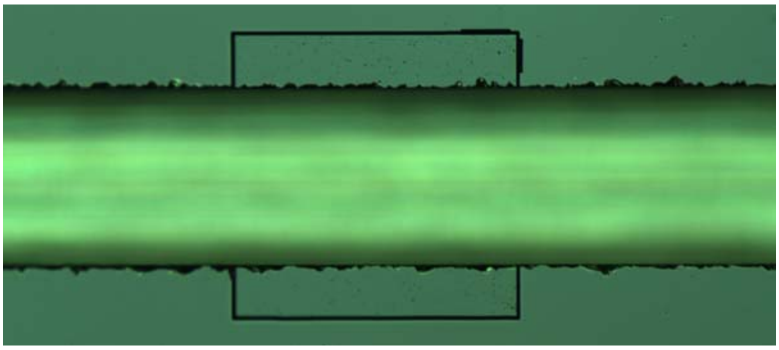


*Figure 30. Image of a saw cut through a dicing alignment structure. The alignment of the saw cut is measured relative to the edges of the structures which require that some of the structures remain both above and below the saw cut.*

## 6.3.1.5.4.6 Acceptance Criteria

The maximum allowed cutting error is generally ±40 µm, including translation and rotation cut misalignments, and saw cut width widening. For some samples, the error margins are ±100 µm. Chips that have been diced out within specifications shall be considered as having passed the test.

Diced out chips that do not pass the test are sorted out from further processing.

## 6.3.1.5.4.7 Validation

Both the alignment of the saw cut relative to the micropropulsion system structures and the evaluation of the cutting errors can be done in the dicing machine. The structures are clearly visible in the microscope of the dicing machine. They more or less retain their geometry and size throughout subsequent processing steps. The edges are distinct and the structures are easy to align and measure distances against. There are several structures per saw cut in case any of the structures are substandard. It is not necessary to know the absolute width of the structures in order to measure the alignment. Both wet and dry etched PCM structures work.

The measurements achieved in the dicing machine are sufficiently accurate. Compared to microscope measurements on the same structures, the total cutting errors differ by 1 %.

The dicing accuracy achieved using the dicing alignment structures is sufficiently good; the errors are measured to be 19.5±6.7 µm whereas the requirements are ±40 µm or ±100 µm. The largest cutting errors originate from cut width widening and not from saw cut misalignment. The former is 15.6±10.1 µm and the latter 3.9±3.5 µm.

The two PCM structures in Figure 29 (a) and (b) can be used to measure total cutting errors smaller than 125 and 100 µm respectively when a 200 µm wide blade is used.

The structure in Figure 29 (b) can be used to evaluate the cutting errors by a simple inspection if the maximum allowed cutting error is ±100 µm. Only the 200 µm and/or the 400 µm wide structures should be visible after cutting if the errors are within specification. An example of a properly cut structure is shown in Figure 30.

## 6.3.1.5.5 DRIE Process Control

### 6.3.1.5.5.1 Scope

DRIE process control is needed to assure the quality, uniformity, and reproducibility of the DRIE process. The DRIE process is one of the most important processes in the manufacturing of the micropropulsion system and also one of the most sensitive. The DRIE process is controlled with PCM structures implemented onto separate PCM wafers.

### 6.3.1.5.5.2 PCM Structures

#### 6.3.1.5.5.2.1 Mask Layout

The DRIE process control structures are implemented on a mask specially designed for the PCM wafers. The structures are mainly the same as those implemented on the masks for one of the micropropulsion system wafers, but additional structures are included to enable lateral etch rate measurements. Figure 31 shows a CAD layout of the mask.

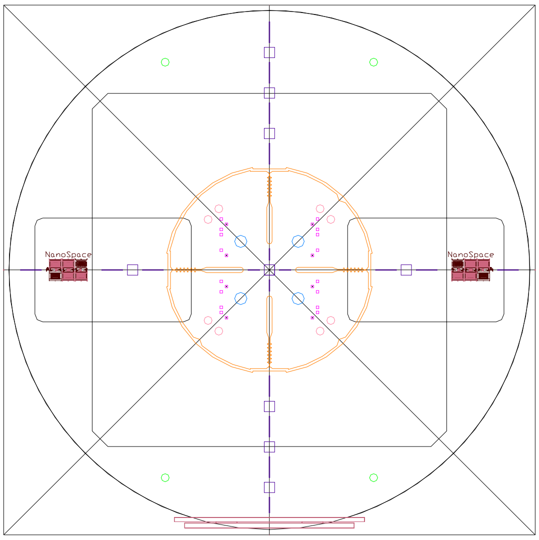



*Figure 31. CAD layout of the DRIE process control wafer.*

#### 6.3.1.5.5.2.2 Manufacturing

The DRIE process control wafers are manufactured according to standard oxidation, lithography, and oxide etching procedures. The DRIE etch step is always run according to the same process parameters and for the same period of time.

#### 6.3.1.5.5.2.3 Handling and Storage

The ready-made DRIE process control wafers are handled and stored under class 100-100000 clean room conditions. The temperature and the relative humidity in the clean room are controlled to be within 21±1°C and 43±5% respectively.

#### 6.3.1.5.5.2.4 Description

The DRIE process control wafers basically have the same design as one of the micropropulsion system wafers, but with an additional set of cavities. The micropropulsion system structures are implemented to imitate the processing conditions for real device wafers as much as possible. The etching process is very sensitive to open area. The cavities, Figure 32, are used for silicon etch depth measurements. The lateral variation can be assessed since the cavities are located at different wafer radii. The silicon etch aspect ratio is measured from cracked or diced up cross-sections of the same structures, Figure 33. The surface morphology of the etched surfaces is inspected both by the naked eye and in a microscope.

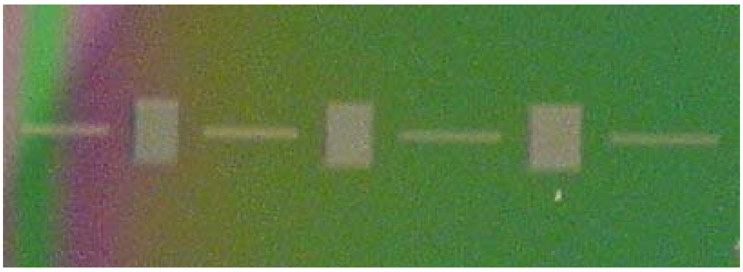


*Figure 32. Cavities used for silicon etch depth measurements.*

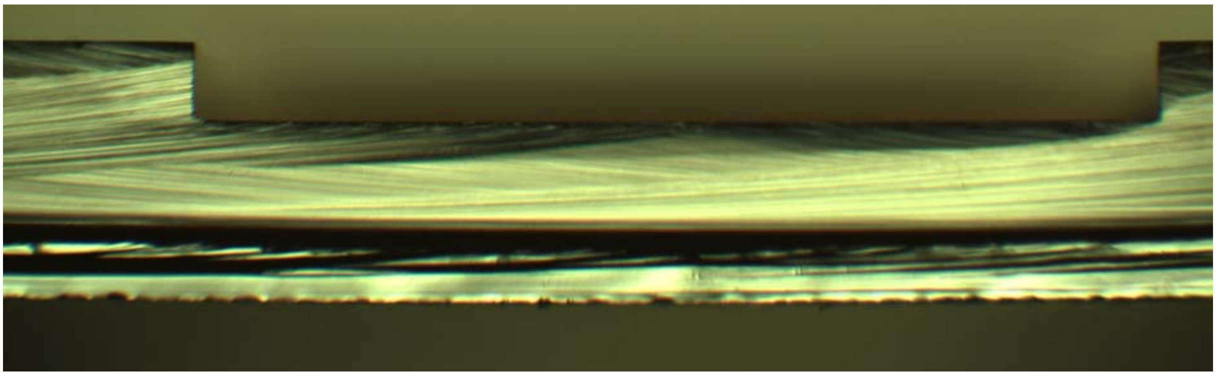


*Figure 33. Cross section of a cavity etched in silicon. The etch aspect ratio is obtained from measuring the angle between the cavity walls and the wafer surface.*

## 6.3.1.5.5.3 Facilities

The DRIE process control wafers are evaluated in a clean room area of class 100-100000, depending on the particular measurement that is being done. The temperature and the relative humidity are controlled to be within 21±1°C and 43±5% respectively.

## 6.3.1.5.5.4 Equipment

A microscope with at least x20 magnification is needed to inspect the morphology of the etched surfaces.

A surface profilometer or a microscope with at least x50 magnification and depth measurement capability is needed to measure the silicon etch depths.

A microscope with x20 magnification and a measurement software programme is needed to measure the etch aspect ratio.

A standard interferometer is used to measure the silicondioxide thickness.

## 6.3.1.5.5.5 Procedure

After the DRIE etching, the morphology of the etched surfaces is examined both by a naked eye and microscope inspection. The surfaces should be fairly smooth, without hillocks, and free from grass.

Hereafter, the etch depths of the rectangular cavities close to the centre and close to the edge of the PCM wafer is measured. At least two measures from each radius should be taken. The silicondioxide thickness is measured on the virgin surface in at least two points away from the edge of the wafer. The silicon etch rate, the lateral silicon etch depth uniformity, and the silicondioxide to silicon etch selectivity, are calculated and compared to the acceptance criteria.

The wafer is hereafter cracked or diced up along the rectangular cavities and the silicon etch aspect ratio is evaluated from the cross-section, see Figure 34.

The DRIE PCM wafers are run on a regular basis to detect any uncontrolled variation in the DRIE process. The wafers are always run after service or maintenance of the machine to ensure that it works properly.

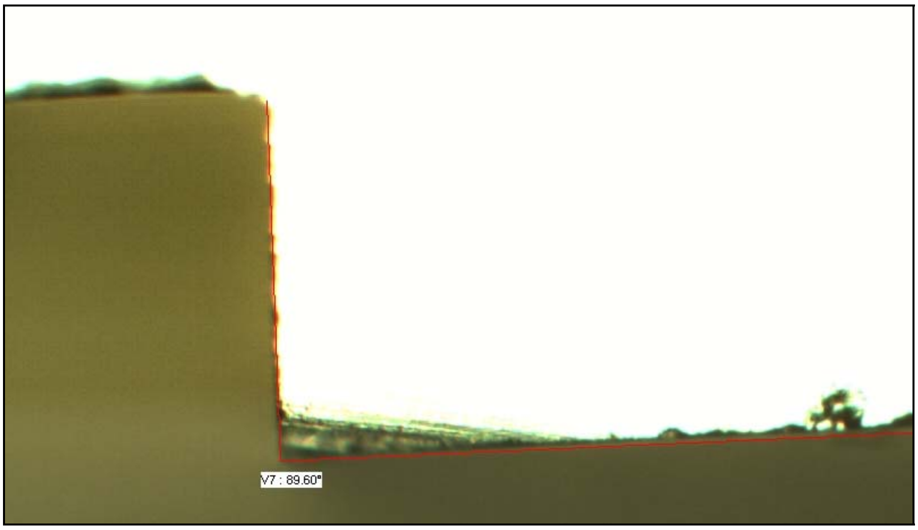



*Figure 34. Measurement of the silicon etch aspect ratio from the cross-section of a cavity diced in two.*

## 6.3.1.5.5.6 Acceptance Criteria

PCM wafers that have been evaluated and where the silicon etch rates are 6±1 µm/min, the lateral etch depth uniformity is within 5%, the silicondioxide to silicon etch rate ratio is 1:240 or better, and the etch aspect ratio is 1:40 or better should be considered as having passed the examination.

If a PCM wafer does not pass the examination, service or maintenance of the machine is required before any DRIE processing can commence.

## 6.3.1.5.5.7 Validation

The DRIE PCM wafers are very useful in controlling the DRIE process. They are processed on a continuous basis to detect any short or long term degradation in the process and always after service or maintenance to ensure that everything is quite in order.

The use of dedicated PCM wafers with a constant structure layout makes it easy to conclude whether the process is according to specification. It is easy to detect any uncontrolled variation in the DRIE process and distinguish it from natural variations. These variations could a manifest themselves as a short or long term degradation of the process caused by, for example, machine wear or failure, or merely contamination of the process chamber.

The inspections and measurements to be done are quick and easy. A simple inspection of the surface morphology of the etched surfaces and silicon etch depth measurements form a good picture of the status of the process. The silicon etch aspect ratio seem to have a tendency to follow the silicon etch rate, the higher the etch rate the better the aspect ratio.

The major drawback with the wafers is that it is difficult to crack the wafers on a straight line through the cavities. It is a bit cumbersome to dice the wafers.

## 6.3.1.5.6 Metallization Thickness Control

### 6.3.1.5.6.1 Scope

Metallization thickness control is needed to control the resulting resistances of thin film conductors deposited by evaporation. The resistances are controlled with PCM wafers. The QCM thickness control implemented into the evaporator has shown to be too unreliable. It is usually enough to rely on the QCM measurements, but some metallization require stricter control.

### 6.3.1.5.6.2 PCM Structures

#### 6.3.1.5.6.2.1 Mask Layout

The metallization thickness control structures are implemented onto a photolithography mask that is used to manufacture shadow masks for the evaporator. There are 31 identical PCM structures distributed over the mask area. Each structure consists of two identical conductors. Figure 35 shows a CAD layout of the mask.

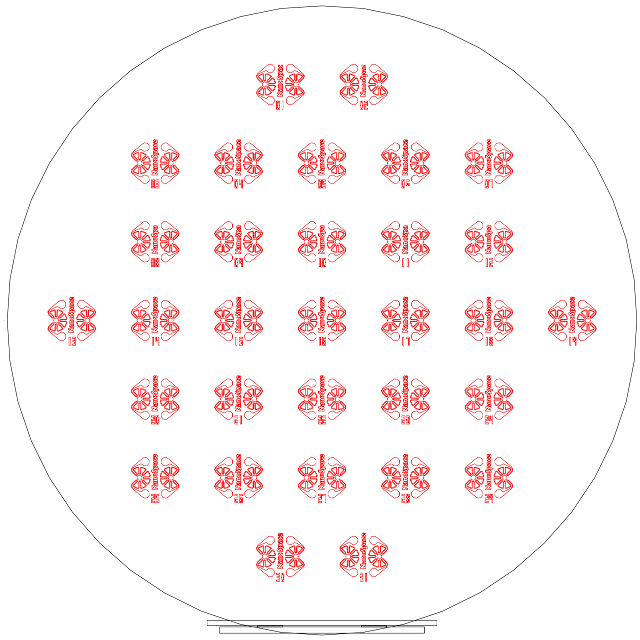


*Figure 35. CAD layout of the photolithography mask used for the manufacturing of metallization thickness control structures (red).*

### 6.3.1.5.6.2.2 Manufacturing

The metallization thickness control structures are deposited onto dummy wafers that run as precursors to the device wafers. The structures are deposited through the same shadow mask as the one used for the thin film conductors of the real device wafers.

### 6.3.1.5.6.2.3 Handling and Storage

The ready-made PCM structures and wafers are handled and stored under class 1000-10000 clean room conditions. The temperature and the relative humidity in the clean room are controlled to be within 21±1°C and 43±5% respectively.

### 6.3.1.5.6.2.4 Description

The metallization thickness PCM structures are evaporated through the same shadow mask and have the same lateral design as the real device structures. The resulting resistance of the PCM conductors is adjusted by varying the thickness of the evaporated metal. An image of the structures is shown in Figure 36.

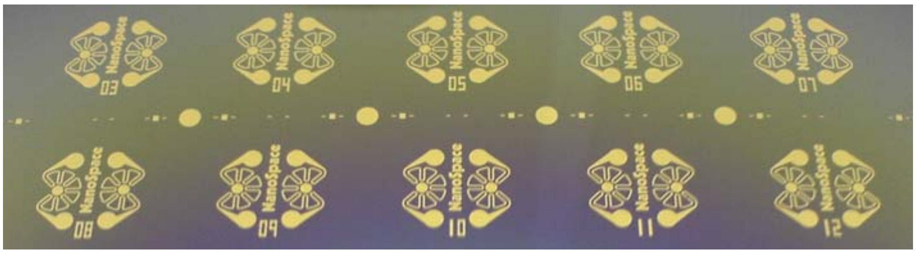



*Figure 36. Metallization thickness PCM structures.*

## 6.3.1.5.6.3 Facilities

The metallization work area is a clean room of class 1000-10000. The temperature and the relative humidity in the clean room are controlled to be within 21±1°C and 43±5% respectively.

## 6.3.1.5.6.4 Equipment

The metallization thickness control structures are evaluated by measuring the conductor resistances with a standard digital multimeter.

## 6.3.1.5.6.5 Procedure

After the evaporation of a metallization thickness PCM wafer, the resistances of the conductors are measured with a digital multimeter. At least two resistance values should be taken from each row of structures, see Figure 35. The metal thickness varies with the radius of the rotating wafer holder in the evaporator. The wafers are oriented so that the radius increases from the top in Figure 35 to the flat.

The average resistance achieved should be compared to the QCM thickness measurement. The evaporation should be repeated under adjusted processing conditions until the average resistance of the PCM conductors is within 50% from the acceptance criterion for the real devices. At this stage appropriate processing conditions can be calculated and the real device wafers can be metallized.

The device wafers should be metallized within a few days after that the PCM structure metallization was approved. The resistances of the device wafer conductors should be measured after evaporation.

#### 6.3.1.5.6.6 Acceptance Criteria

Device structures with resistance values measured to be within 50±10 Ω should be considered as having passed the examination. Devices that do not pass the test are sorted out from further processing.

#### 6.3.1.5.6.7 Validation

The procedure with precursor wafers in the evaporator generally works. The metallization thicknesses on the PCM wafers are possible to reproduce on real device wafers within acceptable error margins. Average resistance values from reproduced metallizations have a standard deviation of 10%.

A major drawback with the procedure is that it is very time consuming.

### 6.3.1.5.7 Metallization Adhesion Control

#### 6.3.1.5.7.1 Scope

Metallization adhesion control is needed to control the adhesion of thin film conductors deposited by evaporation. The adhesion must be sufficient to survive subsequent processing steps, such as dicing and soldering.

The adhesion is controlled with PCM structures. The test method measures adhesion qualitatively, providing a check that the adhesion is acceptable or alternatively identifying a potential problem.

#### 6.3.1.5.7.2 PCM Structures

##### 6.3.1.5.7.2.1 Mask Layout

The adhesion PCM structures are implemented as eight circles into left over areas on the same photolithography mask as the metallization thickness control PCM structures. The photolithography mask is used to manufacture a shadow mask for the evaporator. Figure 37 shows a CAD layout of the mask.

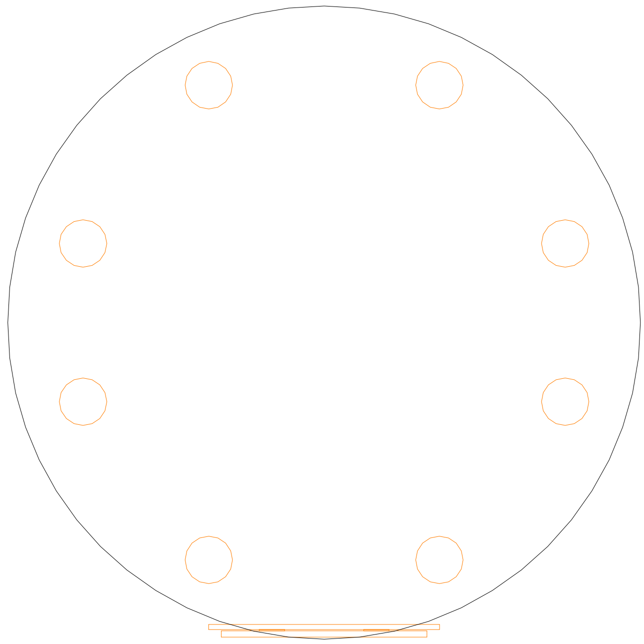


*Figure 37. CAD image showing the mask layout of the adhesion test structures (orange).*

### 6.3.1.5.7.2.2 Manufacturing

The adhesion PCM structures are evaporated in the same production run as the real micropropulsion system wafers, and they are evaporated onto real micropropulsion system wafers. In those cases where evaporation is performed on chip level, spare pieces from the same wafers are used for the adhesion PCM structures.

### 6.3.1.5.7.2.3 Handling and Storage

The ready-made PCM structures and wafers are handled and stored under class 1000-10000 clean room conditions. The temperature and the relative humidity in the clean room are controlled to be within 21±1°C and 43±5% respectively.

### 6.3.1.5.7.2.4 Description

The adhesion PCM structures consist of 7.5 mm diameter circles of metal evaporated onto the wafer surfaces. The fracture initiations are the edges of the structures; they are defined by the shadow mask. The circular shape makes the application of the tape insensitive to direction.

## 6.3.1.5.7.3 Facilities

The work area is a clean room of class 1000-10000. The temperature and the relative humidity in the clean room are controlled to be within 21±1°C and 43±5% respectively.

## 6.3.1.5.7.4 Equipment

A tape with an adhesion to steel of 44 N/100 mm is used for the adhesion test. The tape has a shelf life of 12 months.

A microscope with x20 magnification is needed to examine the surfaces of the tape and the PCM structures.

#### 6.3.1.5.7.5 Procedure

The tape test is performed immediately after evaporation. The wafer or the chip is placed on a smooth flat surface with the PCM structures facing up. A piece of tape about 5 cm long is discarded and removed from the roll. The freshly exposed tape is pressed firmly onto the test structure, touching the adhesive side only at the ends. The tape should cover the test structure completely. Smooth with thumb and forefinger to ensure good contact. To facilitate separation, one end of the tape should be doubled over. The sample is held down with one hand, and peeled up at 90 degrees in one smooth movement with the other hand. The PCM structure is examined for metal removal and the tape for metal transfer.

#### 6.3.1.5.7.6 Acceptance Criteria

Structures that have been tested and where the edges of the PCM structures are smooth, and where the area within the structures are free from flaking or limited to a few <50 micrometer sized flakes, shall be considered as having passed the test.

Wafers that do not pass the test are sorted out from further processing.

#### 6.3.1.5.7.7 Validation

Both the test procedure and the evaluation are easy to carry out. The evaluation is easily comprehensible although subjective to some extent.

It is difficult to evaluate the test results by inspecting the tape surface if the flaking is small.

It would be desirable having smaller diameter PCM structures so that the whole area can be seen under the microscope at once.

### 6.3.1.6 Quality Analysis Methodology Conclusions

The PCM structures in the study are all easy to use, and generally quick and easy to evaluate. The measurement structures sometimes include a scale which simplifies the evaluation since it can be done in many ordinary microscopes. The scales are furthermore detailed which facilitates the operator’s judgement.

The PCM structures have also shown to be efficient and capable to control the processes that they were designed to control. The accuracy achieved with the different structures and methods are sufficiently good.

The tests also made it possible to assess the stability of the manufacturing processes. It is shown to be good in most cases, more than sufficient for our purposes. Less stable processes, like metallization, are at least possible to control using the PCM structures and the associated test methods.

Using the PCM structures and the associated quality analysis methodology, it has shown to be possible to reproduce the manufacturing of the MEMS thruster chip while maintaining the quality and uniformity of the device.

## 6.4 Qualification and Acceptance Test Plan

A generic requirement specification for the subject micropropulsion system was established as an input to this test plan /RD 3/. To justify the selection of the generic requirements, the requirements of two relevant missions were considered, i.e. Prisma and Proba-3. The requirements for Proba-3 are still not fixed, they are most likely going to be revised in the future according to /RD 4/.

### 6.4.1 Proba 3

Proba 3 is the first ESA FF mission. It is intended to be a test bed for enabling technologies for precision FF missions. Another objective is to fly a sun coronagraph payload that can directly benefit from the innovations under test. Proba 3 consists of two spacecraft, the Coronagraph and the Occulter, flying 25-250 m from each other with a positioning accuracy better than one millimetre. Both spacecraft will be equipped with propulsion systems. Since there is no single thruster that is capable of covering both the higher thrust regime for the basic FF mission and the lower thrust regime required for demonstrating the full envelope of future precision FF missions, a combination of high and low thrust thrusters are considered for the spacecraft /RD 5/ and /RD 6.

### 6.4.2 MEMS Micropropulsion System

The cold gas MEMS thruster unit consists of a MEMS thruster chip that is accommodated in a conventional pod and has an electrical interface of flying leads. It has four orthogonal thrusters that can be fired alone or up to all four at the same time. Each thruster is able to deliver a thrust in the micro- to milli-Newton range. The total weight of the MEMS thruster unit is 115 g. The unit operates with $N_2$ as propellant at an applied pressure of 4 Bar. It needs to be connected to a gas reservoir and a pressure regulator to complete the micropropulsion system.

The MEMS thruster chip is made from six micromachined fusion bonded silicon chips. It includes four nozzles and four proportional, paraffin-actuated, normally closed valves. The valves are used to individually regulate the gas flow to the four nozzles. The stroke of the valves is controlled by heating the paraffin with a voltage applied across internal paraffin heaters. The nozzles also have internal heaters, which heat the gas in a similar manner and thus improve the specific impulse. Figure 38 shows photographs of the MEMS thruster chip and the thruster pod.

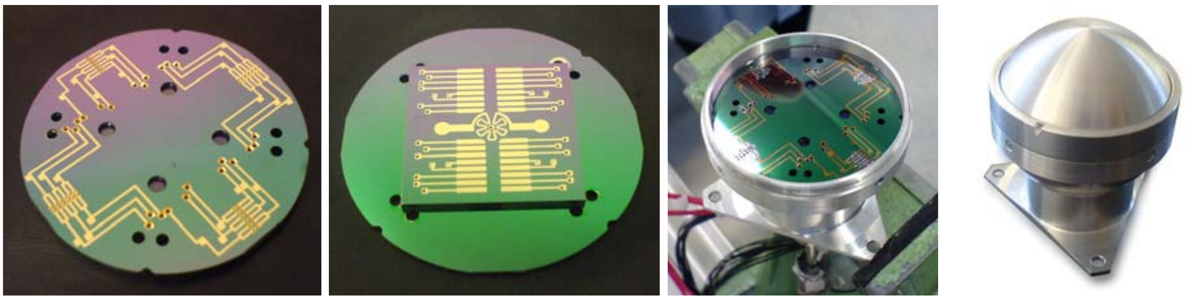


*Figure 38. The photographs to the left show the top and the bottom sides of the MEMS thruster chip while the photographs to the right show the thruster pod.*

### 6.4.3 Qualification Test Plan

The proposed qualification test sequence for the micropropulsion system is given below together with more detailed specifications on the different tests. All qualification tests should be performed on the same micropropulsion system unit; performance and life tests on the same thruster.

#### 6.4.3.1 Test Objectives

The overall test objective is to evaluate and establish a cold gas micropropulsion system design that will pass the qualification tests of the Proba 3 mission. Requirements and objectives related to FF manoeuvres, GNC design, and mission life are the primary design drivers for the micropropulsion system. The test specification is based on requirements given in the requirement specification of the micropropulsion system /RD 3/. The specifications are conformal to the ESA Space Engineering Testing Standard /RD 7/.

The baseline launcher of Proba 3 is Vega; the test specifications in this document are, however, not only compliant to Proba 3 but aims at making the micropropulsion system compliant to as many missions as possible. The ideal situation would be that the micropropulsion system is tested to such levels that it is compliant with any spacecraft mounted on any launch vehicle in the world. This is not fully possible but the last sections in this document are dedicated to justify that the chosen test levels have good chances to be compliant to many launchers from different parts of the world.

One micropropulsion system QM should be manufactured, assembled, and tested. It should preferably be identical to the FM when it comes to the MEMS hardware, but tests could be performed with a MEMS thruster chip having only one fully functioning thruster, and minor defects such as missing nozzle heaters in the others. The QM should be identical to the FM when it comes to parts that are judged to affect the mechanical, electrical, and thermal interfaces to the MEMS hardware. Failure to survive the random vibration tests for example, might as well depend on the interface between the MEMS thruster chip and the pod as on the structural design of the thruster chip itself.

Radiation tests for total ionising dose (TID) are planned to be performed in parallel to the qualification tests above. The radiation tests follow the ESA/SCC basic specification no. 22900 /RD 16/. Three micropropulsion system QM should be manufactured for these tests. The radiation sensitive elements are judged to be the paraffin and the gas heaters. Since each micropropulsion system has four paraffin heaters and twelve gas heaters this would result in 12 and 36 test elements respectively.

#### 6.4.3.2 Test Sequence

The radiation test sequence in Table 10 is planned to be performed on three micropropulsion system QMs. The qualification test sequence for the other environmental tests is shown in Table 11. It is planned to be performed on one QM.

*Table 10. Radiation test sequence for the MEMS micropropulsion system.*

| Test Sequence | Test Description |
|---|---|
| 1 | Functional and Performance |
| 2 | Radiation TID |
| 3 | Functional and Performance |

*Table 11. Qualification test sequence for the MEMS micropropulsion system.*

| Test Sequence | Test Description |
|---|---|
| 1 | Physical Properties |
| 2 | Functional and Performance |
| 3 | Proof Pressure |
| 4 | Leak |
| 5 | Functional and Performance |
| 6 | Sinusodial Vibration |
| 7 | Random Vibration |
| 8 | Shock |
| 9 | Leak |
| 10 | Functional and Performance |
| 11 | Thermal Cycling |
| 12 | Functional and Performance |
| 13 | Leak |
| 14 | Life |
| 15 | Functional and Performance |
| 16 | Disassembling and inspection |

#### 6.4.3.3 Test Specifications

##### 6.4.3.3.1 Radiation TID

The radiation tests are performed with gamma radiation to a total ionising dose of 100 krad. With a qualification margin of two, this would qualify the micropropulsion system for a four year mission in an orbit similar to the one of Proba-3. The irradiation is performed with a Co60 gamma source. The dose rate should be 3.6-36 krad per hour. The temperature should b e+20±10°C and should not vary more than ±3°C during the irradiation exposure. The dose errors should be below 15%, accounting for errors in field uniformity and dosimeter accuracy.

The tests should preferably be performed on naked MEMS chips. If the chips are mounted in to pods, the irradiation time must be adjusted so that the total dose is reached.

##### 6.4.3.3.2 Physical Properties

The micropropulsion system dimensions, mass, centre of gravity, and momentum of inertia are measured in the physical properties test.

##### 6.4.3.3.3 Functional and Performance

The proposed functional and performance firing test sequence for the micropropulsion system is given in Table 12. The test is performed on the same thruster. $N_2$ is used as propellant and the applied pressure is 4 Bar. The mass flow is regulated by adjusting the voltage across the paraffin heaters. The nozzle heaters are run at constant applied voltage; they are turned on and off at the same time as the paraffin heaters.

The thrust is measured as a function of time during the functional and performance test, as well as the power dissipation in the paraffin and nozzle heaters. The micropropulsion system shall be considered having passed the test if:

- the thrust repeatability is within ±10% for the cycling test
- the specific impulse variation is within ±3%
- the response time to 90% of steady state thrust is <1 s
- the tail-off to 10% of steady state thrust is <500 ms
- the valve heater resistance is within ±5%
- the nozzle heater resistance is within ±10%

*Table 12. Functional and performance firing test sequence for the micropropulsion system.*

| Test Sequence | Description | Inlet Pressure [Bar] | Mass Flow [mg/s] | Cycle Time On/Off [s] | Number of Cycles |
|---|---|---|---|---|---|
| 1 | Cycling 1 mN | 4 | 1.70 | 30/30 | 20 |
| 2 | Cycling 10 µN | 4 | 0.02 | 6/54 | 20 |

### 6.4.3.3.4 Proof Pressure

A proof pressure cycle is performed by raising the internal pressure of the micropropulsion system to the proof pressure (6 bar), maintaining the pressure at this level for 5 minutes, and hereafter reducing it to ambient conditions. At least 3 cycles should be performed.

### 6.4.3.3.5 Leak

The leak tests are performed with the micropropulsion system pressurised with He to MEOP. The leak rate is determined with a He leak detector. The external test pressure should be $10^{-3}$ hPa or less and the duration of the test at least 2 hours. The total external leakage should not exceed $1 \cdot 10^{-5}$ scc/s, the total internal leakage should not exceed $1 \cdot 10^{-4}$ scc/s.

### 6.4.3.3.6 Sinusodial Vibration

The sinusoidal vibration tests are performed in each of three mutually perpendicular axes of the micropropulsion system, with a zero to peak amplitude of 11 mm between 5-21 Hz, a peak acceleration of 20 g between 21-60 Hz, and a peak acceleration of 6 g between 60-100 Hz. One sweep should be performed. The sweep rate should be 2 octaves per minute.

The sinusoidal and random vibration tests are performed sequentially, one axis at a time. To evaluate micropropulsion system integrity, a low level sinusoidal vibration test is performed before and after the two qualification level vibration tests on each axis. The resonance search test parameters are: 0.5 g, 5-2000 Hz, 2 octaves per minute.

### 6.4.3.3.7 Random Vibration

The random vibration tests are performed in each of three mutually perpendicular axes of the micropropulsion system. In the direction perpendicular to the fixation plane, the PSD level is increased 3 dB/octave between 20-100 Hz, it is held at 2.2 $g^2$/Hz between 100-300 Hz, and decreased 5dB/octave between 300-2000 Hz. Parallel to the fixation plane, the PSD level is held at 0.9 $g^2$/Hz between 100-300 Hz, the PSD level increase and decrease between 20-

100 Hz and 300-2000 Hz respectively, is the same as for the direction perpendicular to the fixation plane. The test duration is 2.5 minutes in each axis.

The sinusoidal and random vibration tests are performed sequentially, one axis at a time. For each axis, a low level sinusoidal vibration test is performed before and after the qualification level vibration tests, see paragraph 6.4.3.3.6.

#### 6.4.3.3.8 Shock

At least three shocks should be imposed on the micropropulsion system in both directions in each of the three orthogonal axes. It shall be tested on a ringing table test stand to the levels prescribed Table 13 below. The shock levels are calculated with a Q-factor of 10.

*Table 13. Shock test specifications.*

| Frequency [Hz] | SRS level (Q=10) [g] |
|---|---|
| 100 | 20 |
| 600 | 1080 |
| 2000 | 3000 |
| 10000 | 3000 |

#### 6.4.3.3.9 Thermal Cycling

The thermal cycling test is conducted with the micropropulsion system suspended in a temperature cycling chamber. It starts by increasing the temperature to maximum non operating temperature plus 10°C, with the micropropulsion system switched off. After a dwell time of 2 hours, the temperature is decreased to the maximum operating temperature plus 10°C. After 2 hours, functional and performance tests are performed. Hereafter, the system is switched off and the temperature is decreased and maintained at the minimum non operating temperature minus 10°C for 2 hours. The temperature is increased to the minimum operating temperature minus 10°C and the system is switched on. After 2 hours, functional and performance tests are performed. Hereafter, the system is cycled 8 times between maximum and minimum operating temperatures plus and minus 10°C respectively. The dwell time is 2 hours at each temperature extreme. During the last cycle the system is functionally tested at both temperature extremes. The minimum and maximum operating temperatures are 0°C and 50°C respectively; the non operating temperature extremes are -10°C and 60°C.

#### 6.4.3.3.10 Life

The qualification level estimates used as baseline are given in Table 14. They are based on the generic requirements given in the requirement specification of the micropropulsion system /RD 3/. The estimates also cover the requirements of the Proba 3 mission.

*Table 14. Life test qualification level estimates for the MEMS micropropulsion system.*

| Requirement | Qualification Level Estimate |
|---|---|
| Thrust Level | 10 μN—1 mN |
| Smallest Impulse Bit | $6 \cdot 10^{-5}$ Ns |
| Total Impulse | 15000 Ns |
| $I_{sp}$ | 60 s |
| Propellant Throughput | 30 kg |
| Accumulated Burn Time | 3750 h |
| Cycles Life | 100 000 |

The proposed life test sequence is given in Table 15. The whole test is performed on the same thruster. $N_2$ is used as propellant and the applied pressure is 4 Bar. The mass flow is regulated by adjusting the voltage across the paraffin heaters. The nozzle heaters are run at constant applied voltage; they are turned on and off at the same time as the paraffin heaters.

*Table 15. Proposed life test sequence for the micropropulsion system.*

| Test Sequence | Description | Mass Flow [mg/s] | Cycle Time On/Off [s] | Number of Cycles | Impulse Bit [Ns] | Total Firing Time [h] | Propellant Throughput [kg] | Total Impulse [Ns] |
|---|---|---|---|---|---|---|---|---|
| 1 | Continuous 1 mN | 1.70 | 3600/0 | 1 | -- | 1 | $6.1 \cdot 10^{-3}$ | 3.6 |
| 2 | Continuous 0.1 mN | 0.17 | 3600/0 | 1 | -- | 1 | $6.1 \cdot 10^{-4}$ | $3.6 \cdot 10^{-1}$ |
| 3 | Continuous 10 μN | 0.02 | 3600/0 | 1 | -- | 1 | $6.1 \cdot 10^{-5}$ | $3.6 \cdot 10^{-2}$ |
| 4 | Cycling 1 mN | 1.70 | 30/30 | 120 | $3.0 \cdot 10^{-2}$ | 1 | $6.1 \cdot 10^{-3}$ | 3.6 |
| 5 | Continuous 1 mN | 1.70 | 8640000/0 | 1 | -- | 2400 | 15 | $8.6 \cdot 10^{3}$ |
| 6 | Cycling 1 mN | 1.70 | 30/30 | 288000 | $3.0 \cdot 10^{-2}$ | 2400 | 15 | $8.6 \cdot 10^{3}$ |
| 7 | Continuous 10 μN | 0.02 | 3600000/0 | 1 | -- | 1000 | $6.1 \cdot 10^{-2}$ | $3.6 \cdot 10$ |
| 8 | Cycling 10 μN | 0.02 | 6/54 | 600000 | $6.0 \cdot 10^{-5}$ | 1000 | $6.1 \cdot 10^{-2}$ | $3.6 \cdot 10$ |
| 9 | Continuous 1 mN | 1.70 | 3600/0 | 1 | -- | 1 | $6.1 \cdot 10^{-3}$ | 3.6 |
| 10 | Continuous 0.1 mN | 0.17 | 3600/0 | 1 | -- | 1 | $6.1 \cdot 10^{-4}$ | $3.6 \cdot 10^{-1}$ |
| 11 | Continuous 10 μN | 0.02 | 3600/0 | 1 | -- | 1 | $6.1 \cdot 10^{-5}$ | $3.6 \cdot 10^{-2}$ |
| 12 | Cycling 1 mN | 1.70 | 30/30 | 120 | $3.0 \cdot 10^{-2}$ | 1 | $6.1 \cdot 10^{-3}$ | 3.6 |
| Total | -- | -- | -- | 888248 | -- | 6808 | 30 | 17367 |

### 6.4.3.4 Test Levels Justification

Test levels for units on the spacecraft are not specified in the different launch vehicle user's manuals, there are only specifications on system level. The unit level test specifications are unique for every spacecraft-launcher combination and are specified in each project by the launcher authority based on:

- the launch vehicle
- the design of the spacecraft
- the configuration of the spacecraft on the launcher
- the units location on the spacecraft

As a consequence of this it is not simple to set up a universal test specification covering a range of launch vehicles and all possible kinds of spacecraft's and launch configurations aboard those. The specifications in this document are originating from the ECSS standard ECSS-E-10-03A /RD 7/, which originates from Ariane 4 and 5 environment levels.

In cases when Ariane 5 has the most severe environment compared to other launch vehicles the unit level test specification originating from Ariane 5 will likely cover most other launch vehicles also. In cases where other launch vehicles have a more severe environment than Ariane 5, the Ariane 5 native unit level specification shall be raised a bit to comply with as many launch vehicles as possible.

The launch vehicles in the comparison are:

- Ariane 5
- Soyus
- Dnepr
- Rockot
- Cyclon 2K
- Vega
- PSLV
- H-IIA

The specifications in this document have also been compared to actual test specifications used in the SMART-1 project (launched with Ariane 5 generic 2003).

#### 6.4.3.4.1 Sinusodial Vibration

The micropropulsion unit level sine vibration specification is taken from the ECSS standard ECSS-E-10-03A /RD 7/ and thereby originating from Ariane. Figure 39 shows that the Ariane 5 longitudinal sine specification covers all other above 40 Hz. The Vega specification in the graph is preliminary; at the time being it is frozen and is 0.8 g between 5 and 45 Hz and 1.0 g between 45 and 100 Hz. The lateral specification for Vega in Figure 40 is also preliminary. In frozen state it is 0.8 g between 5 and 25 Hz and 0.5 g between 25 and 100 Hz. This means that the Ariane 5 spectrum covers all other above 30 Hz except from Rockot, see Figure 40. The negative marginal to Rockot is minimal.

The micropropulsion system test level (max 20 g in the range 21-60 Hz) is higher than the test level used in the SMART-1 project where the maximum acceleration was 15 g. The micropropulsion system test level is thereby higher than test levels actually used for an Ariane 5 launched spacecraft.

The conclusion is that the sine vibration specification has a good chance to be compliant to many launchers.

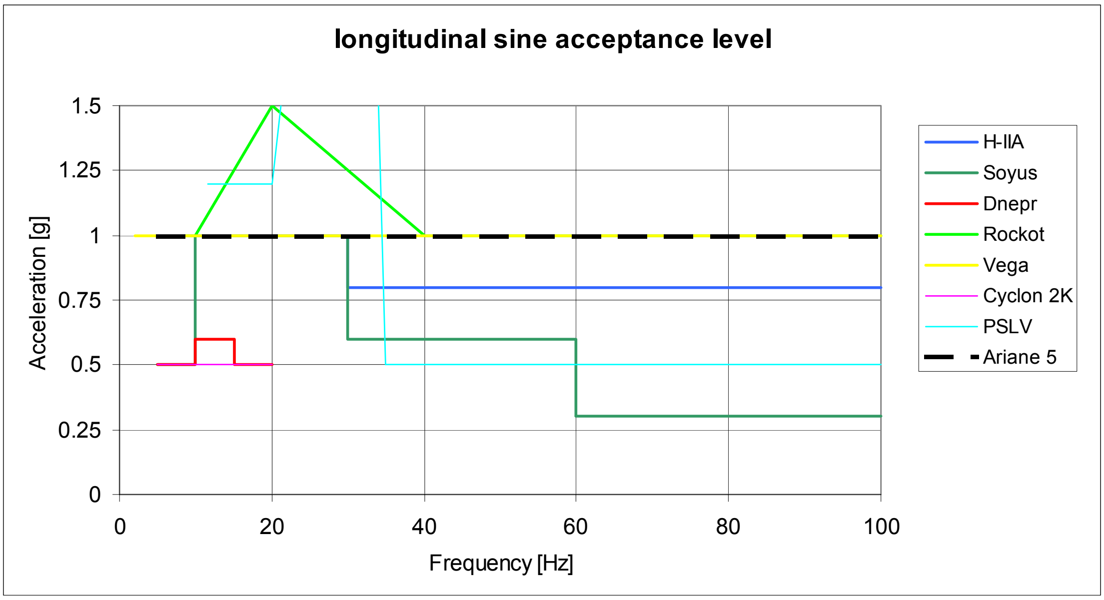



*Figure 39. Comparison of launcher sine acceptance specifications. The Vega specification in the graph is preliminary; at the time being it is frozen and is 0.8 g between 5 and 45 Hz and 1.0 g between 45 and 100 Hz.*

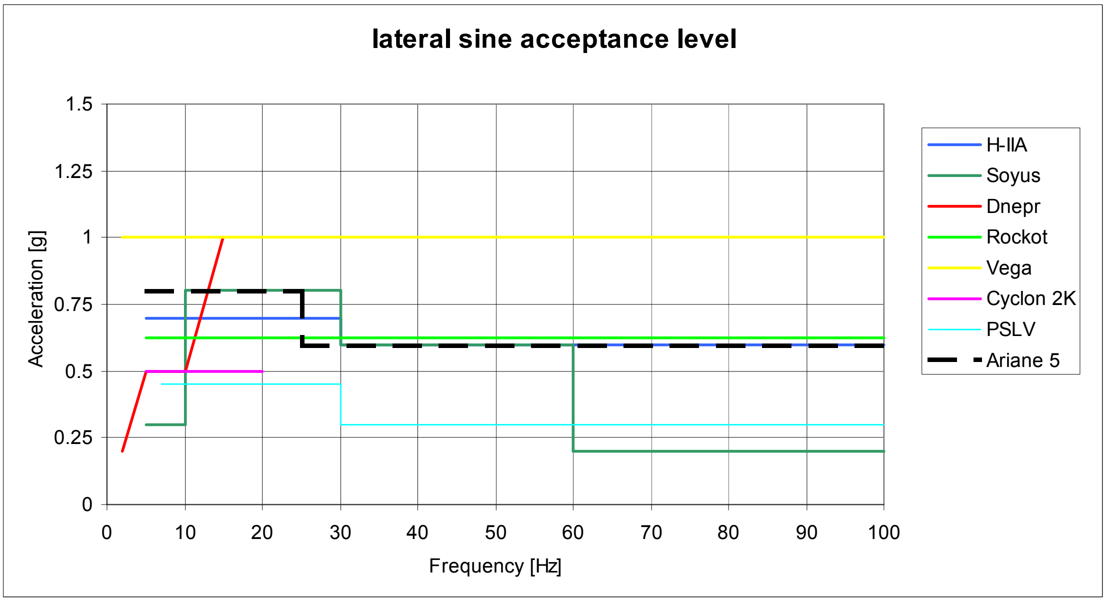



*Figure 40. Comparison of launcher sine acceptance specifications. The Vega specification in the graph is preliminary; at the time being it is frozen and is 0.8 g between 5 and 25 Hz and 0.5 g between 25 and 100 Hz.*

## 6.4.3.4.2 Random Vibration

The micropropulsion system unit level random vibration specification is taken from the ECSS standard ECSS-E-10-03A /RD 7/ and thereby originating from Ariane. As seen in Figure 41 the Ariane 5 acoustic environment is among the most severe in the comparison. The acoustic environment is contributing strongly to the random vibrations imposed on the units on the spacecraft. The most interesting frequency band is between 100 and 300 Hz where the random vibration unit specification has its maximum. Ariane 5 has the highest sound pressure level at those frequencies. Therefore the Ariane 5 unit level random vibration specifications probably will cover also other launcher alternatives.

The conclusion is that the random vibration specification has a good chance to be compliant to many launchers.

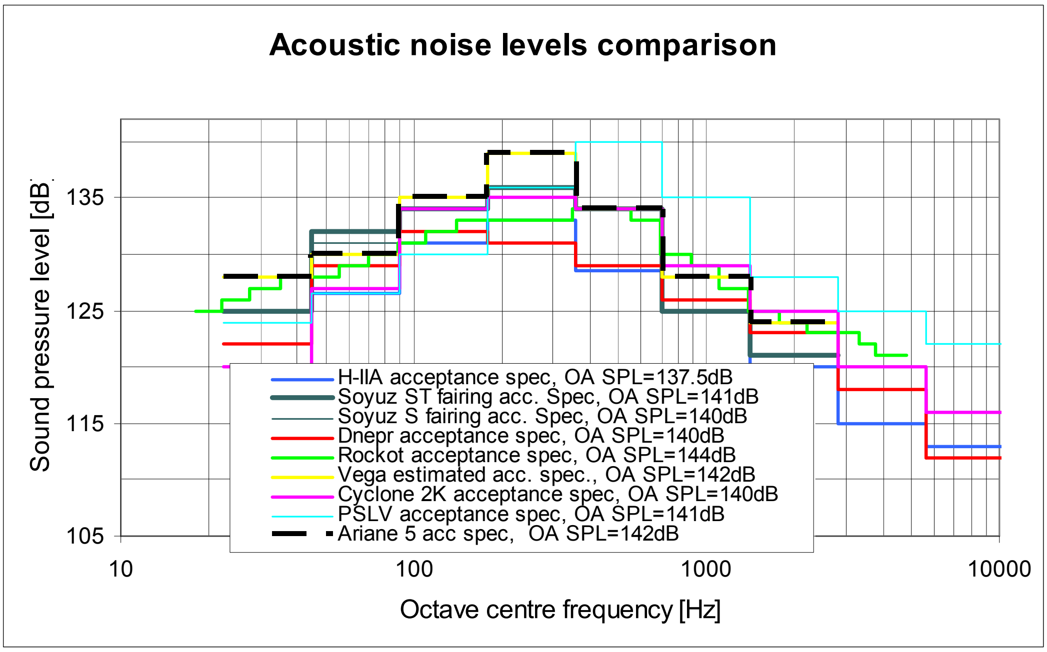



*Figure 41. Comparison of launcher acoustic acceptance specifications.*

## 6.4.3.4.3 Shock

Shock response spectrums (SRS) (valid at the interface between spacecraft and launcher) of different launchers are compared in Figure 42. As seen, the Ariane 5 shock environment is among the most severe. Therefore the unit level shock specifications originating from Ariane 5 probably will cover also other launcher alternatives.

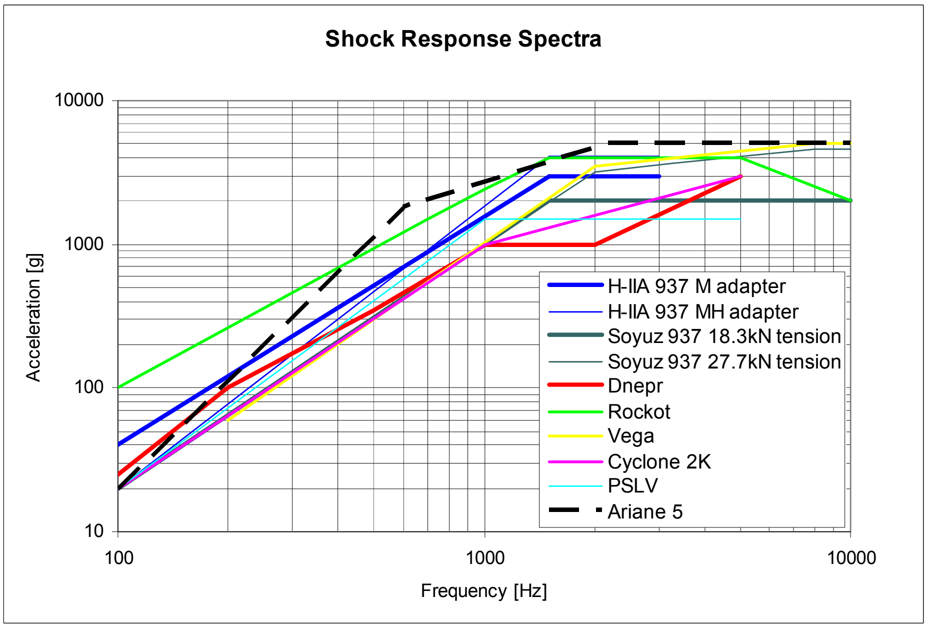



*Figure 42. Comparison of launcher shock specifications.*

SSC has an extensive experience in shock testing from the SMART-1 project. SMART-1 unit level shock tests were performed on a ringing table to test levels derived from the Ariane 5 shock specification. The shock level within a spacecraft differs depending on location and is highest close to the launcher interface. In SMART-1 this was reflected in different zones with different unit level shock specifications, see Table 16 and Figure 43. The highest unit level shock specification in SMART-1 was zone 2.

*Table 16. SMART-1 shock test specifications.*

| Frequency | Zone 1 | Zone 2 | Zone 3 |
|---|---|---|---|
| 100 | 20 | 20 | 20 |
| 600 | 1800 | 1080 | 540 |
| 2000 | 5000 | 3000 | 1500 |
| 10000 | 5000 | 3000 | 1500 |

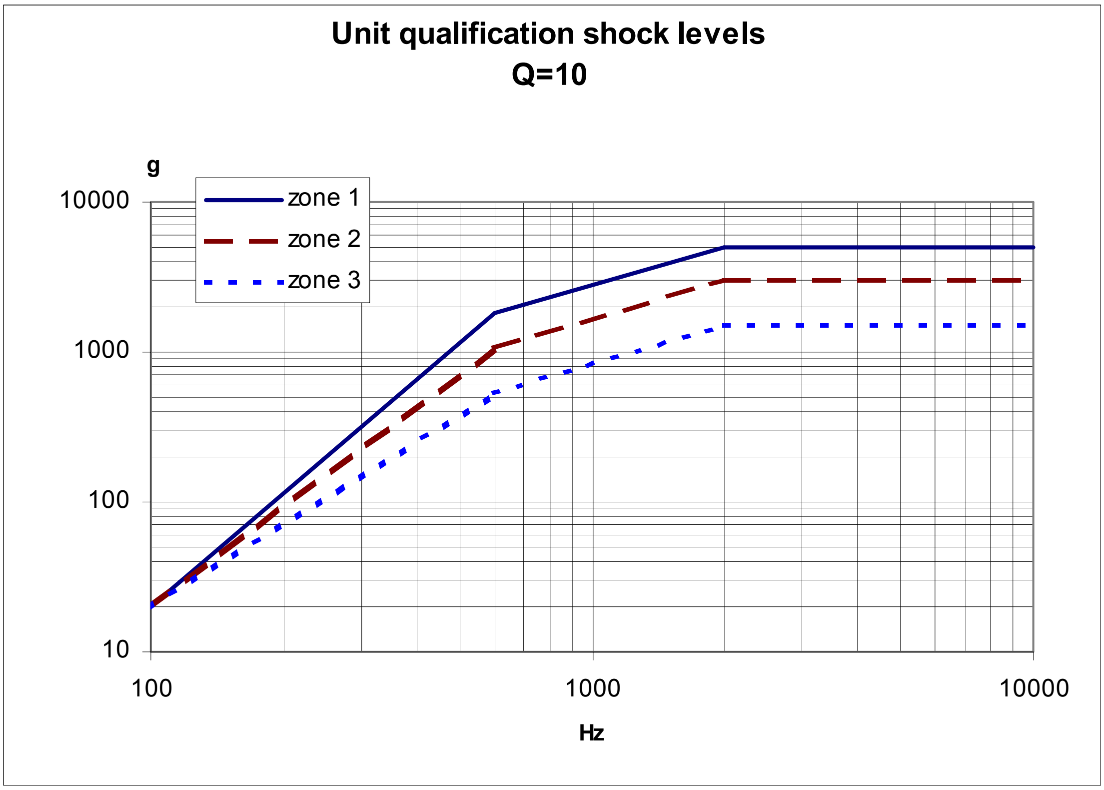



*Figure 43. SMART-1 shock test specifications.*

The conclusion is that the shock specification has a good chance to be compliant to many launchers.

### 6.4.4 Acceptance Test Plan

The purpose of acceptance testing is to demonstrate conformance to specification and to detect manufacturing defects, which have not been detected within the process qualification. The proposed acceptance test sequence for the micropropulsion system is given below together with more detailed specifications on the different tests.

#### 6.4.4.1 Test Objectives

The goal with an acceptance test is to demonstrate the readiness of the system to be delivered and to verify conformance to specification.

All flight models are to be acceptance tested, including flight spares.

#### 6.4.4.2 Acceptance Test Levels

The environmental conditions during acceptance testing should not exceed the expected conditions during the mission (except for the thermal tests where a margin of 5 deg C should be added to compensated for uncertainties in mathematical models) Life time tests and destructive steps, such as disassembling, are excluded.

#### 6.4.4.3 Test Sequence

The acceptance test sequence shown in Table 17 is planned to be performed on all micropropulsion system FMs.

*Table 17. Acceptance test sequence for the MEMS micropropulsion system.*

| Test Sequence | Test Description |
|---|---|
| 1 | Physical Properties |
| 2 | Functional and Performance |
| 3 | Proof Pressure |
| 4 | Leak |
| 5 | Functional and Performance |
| 6 | Sinusodial Vibration |
| 7 | Random Vibration |
| 8 | Shock |
| 9 | Leak |
| 10 | Functional and Performance |
| 11 | Thermal Cycling |
| 12 | Functional and Performance |
| 13 | Leak |

#### 6.4.4.4 Test Specifications

##### 6.4.4.4.1 Physical Properties

The micropropulsion system dimensions, mass, centre of gravity, and momentum of inertia are measured in the physical properties test.

#### 6.4.4.4.2 Functional and Performance

The proposed functional and performance firing test sequence for the micropropulsion system is given in Table 17. The test is performed on all thrusters. $N_2$ is used as propellant and the applied pressure is 4 Bar. The mass flow is regulated by adjusting the voltage across the paraffin heaters. The nozzle heaters are run at constant applied voltage; they are turned on and off at the same time as the paraffin heaters.

The thrust is measured as a function of time during the functional and performance test, as well as the power dissipation in the paraffin and nozzle heaters. The micropropulsion system shall be considered having passed the test if:

- the thrust repeatability is within ±10% for the cycling test
- the specific impulse variation is within ±3%
- the response time to 90% of steady state thrust is <1 s
- the tail-off to 10% of steady state thrust is <500 ms
- the valve heater resistance is within ±5%
- the nozzle heater resistance is within ±10%

*Table 18. Functional and performance firing test sequence for the micropropulsion system.*

| Test Sequence | Description | Inlet Pressure [Bar] | Mass Flow [mg/s] | Cycle Time On/Off [s] | Number of Cycles |
|---|---|---|---|---|---|
| 1 | Cycling 1 mN | 4 | 1.70 | 30/30 | 10 |
| 2 | Cycling 10 µN | 4 | 0.02 | 6/54 | 10 |

#### 6.4.4.4.3 Proof Pressure

A proof pressure cycle is performed by raising the internal pressure of the micropropulsion system to 1,5 the nominal pressure (6 bar) maintaining the pressure at this level for 5 minutes, and hereafter reducing it to ambient conditions. At least 3 cycles should be performed.

#### 6.4.4.4.4 Leak

The leak tests are performed with the micropropulsion system pressurised with He to MEOP. The leak rate is determined with a He leak detector. The external test pressure should be $10^{-3}$ hPa or less and the duration of the test at least 2 hours. The total external leakage should not exceed $1 \cdot 10^{-5}$ scc/s, the total internal leakage should not exceed $1 \cdot 10^{-4}$ scc/s.

#### 6.4.4.4.5 Random Vibration

The random vibration tests are performed in each of three mutually perpendicular axes of the micropropulsion system. The PSD level is increased 3 dB/octave between 20-80 Hz, it is held at 0.04 $g^2$/Hz between 80-350 Hz, and decreased 3 dB/octave between 350-2000 Hz. The test duration is 2 minutes in each axis.

#### 6.4.4.4.6 Shock

Only one shock should be imposed on the micropropulsion system in both directions in each of the three orthogonal axes. It shall be tested on a ringing table test stand to the levels prescribed Table 19 below. The shock levels are calculated with a Q-factor of 10.

*Table 19. Shock test specifications.*

| Frequency [Hz] | SRS level (Q=10) [g] |
|---|---|
| 100 | 5 |
| 600 | 270 |
| 2000 | 750 |
| 10000 | 750 |

#### 6.4.4.4.7 Thermal Cycling

The thermal cycling test is conducted with the micropropulsion system suspended in a temperature cycling chamber. It starts by increasing the temperature to maximum non operating temperature plus 5°C, with the micropropulsion system switched off. After a dwell time of 2 hours, the temperature is decreased to the maximum operating temperature plus 5°C. After 2 hours, functional and performance tests are performed. Hereafter, the system is switched off and the temperature is decreased and maintained at the minimum non operating temperature minus 5°C for 2 hours. The temperature is increased to the minimum operating temperature minus 5°C and the system is switched on. After 2 hours, functional and performance tests are performed. Hereafter, the system is cycled 4 times between maximum and minimum operating temperatures plus and minus 5°C respectively. The dwell time is 2 hours at each temperature extreme. During the last cycle the system is functionally tested at both temperature extremes. The minimum and maximum operating temperatures are 0°C and 50°C respectively; the non operating temperature extremes are -10°C and 60°C.

# 7 Commercial Evaluation

The European Space Agency has set up a transfer programme to stimulate a wider use of technology developed within the European space research community and hence promote the transfer of innovative technology from space to non-space applications. In the statement of work the paragraph of a commercial evaluation was stated as applicable. The technical and financial possibilities to promote a technology transfer from space to other applications is however regarded as small when it comes to the outcome of the development of a methodology for space validation. The technology transfer is rather the other direction, i.e. to apply the miniaturisation in space research area by the use of MEMS. The harsh environment, i.e. vacuum, radiation, extreme g-forces, etc., for which this methodology is being developed is really space specific.

If there will be a future commercialisation of the complex micropropulsion system, for which the methodology have been developed, it is already part of the contractors business plan.

# 8 Main Results Achieved

The main result achieved during this contract is described below.

It is in the nature of MEMS that the procedure is not from structure via component to system as the case is in conventional manufacturing. The high level of integration makes it difficult to perform in-line functional measurements on MEMS components for example; the full functionality is only complete in the last manufacturing step when several wafers are bonded together. This requires that qualification methodologies for MEMS must rely on process qualification rather than product qualification. The major part of the work has been to develop this quality analysis methodology where definition and manufacturing of test structures, followed by validation of the same has been performed. The process qualification methodology is schematically illustrated in Figure 44.

Wafer level tests make it possible to start the testing and sample screening early in the manufacturing process. These tests are meant to control characteristics of device structures and materials, and manufacturing processes. They provide reliability and performance data at various stages in the manufacturing process. Wafer level tests are included in all process packages in the manufacturing of the micropropulsion system. Most of the tests can be performed on actual micropropulsion system wafers and structures, precluding the need for specially designed process control monitoring (PCM) structures or PCM wafers. The wafer level tests performed in this work are presented together with an evaluation of the efficiency of the test structures and test methods. Most of the tests are made to control standard processes used by the MEMS community all over the world, other processes are used specifically for the subject complex micro propulsion system.

The documentation includes configuration documents, specification documents, and MEMS specific documents. The latter are Process Identification Documents (PID), Lot Travellers (LT), MEMS Definition Sheets, and MEMS Flow Charts.

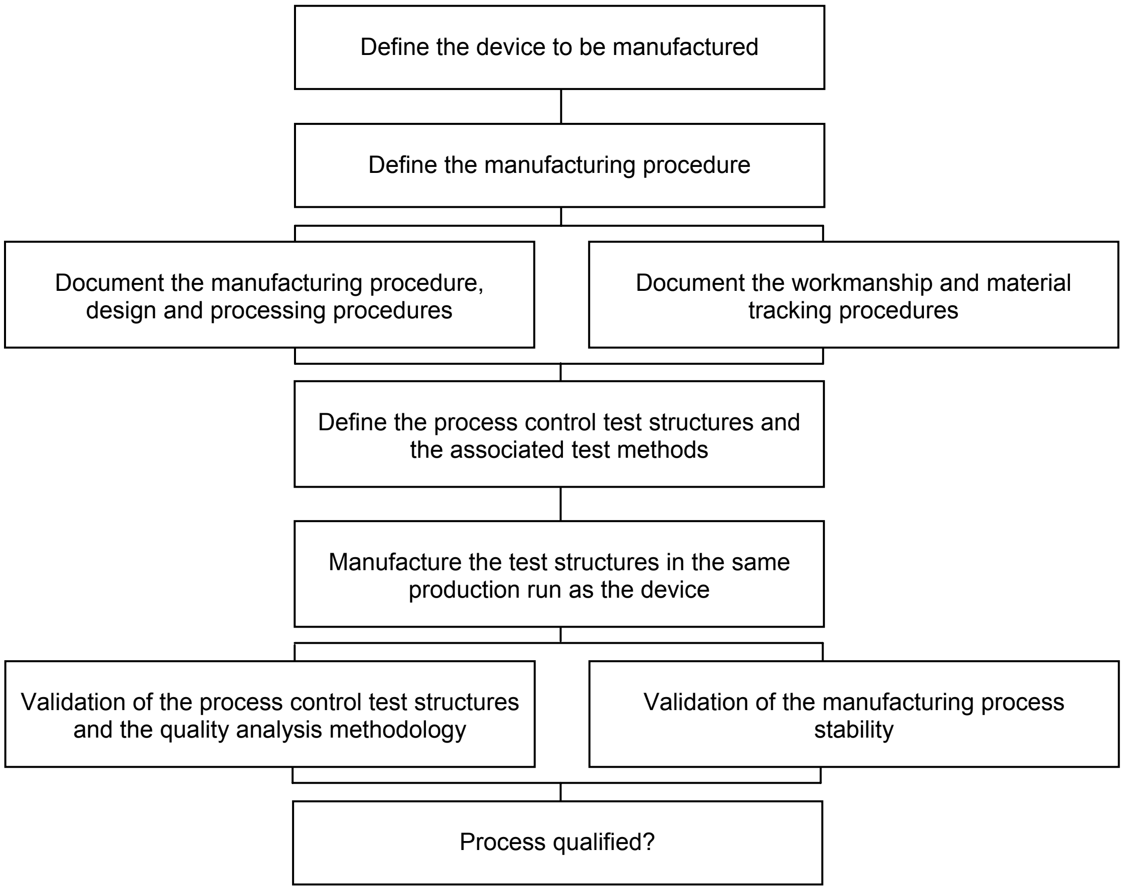



*Figure 44. Schematic illustration of the process quality analysis methodology.*

In conclusion several preliminary steps towards a process qualification methodology for a novel MEMS micropropulsion systems space validation have been taken. The development of quality analysis structures to monitor and control the in-line manufacturing of the micropropulsion system and an associated quality analysis methodology was described and validated during the project.

In general the overall objective has been fulfilled and the intended development support to foster European autonomy as well as industrial competitiveness regarding the spacecraft equipment world market, and to render the European aerospace industry independence, has been successful.