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1 Introduction

Scope of the present document is to describe and justify the design of an ArianeGroup 240N Hydrazine mono-propellant thruster to be used in the VEGA Roll and Attitude Control System (RACS) and similar missions.

The RACS propulsion system is located at the AVUM stage (4th stage) of the VEGA launcher and provides its function directly after ignition of the first (solid) stage. The following figures show the actual configuration of the complete subsystem (Figure 1-1) and the 2 clusters with 3 thrusters each.

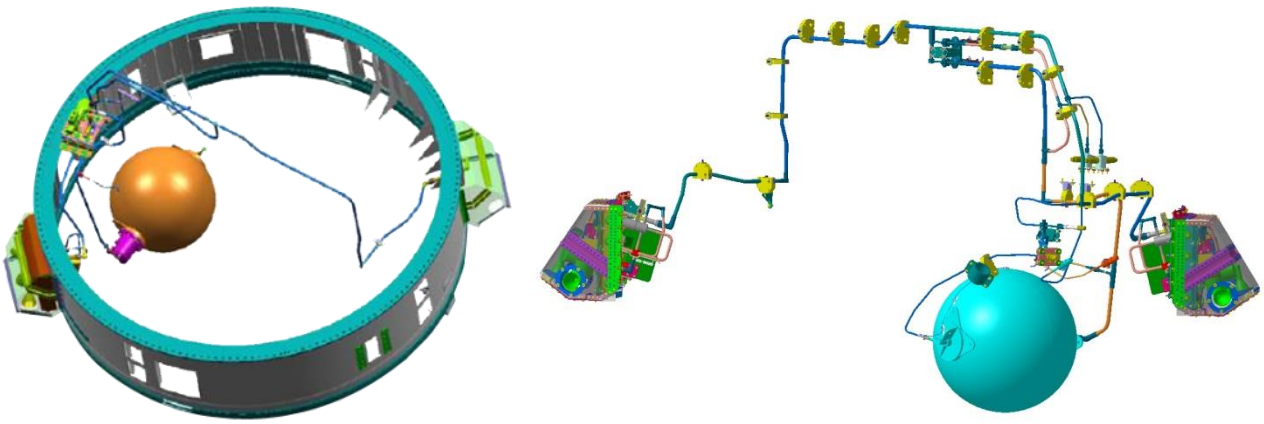


Figure 1-1: VEGA RACS propulsion subsystem

As of today, the Roll and Attitude Control System (RACS) of the European VEGA launcher is a Hydrazine-based propulsion system produced by ArianeGroup GmbH and directly delivered to AVIO, the prime integrator of the VEGA launcher.

While many components of the RACS are sourced from inside Europe, the Hydrazine thrusters with their critical function are procured from outside Europe – under responsibility of ArianeGroup. ArianeGroup considers this dependency and a potential obsolescence a significant risk for its own RACS business but also for the European VEGA launcher as a whole.

In order to pro-actively counter this risk, ArianeGroup was offering its long-term experience and heritage in Hydrazine-based propulsion thruster and system designs and proposes to start a de-risking activity, see proposal in [AD 1].

The aim of the current activity [AD 2] is to maturate a pre-developed thruster design at ArianeGroup and to confirm its suitability prior to a potential qualification for the VEGA RACS system.

2 Applicable and Reference Documents

The following project related document are applicable for this document and used as a reference

2.1 Applicable Documents / Standards

[AD 1] 20.O.079, 240N Hydrazine Thruster DeRisk Activity_Full Proposal

[AD 2] ESA Contract No. 4000138574/21/NL/GLC/rk “240N Hydrazine Thruster De-Risk Activity”

[AD 3] MIL-PRF-26536, Propellant Hydrazine

2.2 Reference Documents

[RD 1] AIAA 96-2865, Development of a 400N Hydrazine thruster for ESA's Atmospheric Reentry Demonstrator

[RD 2] AIAA 2015-4146 Development and Test of a 3D printed Hydrogen Peroxide Flight Control Thruster

[RD 3] FCV400N-RILAM-SPE-0002 Propellant Valve Specification for 400N Engine

[RD 4] ENG-ASLLAM-TN-0054 Hydrazine Thruster Design Justification

[RD 5] CLEAN-ASSLAM-TN-0004 CleanSat BB09 Low Cost Deorbit Engine Public Report

[RD 6] CHT240N-ASLLAM-TN-0001 CHT240N Design Description

2.3 Abbreviations

The following abbreviations are used within this document:

AGG	ArianeGroup GmbH
AOCS	Attitude and Orbit Control System
ALM	Additive Layer Manufacturing
CBH	Catalyst Bed Heater
EOL	End of Life
ISP	Specific impulse
LEO	Low Earth Orbit
MEOP	Maximum Expected Operating Pressure
N2H4	Hydrazine
PMF	Pulse Mode Firing
QT	Qualification Test
RACS	Roll and Attitude Control System
SSF	Steady State Firing
TCA	Thrust Chamber Assembly
TFS	Flight Sensor
TRL	Technology Readiness Level

3 ArianeGroup Development Approach

Basis for the actual development of a 240N Hydrazine thruster are ArianeGroup's flight qualified (TRL9) Hydrazine thrusters in thrust levels between 0,5N and 500N and an ALM-printed 240N development thruster with TRL 5 (breadboard validation in relevant environment).

This 240N ALM printed development thruster was designed according available Hydrazine rules and the injector and catalyst bed were adapted to the propellant H2O2. As this thruster incorporated several flight like elements and as it was tested in a relevant environment TRL5 could be claimed.

The experiences gained during this development program proved that a thruster of this size can be full printed in an ALM design with significant cost advantages.

The main differences between an ALM-thruster design and a classical design is the reduction of individually machined parts. Through combination of functions, the number of parts can be reduced, thus manufacturing and assembly steps can be saved. In an optimum design, FCV interface, heat barrier, head-plate and injector head could be combined in one ALM part, instead of individual production followed by welding-assembly with specialized tooling. This has potential for lower production cost of the final product.

As the technology for the 240N thruster was demonstrated and is well mastered a TRL3 for the proposed development is claimed which is increased to TRL4 via a successful demonstration of the critical function "ALM printed heat barrier / injector", see also following figure:

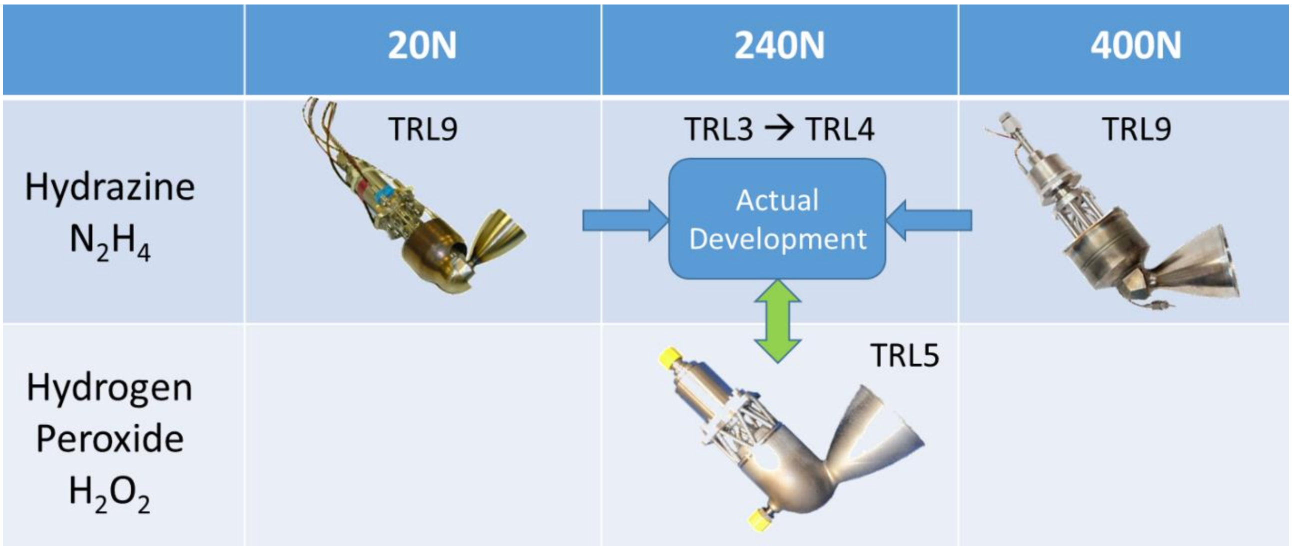


Figure 3-1: VEGA RACS cluster with 240N monopropellant Hydrazine Thrusters

3.1 Detailed Development Logic

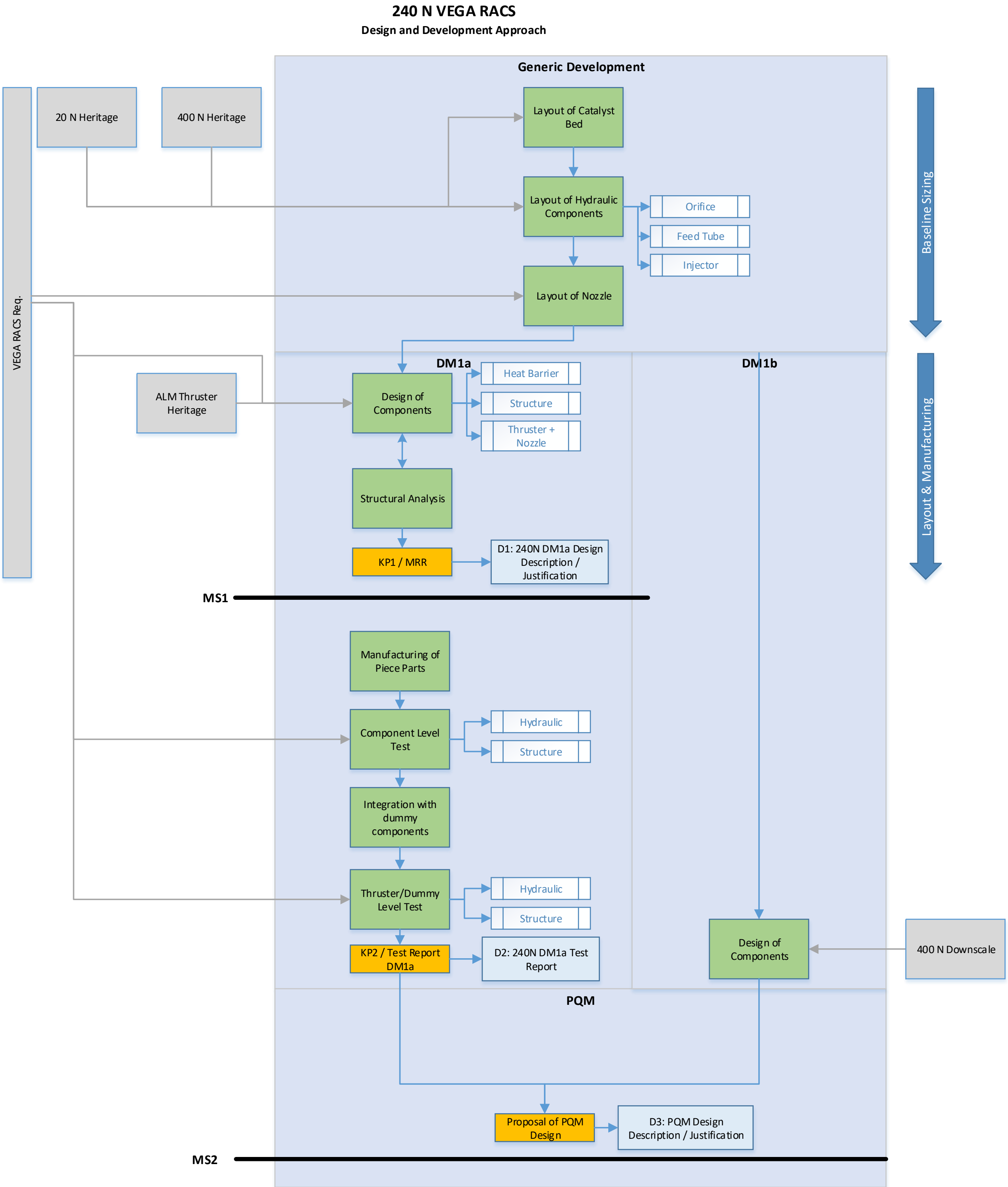


Figure 3-2: Design and Development Logic

The development of the 240N thruster was split into two design routes. In the first route, the DM1a thruster was designed in a disruptive manner regarding engine design and manufacturing techniques. The design target was to be low cost to decrease number of piece parts and manufacturing effort. To achieve a significant reduction of piece parts metal 3D printing (ALM, Additive Layer Manufacturing) was used for the production process.

In parallel to the DM1a activities, a classic design approach via downscale of the 400N thruster with classic manufacturing techniques was conducted for the DM1b design.

The baseline for both DM1a and DM1b thrusters is the ArianeGroup heritage of flight-proven mono-propellant engines in the range of 0.5N to 2.5 kN. This internal know-how [RD 4] was used for the layout of the injector, the catalyst bed and the hydraulic components, which have an effect on thruster performance, i.e. the trimming orifice and feed tubes. Both thrusters had the same basic sizing described in section 5.2

Furthermore, design heritage of the experimental additively manufactured experimental hydrogen peroxide thruster was used for the layout and design of the nozzle and structural components, i.e. the heat barrier, structural interface, but also the thrust chamber itself.

In every step of the design process, the VEGA RACS requirements were considered.

The DM1a thruster was designed according ALM design rules (avoid printing support structure as far as possible), underwent structural analysis for a design optimization loop. The outcome of this design was discussed during Milestone MS1, which acted as Manufacturing Readiness Review (MRR) for the built of the thruster hardware.

After successful completion of MS1 the piece parts of the DM1a thruster were manufactured and tested on component level. Hydraulic tests were conducted on injector level with the 3D printed hydraulic components. These tests included pressure drop and flow tests.

After final assembly of the thruster structural vibration tests were performed to verify the predictions of the structural model. These tests confirmed the design and also the applicability of structural analysis with an ALM printed design.

4 Requirements

4.1 VEGA Requirements

The following table shows the sizing thruster performance requirements:

Design features	Thruster characteristics
Minimum thrust (vacuum) and specific Impulse under vacuum conditions	≥ 240 N @ 26 bar inlet pressure / ISP ≥ 220 s
Propellant	Hydrazine according [AD 3]
Interface	To comply with the actual interface

Table 4-1: CHT240N Main Requirements

4.2 Additional Requirements

A monopropellant thruster in this thrust class is interesting for a number of additional missions. The requirements for these additional missions are as following:

- **VEGA C** launcher: this launcher has an increased propellant throughput; this increased throughput does not affect the design in its first (preliminary development) phase
- **Vega-E** (or Vega Evolution) launcher: this launcher is a further evolution of the Vega-C where a hydrogen peroxide based RACS system is being investigated[1]. This means that the thruster parameters (mainly the material, injector, catalyst bed) have to be adapted to the changed propellant. These parameters that have to be changed are further discussed in § 0.
- **Deorbit Engine:** When a thruster of this class is used for deorbit purposes the total throughput is typically increased whereas the requirements for PMF operational range are significantly reduced. The generic requirements for a deorbit engine of European Primes were collected in [RD 5] with the following 3 resulting design cases:

Case Design Point	Case 1 min. 150N @ 5,5 bar	Case 2 150N @ 18 bar regulated	Case 3 200N average over blow-down
Operation mode	Blow down	Regulated	Blow down
Operating pressure	24 - 5,5 bar	18 bar	14 - 5,5 bar
Design Pressure	24 - 5,5 bar	24 - 5,5 bar	24 - 5,5 bar
Design point[2] @ 24 bar	500 N	194 N	434 N

Table 4-2: Thrust level design points

[1] https://www.esa.int/Enabling_Support/Space_Transportation/Launch_vehicles/Vega-E

[2] The design point definition for a monopropellant thruster is the thrust level at maximum inlet pressure

5 Thruster Layout

Generic Hydrazine thruster layout was done according ArianeGroup internal design document [RD 4].

5.1 Design Elements and functional Description

The following figure shows the basic components of a Hydrazine thruster. These components are discussed and their function is described:

The Thruster is mounted to the structure either at the FCV mounting flange area or at the injector area, see also interface drawings given in Annex A. The location of the ***Mounting*** determines the heat into the structure or into the valve.

The Propellant enters the ***Flow Control Valve*** at the ***Propellant Inlet***. This Inlet can be screwed or welded. ***Thermal Standoffs*** and ***Feed Tube*** are used to feed the Hydrazine into the injector and (thermally) decouple the hot chamber from the valve. This is because liquid wetted hydrazine parts are limited in temperature (without special effort: max. 90°C due to NASA white book standards).

The ***Feed Tube*** is also used to generate a pressure drop that (hydraulically) decouples the decomposition chamber from the feed system. In the area of the feed tube trimming can be performed either via a dedicated orifice or via a crimping of the feed tube.

The ***Injector*** feeds the Hydrazine into the catalyst bed. Required is an equal propellant distribution, therefore typically multi showerhead injector elements are used.

The ***Thrust Chamber*** contains one or two ***Catalyst Beds*** that are enclosed by meshes. The lower mesh is typically supported by a structure. Hydrazine is decomposed in the catalyst bed and afterwards expelled in the nozzle to generate thrust.

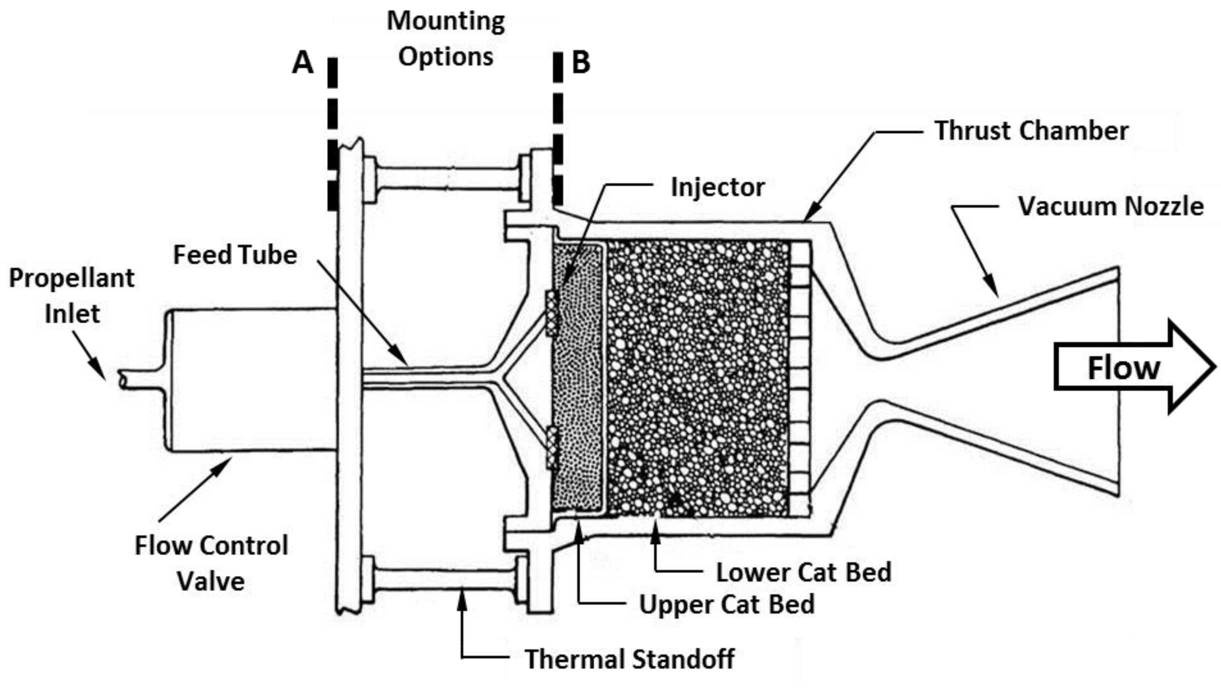
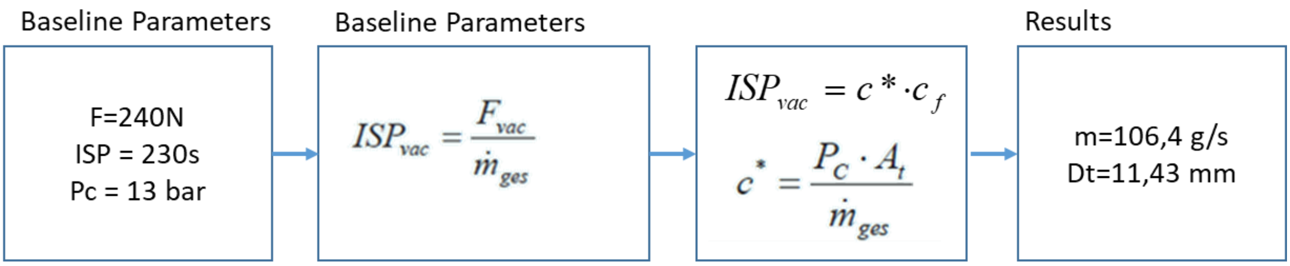


Figure 5-1: Generic Hydrazine Thruster Design acc [RD 4]

5.2 Basic Thruster Sizing

The basic sizing was performed according to the following classical layout scheme starting with a given thrust level and an estimated performance; the throat diameter is calculated with an estimated decomposition chamber pressure of 50% of the feeding pressure and is then used for further dimensioning of the decomposition chamber.



5.3 Hydrazine decomposition and catalyst selection

The function of a hydrazine thruster is to provide thrust via the catalytic decomposition of Hydrazine. When Hydrazine is in contact with a catalyst it decomposes according to the following formula where x is the ammonia dissociation rate:

$$N_2H_4 \Rightarrow \frac{4}{3}\cdot(1-x)NH_3 + \frac{1}{3}\cdot(1+2\cdot x)N_2 + (2\cdot x)H_2 + (112 - 62{,}5\cdot x)\left[\frac{KJ}{mol}\right]$$

This ammonia dissociation rate determines the decomposition temperature itself and the specific impulse, see following figure (sample for an expansion ratio of ε=40):

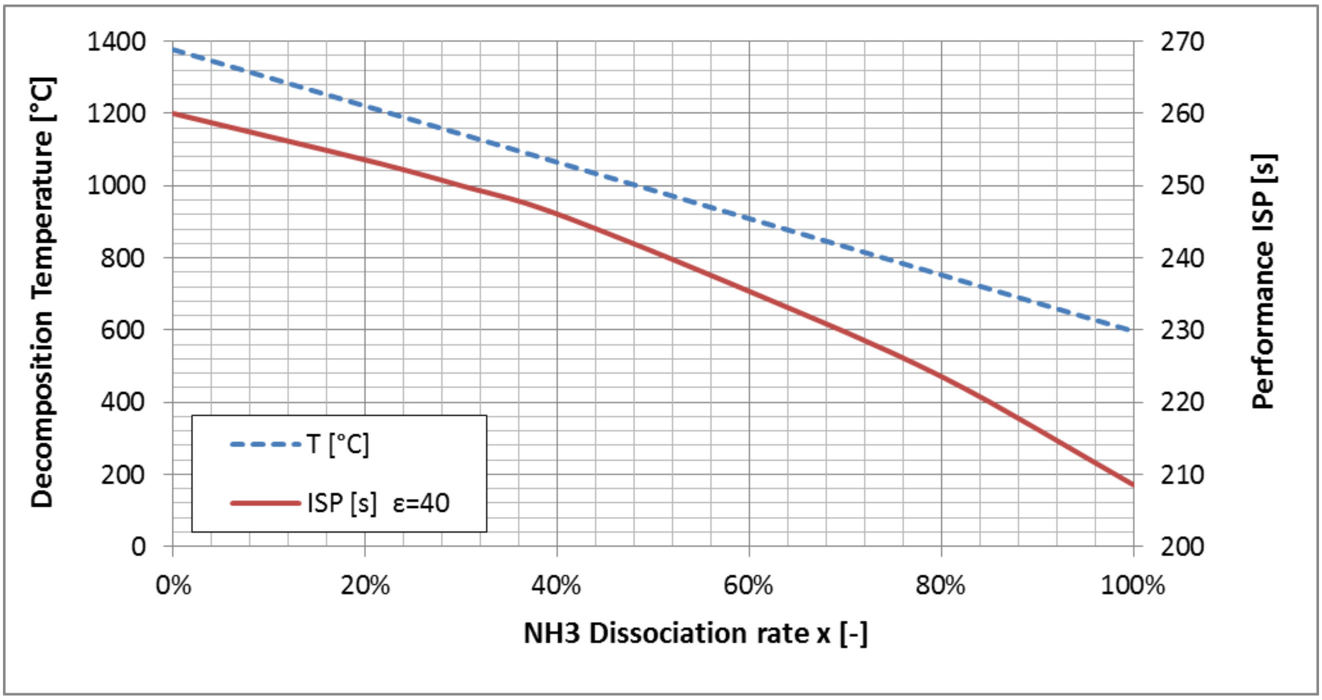


Figure 5-2: Hydrazine performance parameters as a function of ammonia dissociation rate

In modern hydrazine thrusters the ammonia dissociation rate is 40±20% and is adjusted via the catalyst bed configuration (bed diameter, length, catalyst type). The design of a real catalyst bed however has to consider additional effects like operation range (inlet pressure and temperature) but also natural catalyst loss due to engine operation.

If the operation is limited to steady state operation at a narrow and know inlet pressure range the ammonia dissociation rate can be lowered via a shorter catalyst bed and thus the performance can be increased.

The catalyst bed design is based on historic design rules established in the past and AGG internal design rules [RD 4]. For both designs of the thruster the European heritage catalyst also used in ArianeGroup's 400N Hydrazine thruster is used.

Established catalysts typically use an amount of 30% to 35% weight% of Iridium which is a cost driver for catalysts, therefore the amount of catalyst has to be minimized.

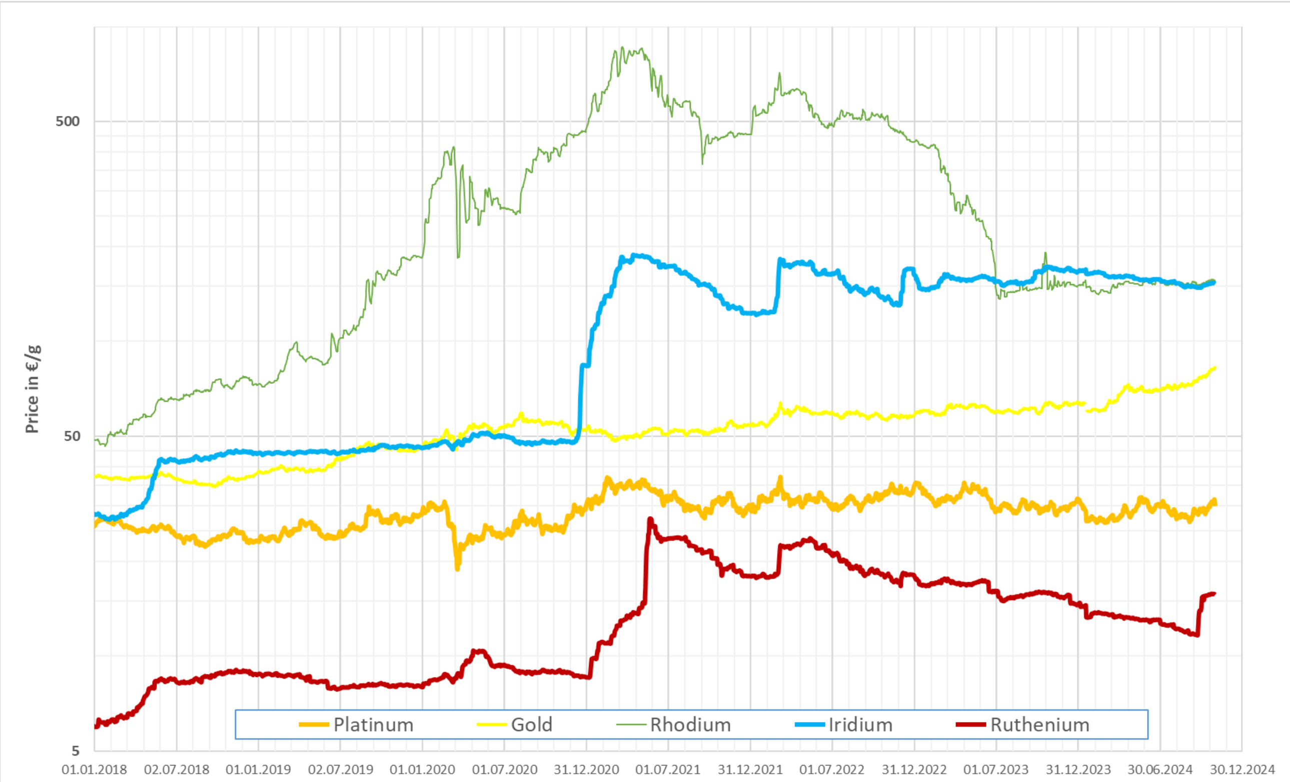


Figure 5-3: Active Catalyst Material Cost – Historic Chart

5.4 Thruster Construction Material

Hydrazine decomposition temperatures are given in Figure 5-2 in dependence of the ammonia dissociation rate. Maximum 1400 °C can be expected, if no ammonia dissociation occurs. For the design baseline a 40% ammonia dissociation is assumed, resulting in a thrust chamber temperature of approximately 1050 °C. These temperatures can be well handled by nickel-base alloys, also called super-alloys. Next to the maximum temperature also other properties and parameters have to be considered, such as:

- Strength
- Compatibility to the propellant and its dissociation products (also to a possible green propellant solution of hydrogen peroxide)
- Manufacturability (regarding additive manufacturing and wear of toolings)
- Cost
- Availability

The investigated materials and their technical data are summarized in the table below:

Material	Melting Temperature [°C]	max. Operating Temperature [°C]	Cost [$/kg]	UTS [MPa]	YS [MPa]	Elongation	3D printable	Heritage
HY 214	1355-1400	1260		960	565	43%	(y)	
Hastelloy X	1260-1355	1177	≈ 200	772±24	595±28	20±6%	y	
CoCr MP1	1350-1430	1150	330	1100±100	600±50	20%	y	
HY 188	1315-1410	1150	≈ 200	945	465	53%	y	
HY 230	1290-1375	1150		860	390	48%	(n)	
HY 25	1329-1410	1093		1005	475	51%	(n)	ArianeGroup
IN 625	1290-1350	1093	192	930±100	650±50	35±5%	y	
Hastelloy C-4	1335-1380	1000		805	421	40%	n	
VDM 600H	1370-1425	1000		550	180	30%	n	
VDM 825	1370-1400	1000		585	240	30%	n	
Inconel 600	1354-1413	950		676	290	30-50%	y	
HY 282	1300-1375	927		1180	710	26%	y	
316L	1375-1400	925	180	540±55	470±90	50±20%	y	
Nimonic 90	1310-1370	920		1180	831		n	
Hastelloy B-3	1370-1418	900		883	421	40%	n	
IN718	1210-1344	700	192	1380±100	1240±100	18±5%	y	
CoCrMo		650		1400	690			
CoCr SP2	1380-1440		625	1350	850	3%	y	

* under investigation

Table 5-1: Material List.

ArianeGroup has experience in 3D printing Hastelloy X components. Currently, Ariane 6 parts are printed in that material. The process is well managed inside ArianeGroup. Furthermore, Hastelloy X provides excellent material characteristics. Therefore chosen as the baseline material for the 3D printed parts of the DM1a.

5.5 Hydraulic Components

5.5.1 Flow Control Valve

Propellant flow from the feeding system to the thruster is controlled via the Flow Control Valve (FCV). Several potential candidates are considered for the DM1a thruster.

The following valves were considered for the DM1a thruster:

- ArianeGroup 400N Bipropellant Thruster FCV [RD 3]
- ArianeGroup 400N Monopropellant Thruster FCV
- MOOG (US)
- ValveTech (US)

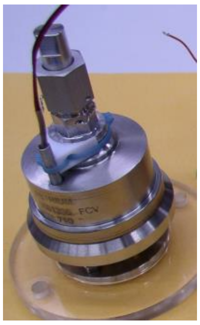
AGG 400N Monopropellant (D)	AGG 400N Bipropellant (D)	MOOG (US)	ValveTech (US)
			

Table 5-2: Investigated FCV Options.

5.5.2 Trimming

A trimming device is required for performance adjustment via pressure drop setting. Trimming can be achie-ved with the following options:

- **Orifice:** Implementation of an orifice upstream or downstream of the FCV: This orifice is an addi-tional external part, has to be calibrated, kept in stock and requires an additional sealing.
- **Crimping** of feed the tube such that a defined pressure drop is achieved: This crimping can be done online during the manufacturing process when the hydraulic characteristics of the injector are measured and re-quires no additional parts. With multiple feed tubes however crimping is not fea-sible

For the DM1a thruster an exchangeable trimming orifice between FCV and thruster was selected.

5.5.3 Feed Tube

The feed tube is used to distribute the propellant from the FCV to the injector. The function is to decouple thermal loads from the hot parts of the thruster from the propellant feeding components. Furthermore, thermal expansion of the heat barrier was compensated via an elastic tube (pigtail, bending).

5.5.4 Injector

The injector is required to evenly distribute the propellant across the catalyst bed.

When the FCV is activated propellant is delivered through the heat barrier to the injector. The injector has to ensure a good decomposition over a wide range of operating conditions and during the entire life of the thruster. Special considerations have to be taken to evenly distribute the propellant flow and optimize loading.

For Hydrazine thrusters typically showerhead injectors with multiple holes are used. Key design parameters are pressure drop, number of holes and the arrangement of the sprays towards the catalyst bed.

For DM1a such a classical showerhead injector was used.

5.6 Thermal Standoff

The function of the thermal standoff (or heat barrier) is to decouple high temperatures from the hydrazine decomposition process from the valve and propellant line. Heat soak back should be minimized as possible to prevent decomposition of propellant before reaching the catalyst bed. As a generic rule, 90°C is the maximum temperature of liquid hydrazine wetted parts.

To the heat barrier the FCV is attached. The FCV controls propellant flow through the orifice and through the heat barrier towards the injector and the catalyst bed. Furthermore, into the heat barrier a propellant line is integrated, connecting the FCV and orifice with the downstream injector and catalyst bed.

The functions of the heat barrier can be summarized as following:

- **Structural**: Transfer loads from the mounting flange to the thrust chamber. From this point of view, the heat barrier has to be very stiff
- **Thermal**: Heat transfer from the thruster to the FCV was limited. From this point of view, the heat barrier has to be thin, to minimize heat transfer

Typically, heat barriers can be designed as perforated tubes, as a bolted standoff or as perforated tube, which is typically done for small thrusters. New manufacturing technologies, such as 3D printing, allow further functional integration, such as the integration of the feed tube via one manufacturing step. The total number piece parts can also be reduced.

5.7 Nozzle

At the end of the catalyst bed the decomposed gases are collected in a stagnation chamber before they are expelled into the subsonic / supersonic nozzle. The expansion ratio of the nozzle defines the specific impulse. As the thruster is used in vacuum, the nozzle cannot work fully adapted. In the design the compromise between performance weight and structural integrity has to be found.

Several nozzle configurations are possible, see also following figure:

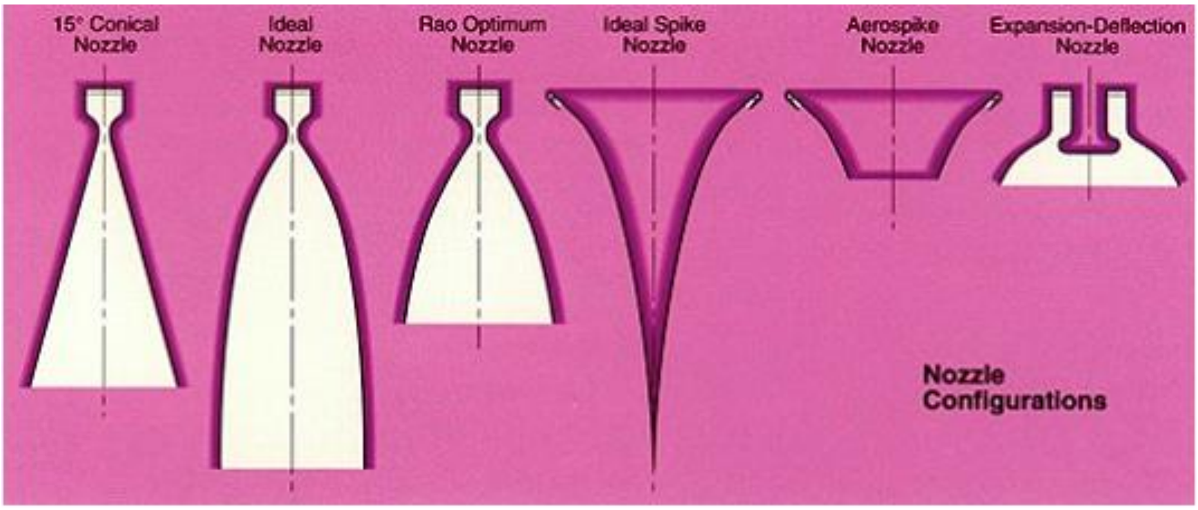


Figure 5-4: Nozzle configurations[3]

For monopropellant thruster vacuum nozzles the following configurations are technically used.

- A simple 15° conical nozzle
- An ideal nozzle giving the highest performance
- A Rao optimized nozzle giving a slightly lower performance compared to the ideal nozzle but has a significantly lower overall length

The expansion nozzle must withstand the maximum temperatures of the hydrazine decomposition which are expected to be as high as 1050 °C. Highest heat loads is induced on the throat section of the nozzle.

Next to heat loads, the nozzle must withstand structural loads induced from its own operation but also from the launcher.

For the VEGA RACS application the thruster must have a 90° canted nozzle. A Rao optimized nozzle was selected.

[3] http://www.rocket-propulsion.info/resources/articles/NozzleDesign.pdf

6 DM1a Layout

The DM1a thruster should comprise additively manufactured components wherever rational to investigate a cost effective alternative to classic manufacturing techniques.

The thruster layout is based on the VEGA RACS requirements and the ArianeGroup monopropellant thruster experience. The final design proposal is summarized in the table below. A more detailed justification of COTS components and design is described in the non-public design justification [RD 6].

Item	DM1a Configuration / Concept
Flow Control Valve	ArianeGroup 400 N Bi-Propellant FCV
Trimming	Orifice
Thermal Standoff	3D printed Hastelloy X
Injector	Three injector elements with semi spherical aspiration mesh
Catalyst Bed	Two beds
Nozzle	90° canted nozzle, RAO optimized
Sealing Concept	O-Ring / C-Ring
Interface	To be adapted to the requirements

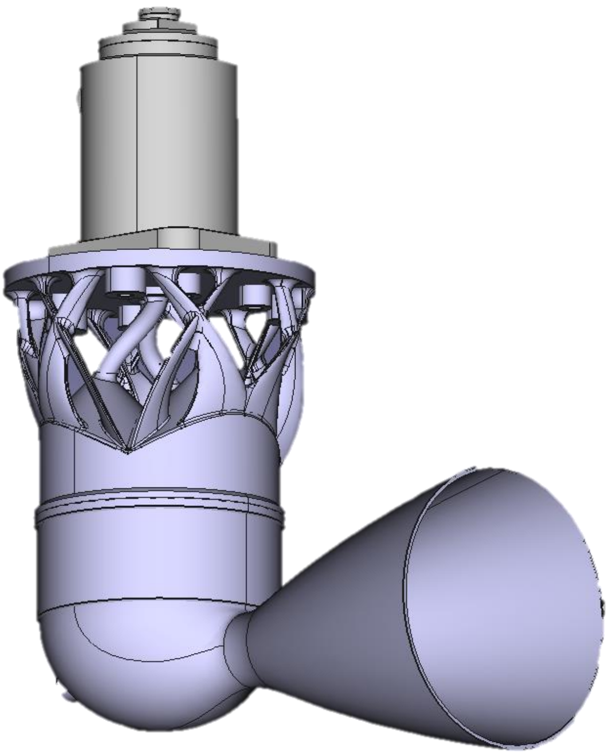


Figure 6-1: DM1a design including FCV.

6.1 Flow Control Valve

The ArianeGroup 400N Bipropellant FCV has been chosen as the cost efficient solution for the 240N DM1a thruster. The FCV is designed in normally closed configurations and provides two redundant solenoids.

The design pressure drop of the valve is low with 1.5 bar at 100 g/s water flow. The operating pressure of the valve is suitable for VEGA RACS application with a range of 8 to 34 bar absolute.

The baseline design offers a tubing interface per SAE AS4395E02, which has to be adapted for the implementation into VEGA RACS. The adaptation effort is considered low.

The wetted parts are manufactured from stainless steels 430, 304L or 347. The valve poppet is manufactured from PTFE.

6.2 Trimming Concept

Trimming was done via a trimming orifice. With this orifice the mass flow across the thruster can be set during the integration process. Orifices of several hydraulic diameters can be manufactured cost efficiently. During the integration process the orifices can be swapped till the required mass flow is met. The final orifice was welded into the thermal barrier.

Since no performance hot firing tests are planned, the hydraulic geometry could be chosen arbitrarily. Nevertheless, during cold flow tests of the hydraulic components, the effect of the orifice on the 3D printed components was investigated.

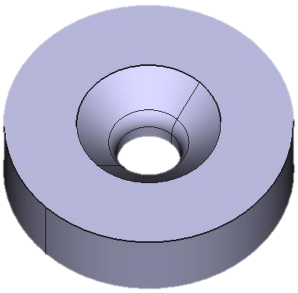


Figure 6-2: Orifice

6.3 Thermal Standoff

For the DM1a thruster, the thermal standoff is additively manufactured via laser metal sintering. This component is furthermore used as flange for connection to the space craft structure. Additionally, the propellant feed tube and the upstream catalyst bed are integrated in the 3D printed component.

The other components, i.e. injector and downstream catalyst bed incl. nozzle are attached via welding interface.

The thermal standoff must provide an interface for the trimming orifice and the FCV. These interfaces must be machined after the printing process to provide a smooth surface.

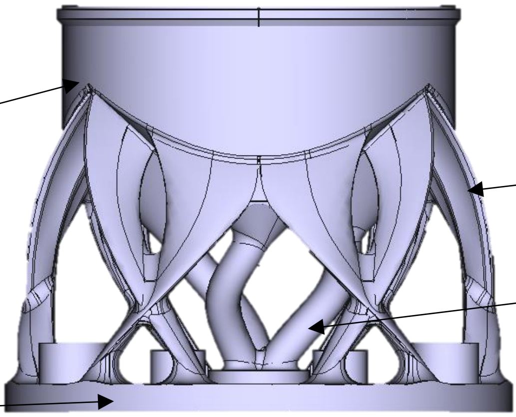


Figure 6-3: Thermal standoff with upstream catalyst bed as integrated component.

6.4 Injector

A classical showerhead injector is used to allow even distribution of the propellant across the catalyst. The injectors are required to have reproducible performance and require precise manufacturing. Therefore, this thruster part was manufactured conventionally.

6.5 Catalyst Bed

The catalyst bed is separated into two parts. The upstream catalyst bed with KC12GA as high activity catalyst. And the downstream bed with Ru/Ir 16/16 with lower activity, to reduce further ammonia dissociation. Both beds are limited by filters to prevent mixing of the catalyst materials and to provide a tight packing of the catalyst. The first filter shall keep a defined distance between injector and upstream catalyst. The second filter is necessary to prevent mixing of both catalyst materials. A last filter is used to limit the catalyst bed and allow only exhaust gases to reach the nozzle.

The downstream catalyst bed and the nozzle were manufactured as another part via 3D printing. Both catalyst beds are assembled via electron beam welding. Therefore, the welding interface of the 3D printed components had to be post-processed accordingly. The downstream catalyst bed is included into the nozzle part, as described below.

6.6 Nozzle

Boundary condition of the nozzle is the exit area, which shall match the envelope of the currently used thruster. The nozzle and the downstream catalyst bed are comprised into one component which was manufactured additively. Due to the 90° canted nozzle design a supporting structure is required during the printing process, which was removed via classical machining.

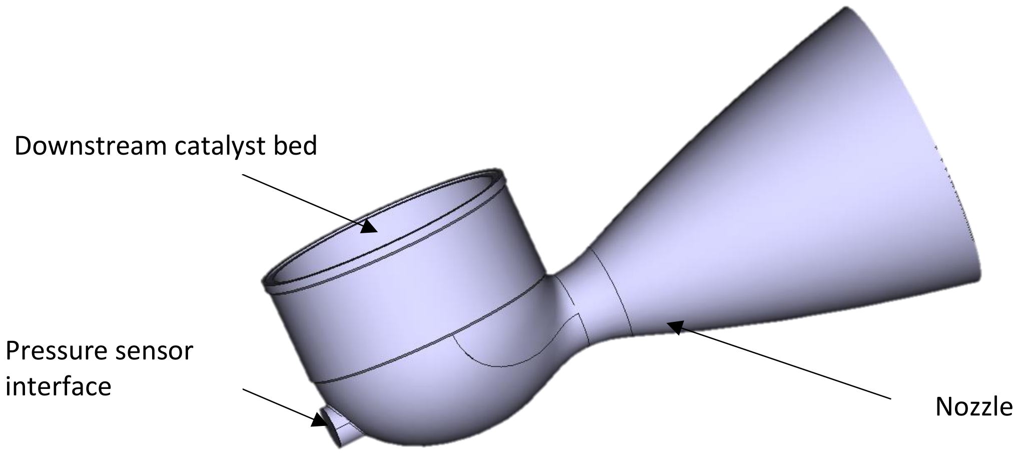


Figure 6-4: Downstream catalyst bed and nozzle as integrated component.

6.7 Sealing Concept

Only a sealing between the FCV and the thruster is required. The FCV of choice comprises a sealing concept which is outside of the scope of this project.

The other components were joined by welding.

6.8 Structural Analysis

Simulation analyses have been performed with the DM1a design proposal. The aim was to estimate structural loads which occur during operation. The design process has been supported by these analyses. Structural loads are induced from the VEGA launcher into the thruster during the launch process. Modal analysis, frequency response (sine) and random analysis have been performed.

6.8.1 Model Description

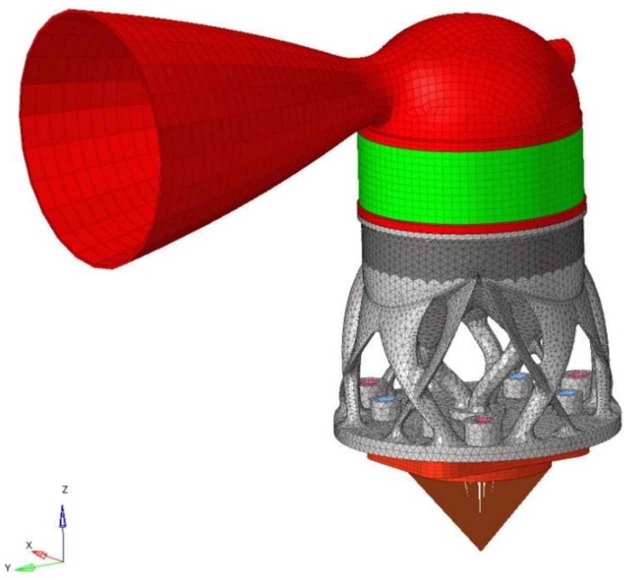


Figure 6-5: Mesh of the analysis model.

The FE model has been derived from the CAD model. It includes the nozzle, heat barrier, and internal components such as filters, injectors and catalyst, as well as the FCV as a mass dummy. The nozzle has been modelled using hexahedral elements incl. shell elements for surface stress extraction. The max. element size is approx. 2mm with at least 4 elements across the thickness in critical areas (throat section).

The heat barrier has been modelled using non-linear tetra elements with a max. element size of 1.5mm.

The FCV has been modelled with hexahedral elements including the flange and seat sub-assembly. The rest of the FCV has been modelled with a concentrated mass located at the CoG.

Welded interfaces between the nozzle part and the heat barrier have been performed using MSC Nastran glued contact.

The following material data has been used:

Section	Material	E-Modulus	ν	ρ
Nozzle + Heat barrier	Hastelloy X LBM	190.2 GPa	0.32	8220 kg/m³
Filters	Haynes 25	225 GPa	0.298	9130 kg/m³
FCV Flange	WL1.4546.9	199.9 GPa	0.32	7900 kg/m³

Table 6-1: Material data for the FEM analysis.

6.8.2 Analysis Results

The main modal frequencies of the thruster are well above 150 Hz as required from the specification. With the lowest value being 699 Hz with excitation in thruster x according to Figure 6-5.

The sine and random vibration levels according to the specification have been applied to the model. The maximum von Mises Stress has been calculated for a frequency range of 5 – 2000 Hz. Sine vibration margin of safety has been identified to be above 10 for the most critical components nozzle and heat barrier. Sine loading is not critical for the thruster in particular for the nozzle. Results show that the thruster will not show issues with strength.

The location of the maximum stress is similar for all loading directions as depicted in the figure below:

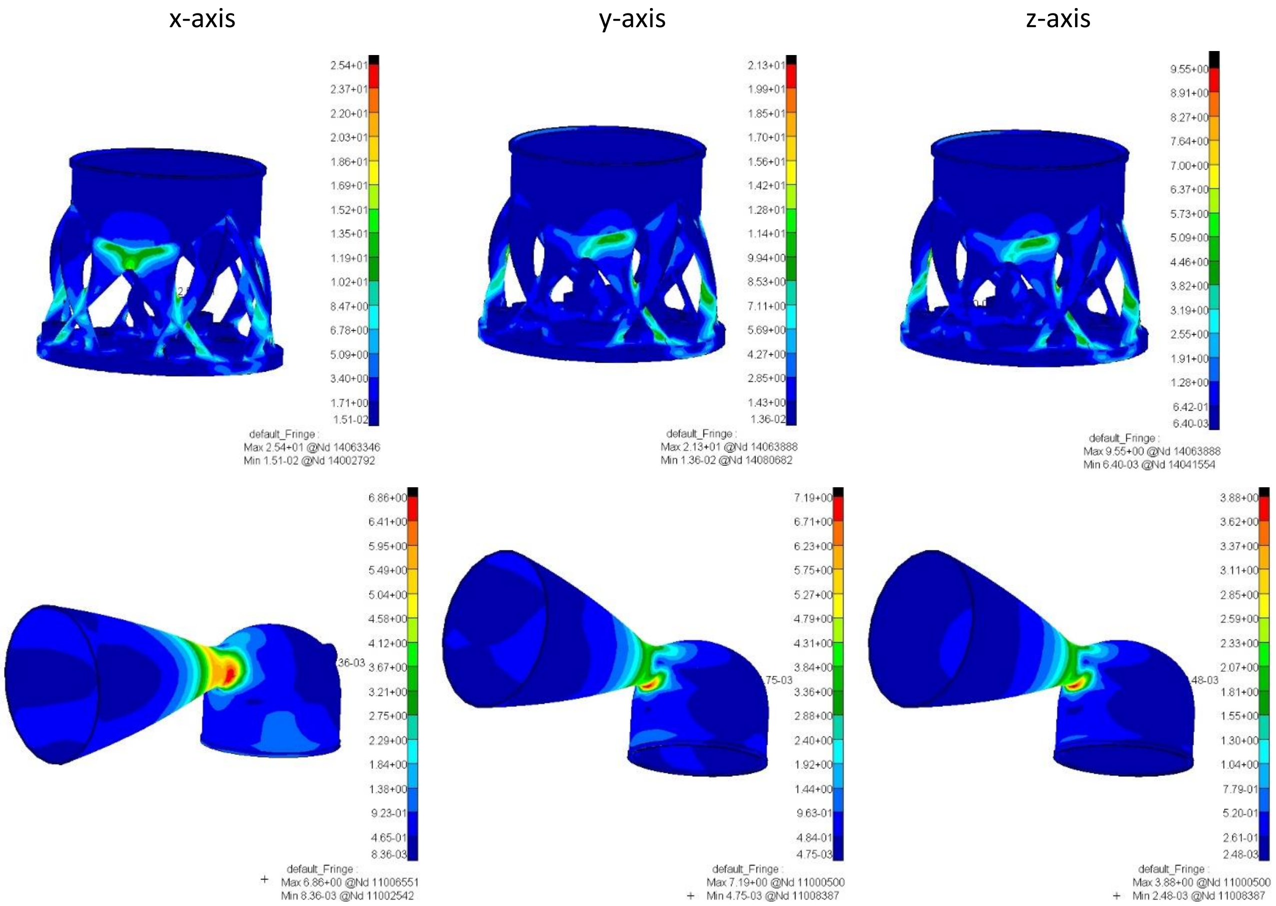


Figure 6-6: Von Mises Stress of the heat barrier and the nozzle for sine vibration excitation.

The expected response to the sine vibration has been extracted. Additionally, three positions for stress sensor attachment have been identified for structural vibration test.

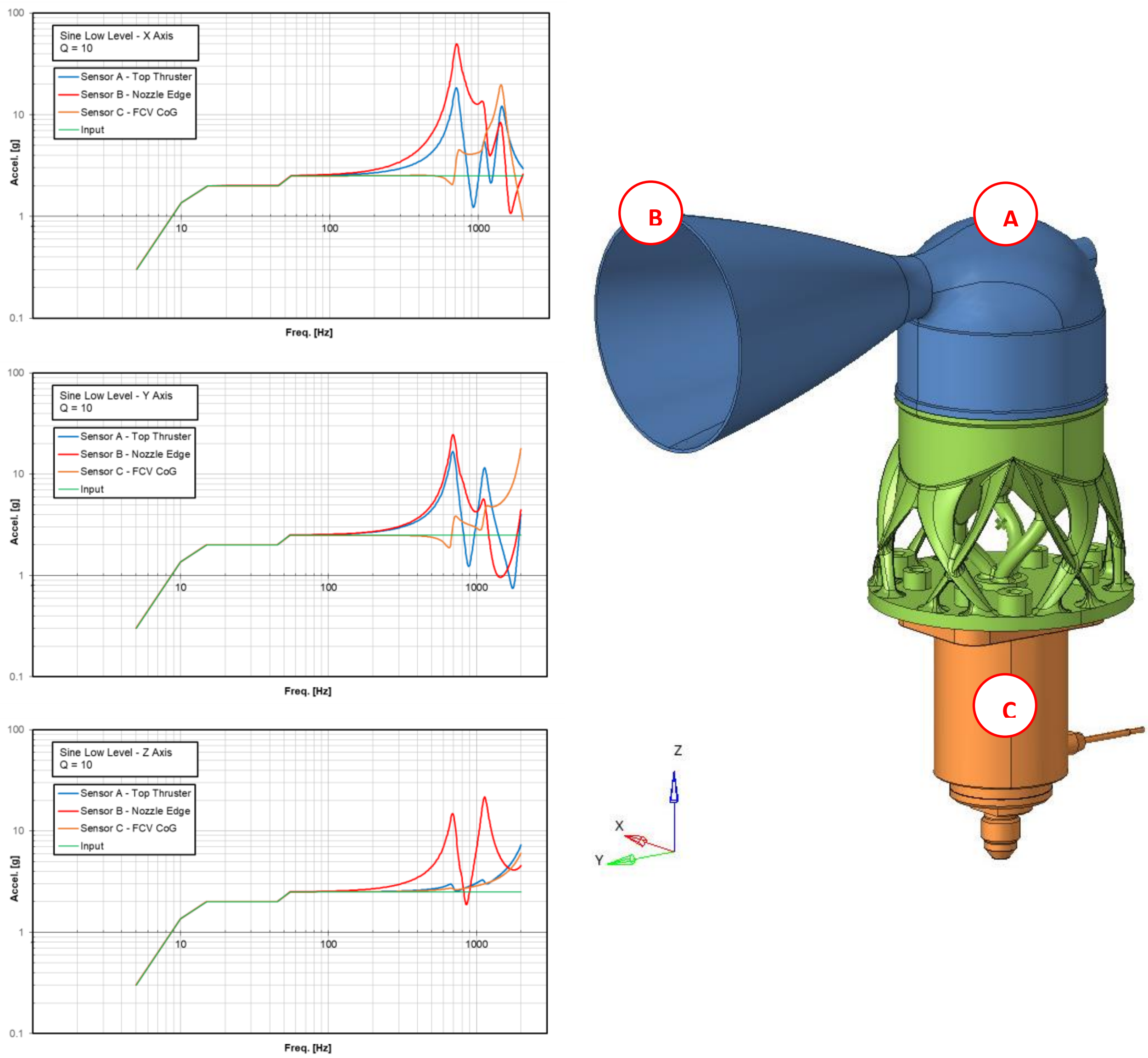


Figure 6-7: Expected response to sine vibration.

Margins of safety to random vibration levels against yield stress have been calculated to be between 0.77 (heat barrier y-axis) and 7.82 (nozzle z-axis). Random vibration is more critical than sine vibration nonetheless MoS are high enough that no issues is present in the heat barrier or the nozzle.

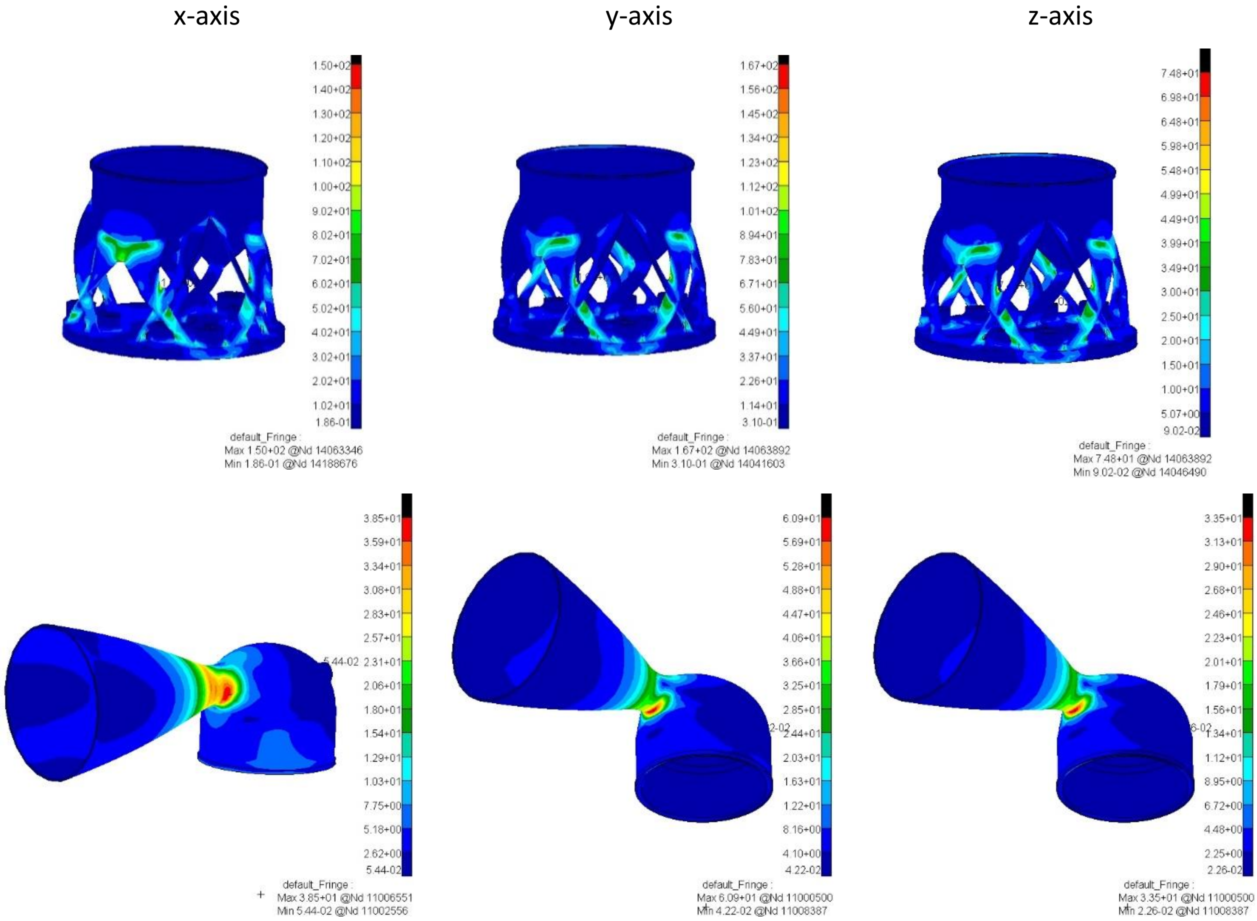
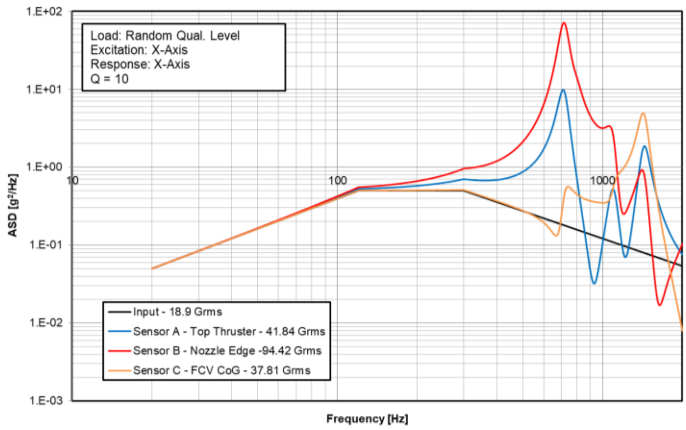


Figure 6-8: Von Mises Stress of the heat barrier and the nozzle for random vibration excitation. Results presented as 3σ RMS.

The expected response to random vibration is depicted in the figure below. The sensor attachment positions are described in Figure 6-7.



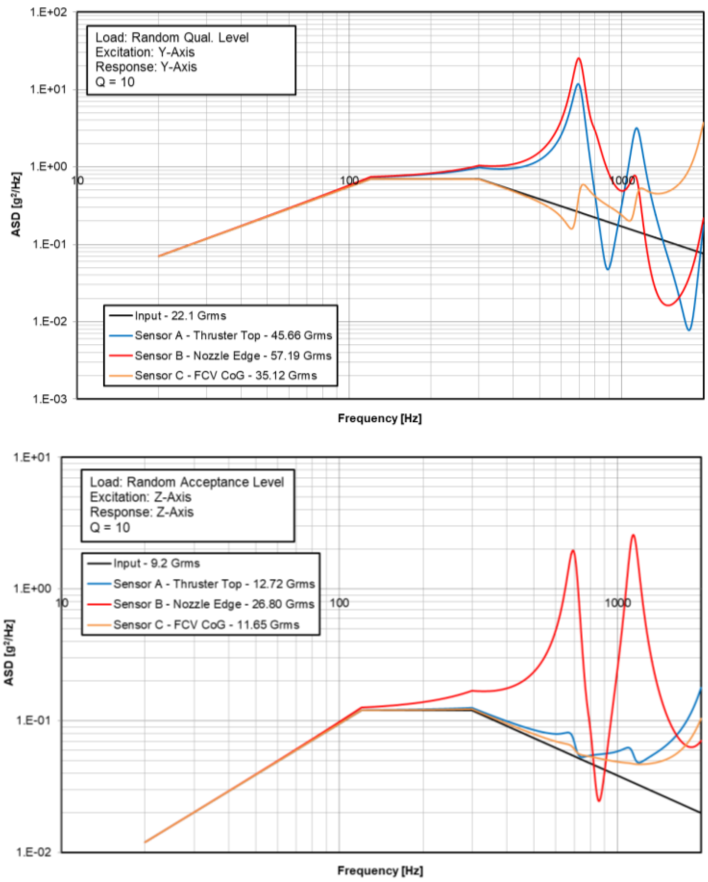


Figure 6-9: Expected random vibration response.

Summary:

Preliminary structural analysis has been performed. The calculations show a minimum frequency of 699 Hz, therefore sine vibration is not critical to the thruster strength.

The most critical load are the random qualification levels. The calculation results show a minimum margin of safety of 0.7. Vibration tests need to be performed in order to understand the thruster behaviour and damping levels. These tests is used to validate the FEM technique. The calculations show that the current design can be manufactured and tested.

6.9 DM1a Thruster (as built)

The following figure shows the DM1a thruster as built (thruster hardware without FCV):

Figure 6-10: DM1a Hardware (assembled fully functional thruster with pc tube)

7 DM1b Thruster Layout

The DM1b thruster is a downscale of the ArianeGroup 400N class Hydrazine Thruster, see also following figure. This thruster was qualified for the Ariane5 program and in between qualified and used for exploration missions and as a deorbit engine for larger LEO satellites.

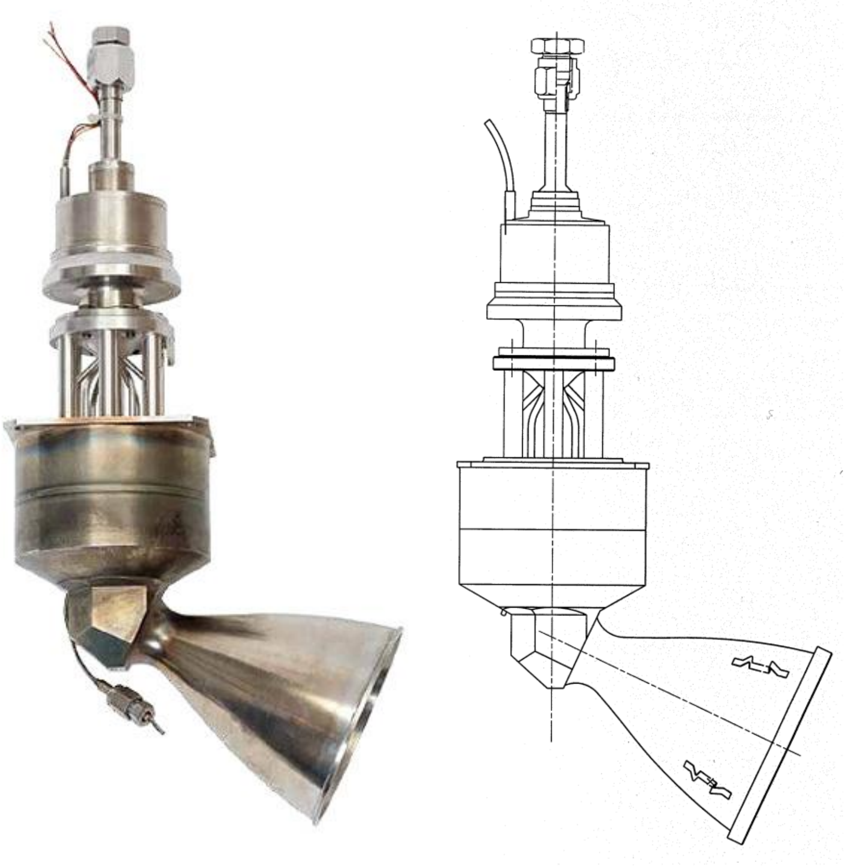


Figure 7-1: Ariane 5 400N SCA (Systéme Contrôle d'Attitude) thruster

Due to its heritage and the manufacturing technologies that were available when this thruster was developed in the late 1980’s it features a quite complex design of the heat barrier and the canted nozzle with many single pieceparts and joining steps.

Due the cost disadvantage the DM1b design (downscale of a qualified design with all the thermal and structural models in place) is considered as a backup solution in case DM1a does not work.

8 DM1a Test Results

8.1 Incoming Inspection

The additively manufactured parts were inspected to ensure freedom of external defects, deformation, surface damage or any obvious contamination. The concurrence of the manufactured parts and their drawings has to be checked.

After the first print an anomaly was detected (see red marked areas in the following figure). Most likely cause is that the vertical support is pushed inside when the central part cooled down. This issue was solved with a redesign and a reprint of the hardware. After the reprint this area was according to build definition and was accepted.

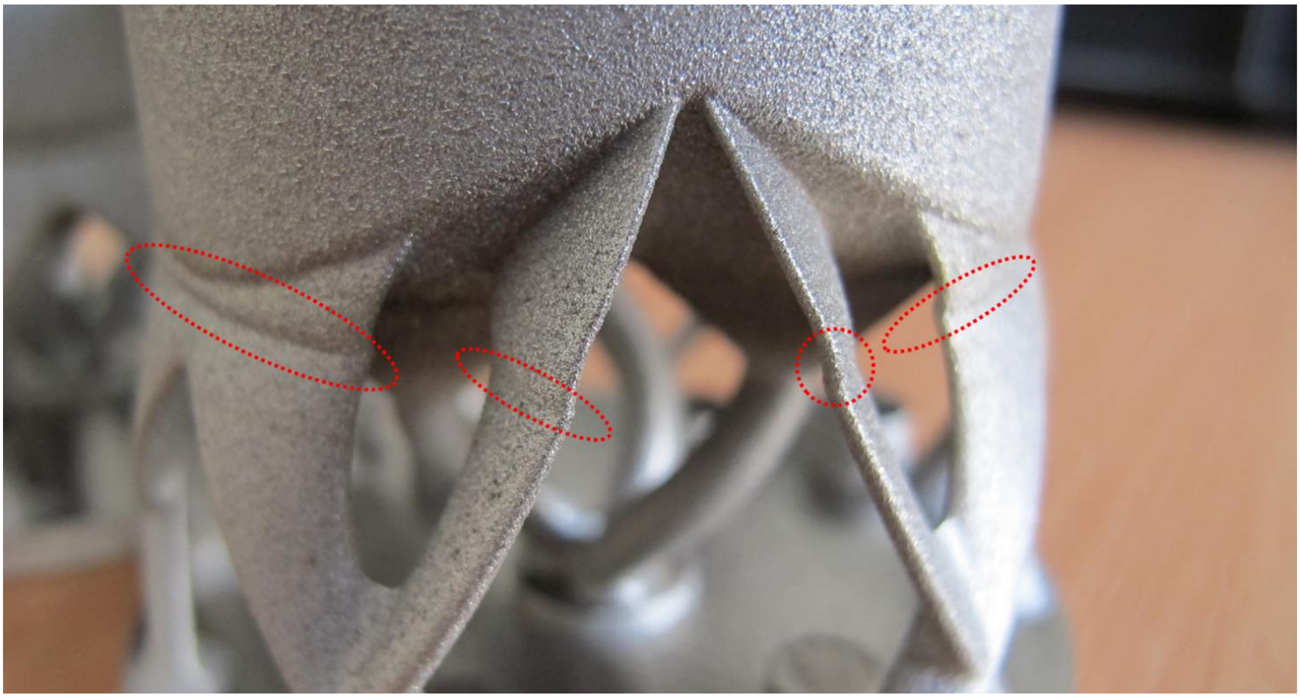


Figure 8-1: Print anomaly at first printing attempt

8.2 Visual Inspection

The visual inspection of the machined parts confirmed the good manufacturing status and that the tolerances necessary for the good weld joint were as designed.

8.3 Physical Properties Examination

The dimensions of the integrated components were calculated based on CAD and FEM data, see following table; the average mass that was measured including PC measurement tube and cables was 1278 [g] which fits quite well with the predictions

	CAD	FEM	Diff. [%]
Mass [gr]	1260.35	1247.67	-1.01
CoG X [mm]	-0.00035	0.000851	-
CoG Y [mm]	5.578	5.582423	0.08
CoG Z [mm]	24.85	24.57316	-1.11

Table 8-1: Physical Properties.

8.4 Hydraulic Tests with water

The pressure drop of the feed lines of the printed heat barrier was measured with water. Mass flow rate is 10 g/s to 120 g/s of water with steps of 10 g/s. The following graph shows the test results of 2 injector tubes in comparison to a classical bare tube of the same inner diameter and the same tube length.

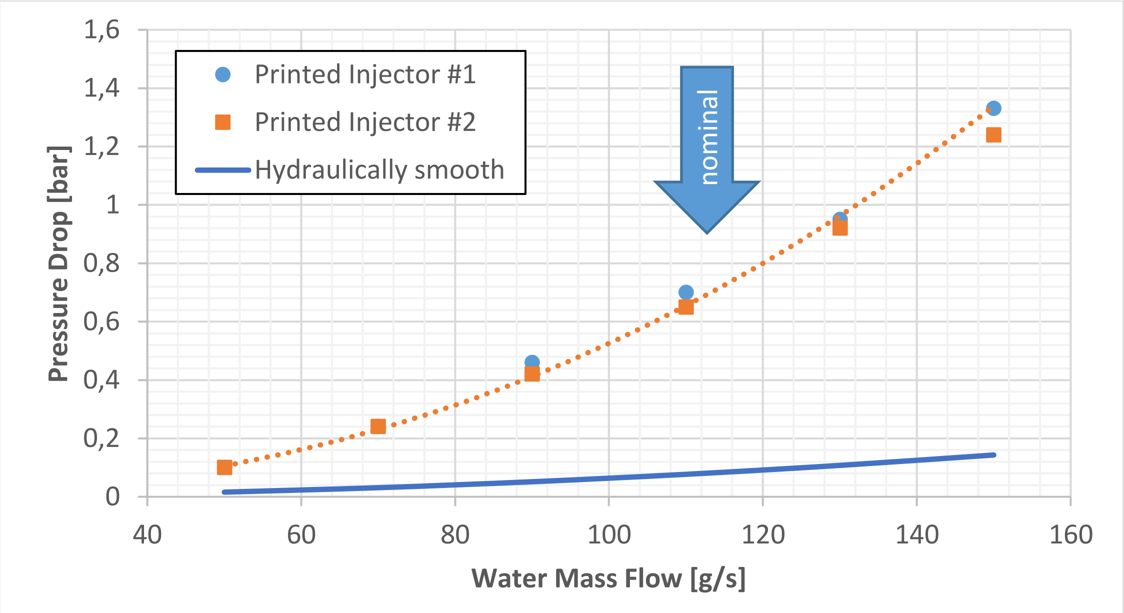


Figure 8-2: Pressure drop measurement of injector feed channels

The graph shows a significantly higher (approx.. a factor of 9) pressure drop of the printed tubes compared to the bare tubes that is potentially caused by:

- A higher variation of actual as built diameter compared to as designed
- A higher surface roughness of the printed parts

As a consequence either the hydraulic flow area has to be increased or a rework of the flow passages has to be foreseen.

8.5 Vibration Tests

The thruster dummy was subjected to random vibration in each of three mutually perpendicular axes according to Table 8-2.

	Control in Thruster X	Control in Thruster Y	Control in Thruster Z
Frequency	**PSD**	**PSD**	**PSd**
20 Hz	0,050 g²/Hz	0,070 g²/Hz	0,012 g²/Hz
120 Hz	0,500 g²/Hz	0,700 g²/Hz	0,120 g²/Hz
300 Hz	0,500 g²/Hz	0,700 g²/Hz	0,120 g²/Hz
2000 Hz	0,054 g²/Hz	0,076 g²/Hz	0,020 g²/Hz
overall	18,9 g_{RMS} for 2 minutes	22,1 g_{RMS} for 2 minutes	9,2 g_{RMS} for 2 minutes

Table 8-2: Random Vibration Test.

8.5.1 Instrumentation

The following sensors were installed to allow a correlation of the results with the predictions of the structural model:

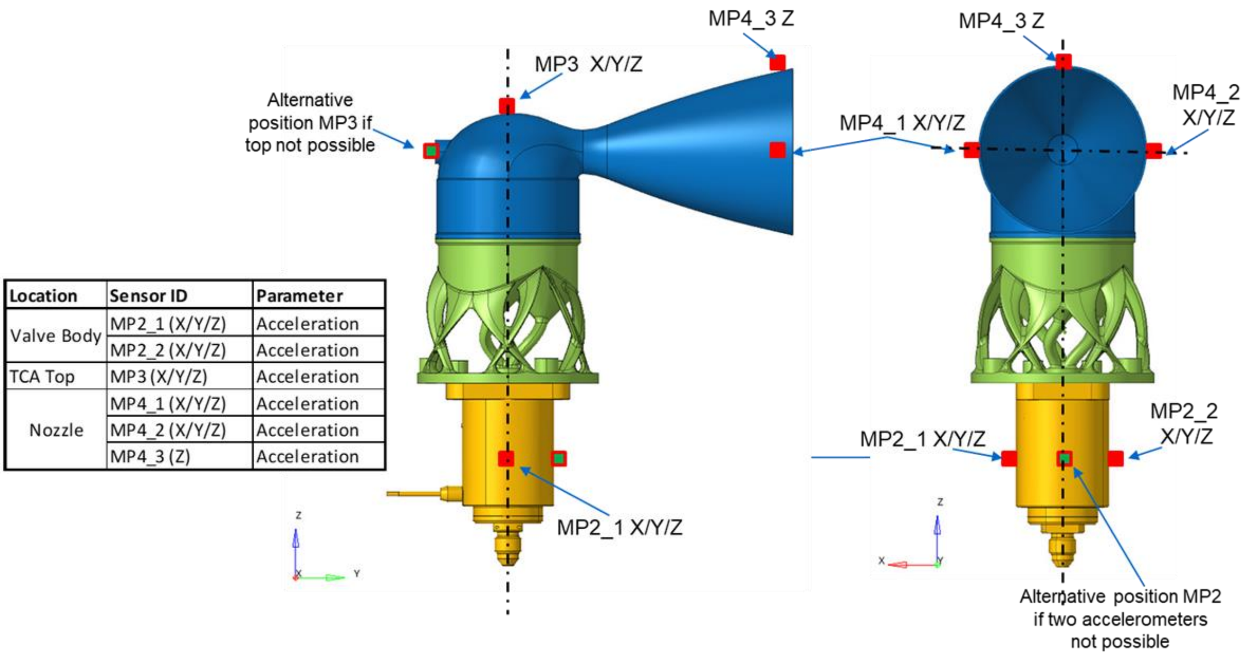


Figure 8-3: Random Vibration test instrumentation

8.5.2 Test Setup

The following figure shows as an example the thruster mounted on the shaker:

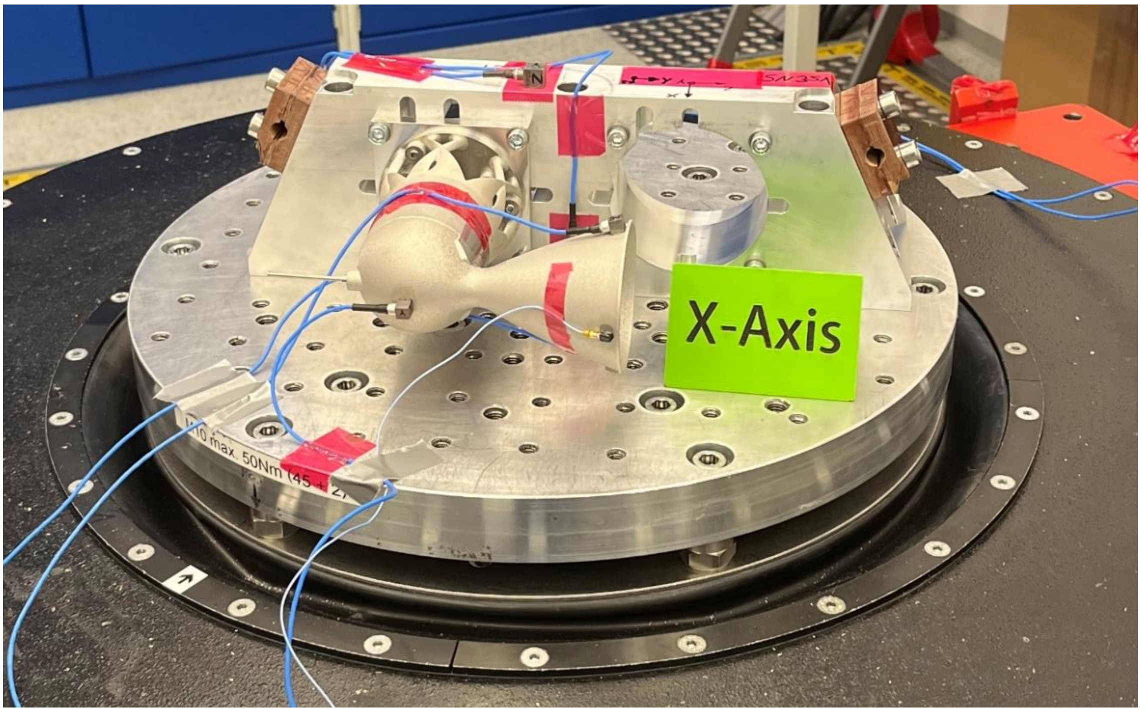


Figure 8-4: Thruster installed for vibration tests (X-axis)

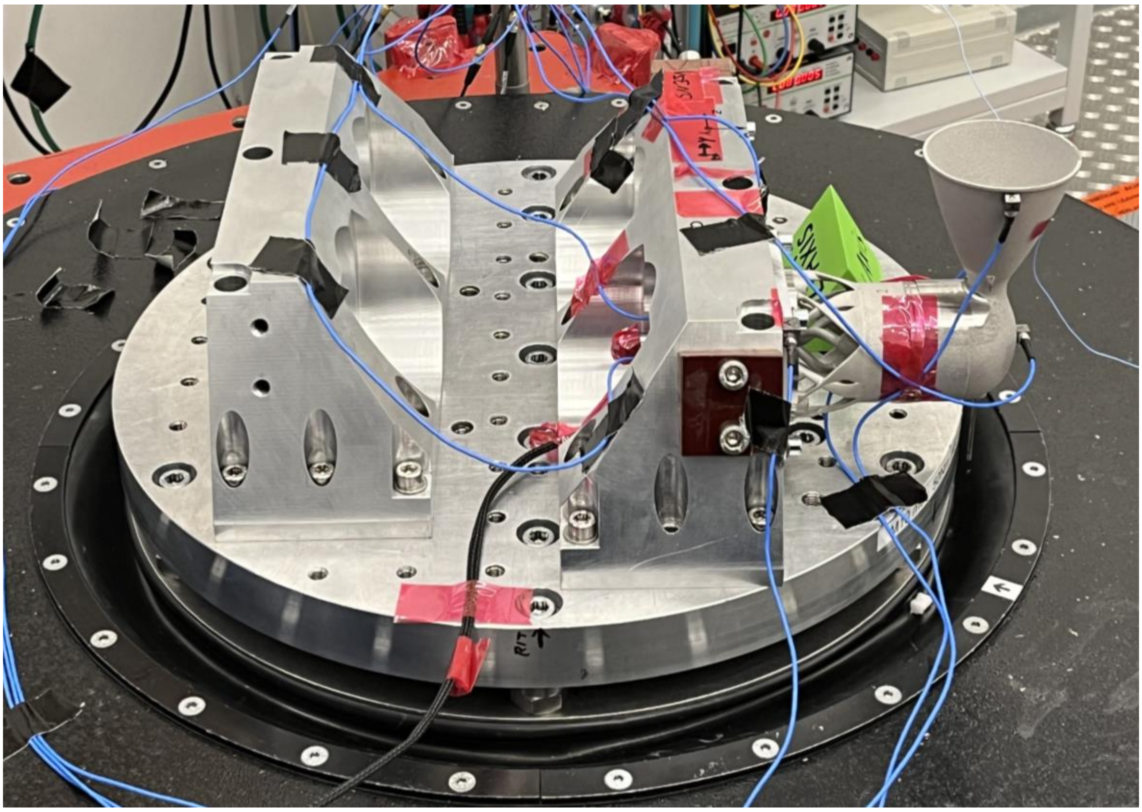


Figure 8-5: Thruster installed for vibration tests (Y-axis)

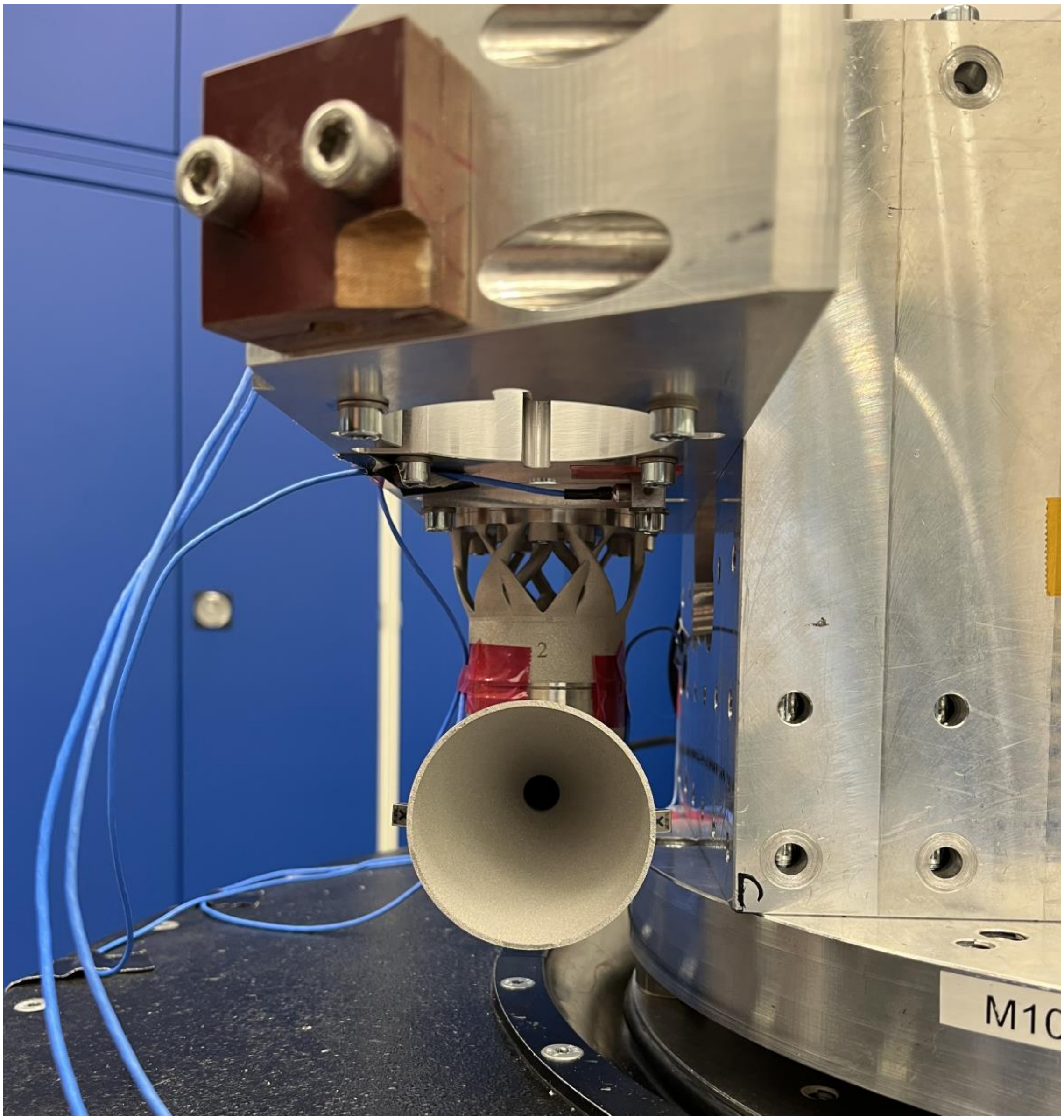


Figure 8-6: Thruster installed for vibration tests (Y-axis)

8.5.3 Random Vibration Test Results

A random response analysis has been performed with the FE model using MSC Nastran SOL 111 and compared against the vibration tests performed at -3db from acceptance level, see following table:

Random Vibration Qualification Level					
Thruster X Axis		Thruster Y Axis		Thruster Z Axis	
Freq. [Hz]	ASD [g²/Hz]	Freq. Hz]	ASD [g²/Hz]	Freq. Hz]	ASD [g²/Hz]
20	0.05	20	0.07	20	0.012
120	0.5	120	0.7	120	0.12
300	0.5	300	0.7	300	0.12
2000	0.054	2000	0.076	2000	0.02
gRMS	18.9	gRMS	22.42	gRMS	9.99
Random Vibration Acceptance Level					
Thruster X Axis		Thruster Y Axis		Thruster Z Axis	
Freq. [Hz]	ASD [g²/Hz]	Freq. Hz]	ASD [g²/Hz]	Freq. Hz]	ASD [g²/Hz]
20	0.0251	20	0.0351	20	0.0060
120	0.2506	120	0.3508	120	0.0601
300	0.2506	300	0.3508	300	0.0601
2000	0.0271	2000	0.0381	2000	0.0100
gRMS	13.4	gRMS	15.87	gRMS	6.51
Random Vibration Test -3db from Acceptance					
Thruster X Axis		Thruster Y Axis		Thruster Z Axis	
Freq. [Hz]	ASD [g²/Hz]	Freq. Hz]	ASD [g²/Hz]	Freq. Hz]	ASD [g²/Hz]
20	0.0126	20	0.0176	20	0.0030
120	0.1256	120	0.1758	120	0.0301
300	0.1256	300	0.1758	300	0.0301
2000	0.0136	2000	0.0191	2000	0.0050
gRMS	9.47	gRMS	11.24	gRMS	5.01

A partial calibration have been performed of the modal damping used in the model mainly to match main modes in order to have enough accuracy to perform an estimated strength analysis for dynamic loads at qualification level. The locations compared are according to the location of accelerometers in the nozzle, TCA and FCV as shown in Figure 8-3.

As an example the comparison between the random tests at -3db from acceptance level and the FE analysis results for the main response directions at the nozzle at MP4_1 accelerometer position are shown in Figure 8-7 to Figure 8-9. In general the FE model can capture correctly the general behaviour of the thruster. The highest difference in general is when loading in the Z direction. This can be associated in part that the test jig has been improvised and can induced some extra modes and accelerations not capture by the FE analysis as the assumptions are that the jig is perfectly rigid, see Figure 8-6.

In terms of locations where the difference is maximum is of course on the FCV as the model is only capable of capture the main mode as it is modelled as a rigid element. Nonetheless in general the model is acceptable for the prediction of stresses at the tested level and at qualification level.

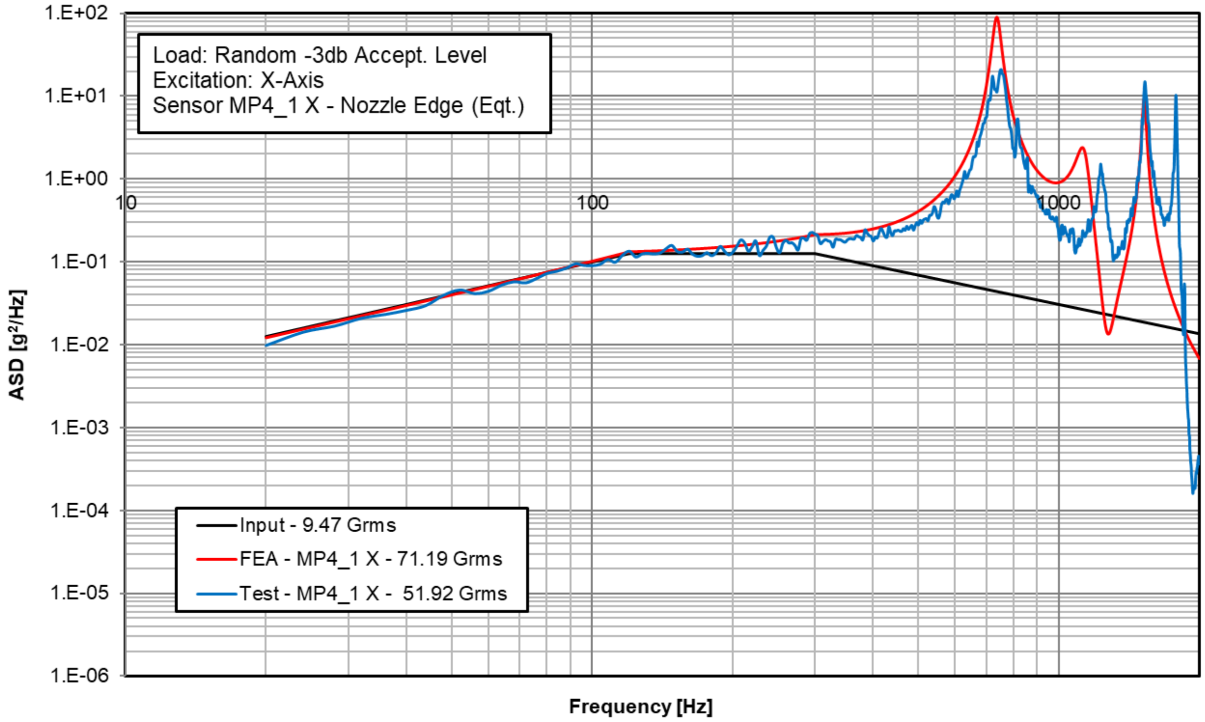


Figure 8-7: Comparison between FEM and tests at nozzle (MP4_1) for random X-Axis and X response

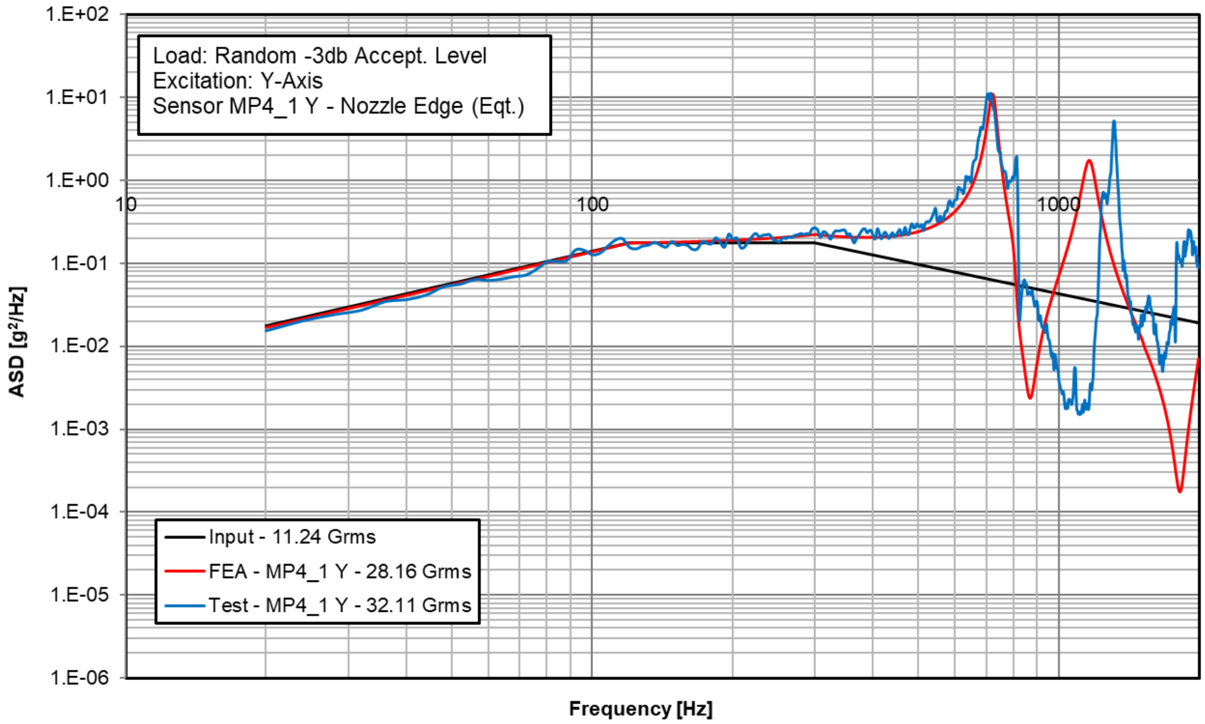


Figure 8-8: Comparison between FEM and tests at nozzle (MP4_1) for random Y-Axis and Y response

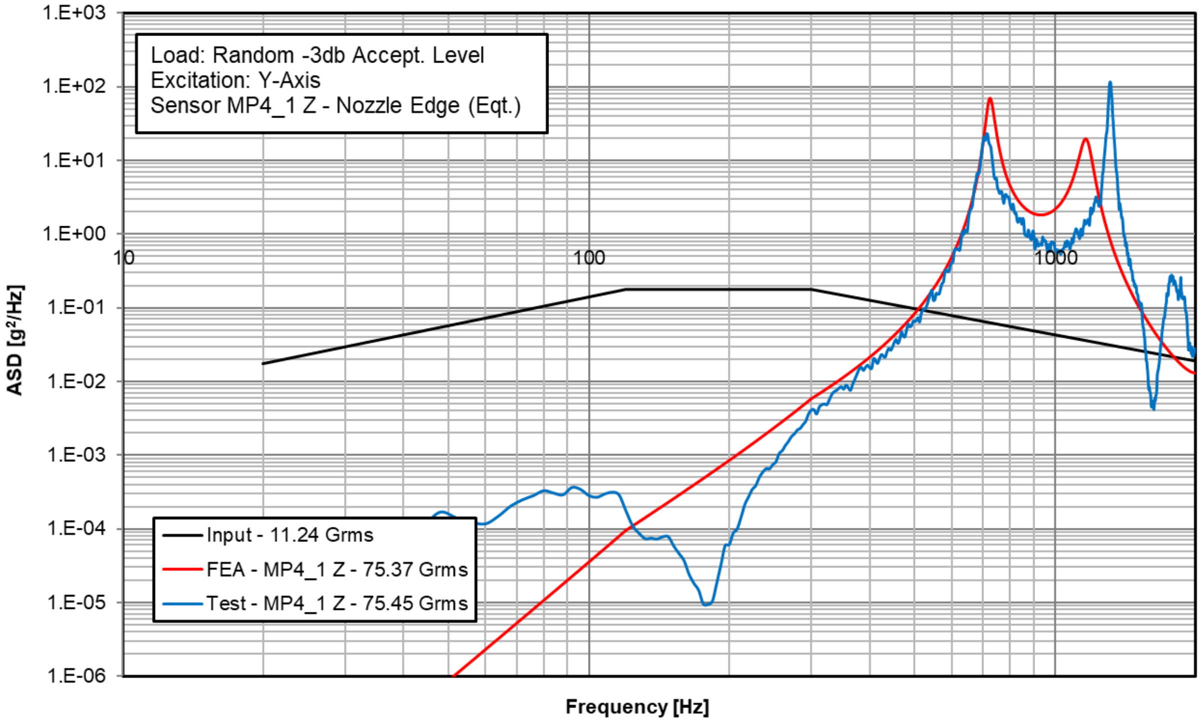


Figure 8-9: Comparison between FEM and tests at nozzle (MP4_1) for random Y-Axis and Z response

In general it can be concluded that the FE model is reliable enough to predict the thruster dynamic behavior or at least small modifications can be performed to have a better correlation. The general design of the thruster shows that it is able at least to sustain the dynamic loads. Further verification needs to be performed for its behavior for hot vibration as well as general thermo-mechanical fatigue behavior during operation.

8.6 Final Inspection

A final inspection was performed in order to identify any defect or deformation during the preceding testing procedure. After the test series was completed no defect or deformation could be identified.

9 Summary / Outlook

9.1 Summary / Results of actual GSTP Program

In order to pro-actively counter the risk of a non-availability of a 240N thruster for the VEGA RACS system, ArianeGroup was contacted to maturate and pre-develop a 240N thruster with advanced manufacturing methods and to confirm its suitability prior to a full development / qualification.

During the actual GSTP contract [AD 2] a 240N class Hydrazine thruster was designed in a classical (DM1b) and in a cost optimized version (DM1a). The cost optimized version used additive manufacturing in order to speed up the development process, to lower the number of single piece parts and thus lower the development and manufacturing cost.

The following critical elements of an additively printed thruster were successfully verified during this program:

- A first critical element of the thruster design is the heat barrier that has to be stiff on one hand to cover mechanical loads but needs to have a low cross section to limit thermal flux to the injector. This heat barrier was optimized using additive manufacturing with the target not to have an additional support structure. The design was further optimized via structural analysis and finally a demonstrator was printed and tested during a vibration test that confirmed the structural analysis.
- The second critical element is the hydraulic path where significantly different pressure loss coefficients compared to classical tubes have to be considered due to the printed feed tubes. Hydraulic tests were performed with the injector head.The tests confirmed the initial assumptions of pressure loss coefficients for printed tubes that were gained in [RD 2].

For the DM1a thruster design a first complete thruster design was performed and this design was stepwise optimized based on structural calculations. The stress calculations show a minimum freq. at 699Hz. Sine vibration is not critical for the thruster strength; random vibration at VEGA-RACS qualification levels is the most critical load.

A complete functional thruster was manufactured via ALM printing and finally fully integrated. This additional work could be performed due to synergies with another program (240N Hydrogen Peroxide thruster) where the only difference compared to the Hydrazine version is the catalytic bed

Hydraulic tests of the printed parts were performed that showed a higher pressure drop of printed tubes compared to classical tubes – this difference has to be taken into account and change of print parameters or a post-processing to be implemented.

Vibration tests were performed and the results confirmed the assumptions of the structural analysis.

The Contact was fulfilled and exceeded as a fully functional flight like thruster was built that is now ready for hot firing tests.

9.2 Outlook

9.2.1 Classical (Hydrazine based) Development

According to the proposal [AD 1] to continue the actual development and to proof the functional behavior a phase 2 is proposed, see also following **Figure 9-1**. During this Phase 2 a manufacturing and test of a PQM hardware is foreseen to allow a CDR against actual requirements.

The final manufacturing and test of qualification hardware and subsequent documentation is pending on the overall qualification program. As part of Phase 2 phase a dedicated assessment of NRC and RC cost with subsequent funding scheme is performed.

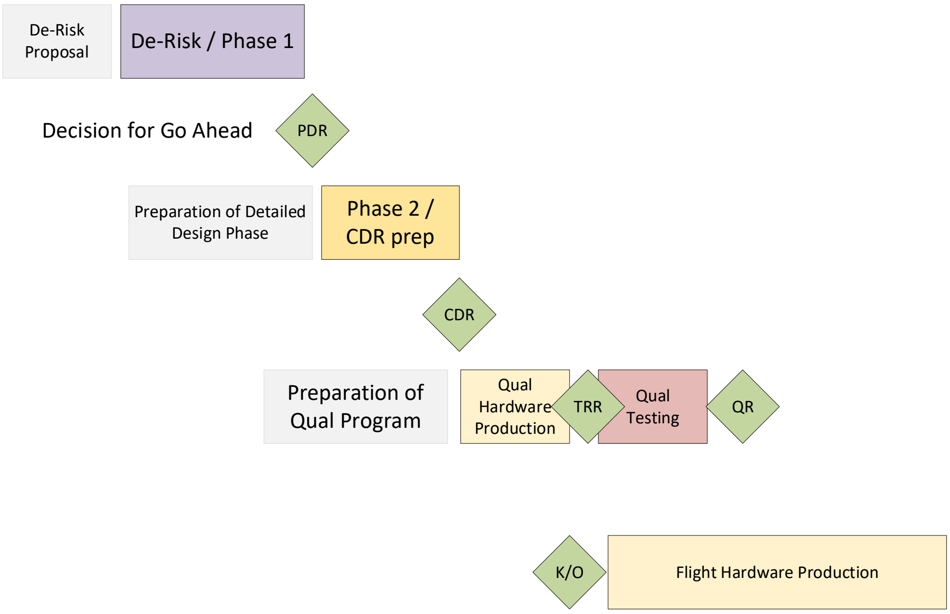


Figure 9-1: Generic Development Roadmap 240N Roll control Thruster [RD 2]

9.2.2 Green (Hydrogen Peroxide based) Development

During an internally funded development program a 240N class Hydrogen Peroxide Thruster was developed, manufactured and tested [RD 2].

The tests showed that classical design rules for Hydrazine thrusters can be adapted to the new propellant; the following differences have to be taken into account in the thruster design:

- **Hydraulics:** In order to achieve a similar combustion chamber pressure the pressure losses of FCV, trim orifice, feed tube, injector and catalyst bed have to be adapted to the changes in mass flow and propellant density.
- **Catalyst:** A different catalyst active material has to be chosen (e.g. 5% Pt instead of 30% Ir), see also [RD 2].
- **Catalyst bed:** The catalyst bed functional parameters (i.e. cat bed load) have to be adapted to the changed propellant. Based on the experience gained, the catalyst bed diameter can be the same as

for Hydrazine thruster, that means the cat bed load can be adjusted via a simple adaptation of the cylindrical length of the catalyst bed.

- **Propellant wetted parts:** In the FCV compatible materials have to be used; if e.g. stainless steel is used the type of the material, the passivation and the grade of the Hydrogen Peroxide has to be properly selected

The following figure shows the design and printed piece parts of this thruster that has a similar design as the actual DM1a thruster. The printed parts of the DM1a thruster can be converted to a H2O2 version by simply using a different catalyst bed design.

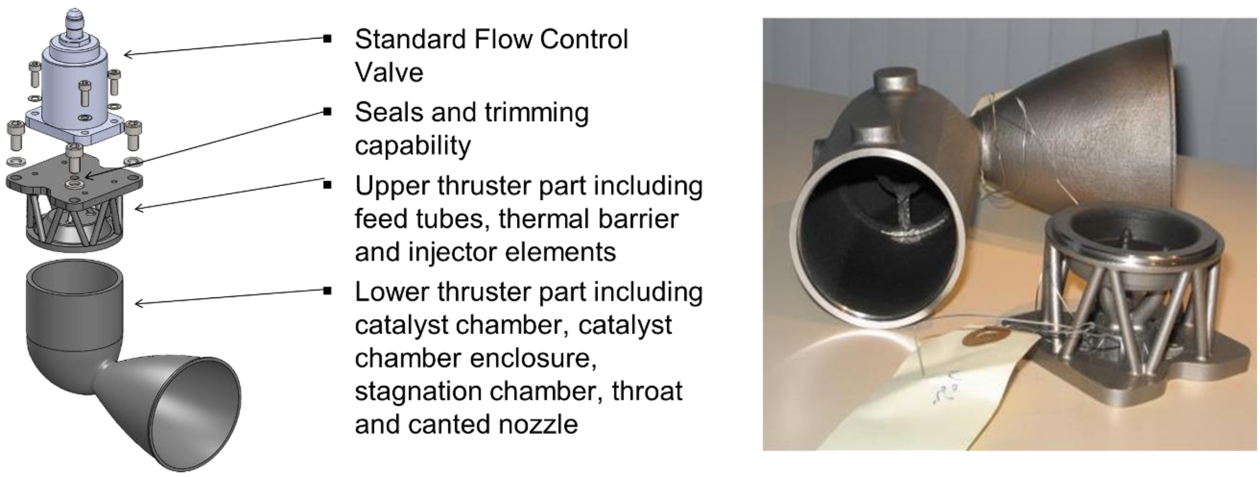


Figure 9-2: ALM printed 240N Roll control Thruster [RD 2]