OVERVIEW OF THE DEVELOPMENT OF A H2O2 BASED CHEMICAL ATTITUDE CONTROL SYSTEM FOR VEGA-C

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ABSTRACT:

Under an ESA contract with AVIO, Nammo is developing a green propellant Roll and Attitude Control System (RACS) for VEGA-C replacing the current hydrazine sub-system. This RACS is based on Hydrogen Peroxide (H2O2), a propellant with which Nammo has built an extensive expertise over the course of the last decade.

The RACS mission is to provide fine trajectory modification during the full launch profile, from lift-off to the deorbiting manoeuvre after release of the payload(s). The RACS thus requires an extreme versatility, allowing both long firing and very short pulses, both at sea level and in hard vacuum.

The RACS is composed principally of two thruster clusters fed by a common propellant tank via a tubing system.

The article will provide an overview of the RACS design and development, its overall status and planning and main achievements. It will as well focus on the specificities of H2O2 for such applications. As three sister paper had to be cancelled due to the covid-19 pandemic, this paper as well provide some insight that should have been presented in those papers.

1. BACKGROUND HISTORY

Nammo Raufoss AS historical field of expertise was tactical solid rocket motors (SRM). A first incursion into the space sector was done in the 90's with a contract continuing up to this date to deliver the FE/FA motors for Ariane 5; motors responsible respectively for the separation of the side boosters and the acceleration after separation of the second stage. These activities led to further solid motor delivery with the Distancing Rocket motor for Ariane 6, and the P120-C igniter for both VEGA-C and Ariane 6.

As a first spin-off to this solid motor technology, Nammo started investigated in early 2000 the hybrid technology. This technology has indeed the potential to enable the simplicity of a solid motor, with the controllability of a liquid, at a low development and recurring costs. During the first phase of the development [1], Hydrogen Peroxide has been chosen as liquid oxidizer, thanks to its storability, industrial availability and high density, which yield the best compromise for the identified market of the technology: sounding rocket and micro-launcher propulsion. It is in addition a Green propellant, fitting ideally in the framework of ESA to stir away as much as possible any future development from toxic propellants. The working principle of the motor is highlighted in Figure 1: the liquid oxidizer is entering the motor through a silver-based catalyst bed, in which it is decomposed into hot gases at sufficiently high temperature to ignite spontaneously the solid fuel.

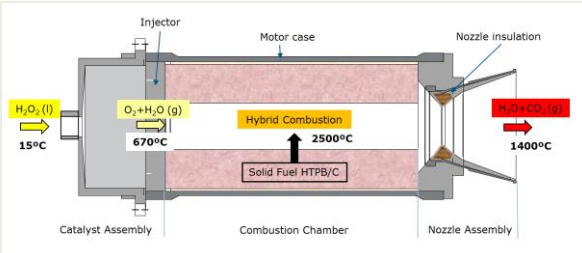

Figure 1. Working Principle of the UM1.

This development culminated so far with the development of the UM1 motor and the successful launch of the Nucleus, a prototype sounding rocket [2]. Further development is being carried to increase the capability of the motor technology, in terms of dry mass reduction, low cost manufacturing and scalability toward a size fitting for booster stage of a low-cost micro-launcher.

The development of monopropellant thrusters came then as a spin-off to the hybrid technology, basing the development on the same oxidizer and catalyst technology. This work was initiated in 2012 with a maturation work for a Hot Gas Reaction System (HGRS) for Ariane 5 ME. This work led to the development of a prototype high performance thruster [3] and a prototype propellant tank with positive expulsion device (PED) [4]. This preliminary work culminated with a system testing, linking two PED tanks to two thrusters, as shown in Figure 2.

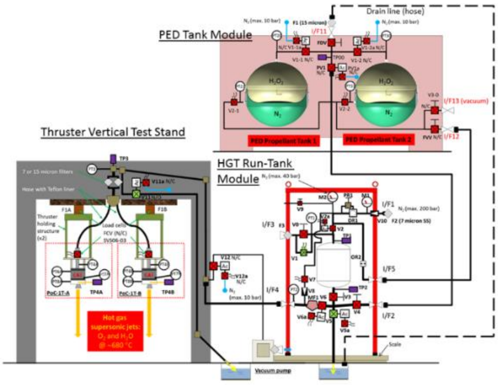

Figure 2: Schematic of the System Test Set-up during Maturation Work

The thruster prototype, the Proof-of-Concept (PoC) 1, was then as well tested in vacuum condition at DLR Lampoldshausen [3], as shown in Figure 3.

Figure 3: Nammo 200N Monopropellant PoC1 Thruster after Completing Vacuum Test Campaign at DLR Lampoldshausen, March 2015

Following the cancellation of Ariane 5 ME in favour of Ariane 6, the development of the HGRS was put on hold, while further maturation work on the thruster technology was performed with ESA as highlighted in Figure 29.

The work done by Nammo Raufoss AS on the HGRS was heavily linked with Moog Europe [3], which was producing the Flow Control Valve (FCV) for the thrusters and the Service Valves (SVs) for filling (Fill&Drain Valve – FDV) and pressurizing (Fill&Vent Valve – FVV) the RACS. As a strategic decision to consolidate the position of Nammo in the space sector, as well as increasing the in-house capabilities of Nammo for the development of such propulsion systems, Nammo acquired the Moog sites in UK (Cheltenham and Westcott) and Ireland (Dublin) leading to the creation of Nammo UK and Nammo Ireland Ltd.

The development of a H2O2 based attitude control system using Nammo's technology was then picked up for further development by ESA and AVIO for VEGA-E, where green propellants are the baseline for all liquid motors.

The main propulsion would be with a LOX-Methane motor under development and the Roll and Attitude Control System (RACS) would then be replaced from the existing hydrazine sub-system to the Nammo technology. While the green turn is planned for VEGA-E, convergence of development plans between Nammo RACS and VEGA-C led all parties to anticipate the inclusion of the solution to VEGA-C. This RACS for VEGA-C is then the focus of the current ESA development contract with AVIO for Nammo's technology; and the subject of this paper.

2. SYSTEM ARCHITECTURE AND PERFORMANCE

2.1. Overview

The upper stage of the VEGA C, the AVUM (see Figure 4), is composed of a main liquid propulsion system (LPS+) and a Roll and Attitude Control System (RACS) to control the attitude of the launch vehicle during the ascent phase, for payload delivery and for deorbiting purposes at the end of the mission. The propellants used in the baseline are nitrogen tetroxide (NTO) and Unsymmetrical dimethylhydrazine (UDMH) for the LPS+ and hydrazine for the RACS. Those propellants are considered toxic and highly dangerous during handling. Only the RACS is then changed to green propellant with H2O2.

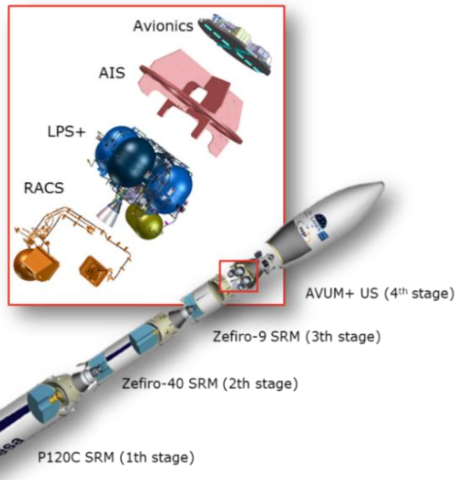

Figure 4: Model of VEGA-C with Details on the AVUM. Source: AVIO

The architecture of the RACS for VEGA-C is schematically shown in Figure 5.

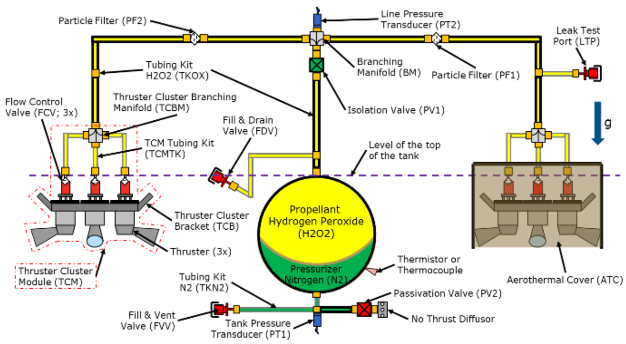

Figure 5: Schematic Architecture of NAMMO RACS

Six monopropellant thrusters are divided in two Thruster Cluster Modules (TCM) located diametrically opposed on the outer surface of the AVUM. Four thrusters (two in each cluster) are needed for roll control. The two remaining are then used for yaw and pitch control, as well as stage distancing during stage separation or for mission dependant linear boosts (separation between payloads for example).

Each thruster is fitted with a Flow Control Valve (FCV), regulating the mass flow according to the requested activation mode. The three thrusters in a cluster are attached to a Thrust Cluster Bracket (TCB), which makes the mechanical connection with the AVUM structure. An AeroThermal Cover (ATC) envelops the thrusters to protect them from the aerothermal effects during the atmospheric phase of the launch.

The thrusters are all fed from a common tank, pressurized with Nitrogen. The Nitrogen is stored in the same tank as the propellant, which lead to an operation of the system in Blow-down; the pressure decreasing with the use of the propellant. A Positive Expulsion Device (PED) is then used to separate the pressurizer from the propellant and to ensure that propellant is fed to the thrusters under any circumstances, including high acceleration and launcher roll rate and zero-g conditions.

The H2O2 propellant is metastable in the range of concentration used. This leads to a natural decomposition rate, which can only be limited with proper compatibility of the materials in contact and good temperature control (see chapter 5 for more information on the propellant). The materials of all the H2O2 wetted surfaces, and primarily the tank, have therefore to be selected in accordance to their compatibility with the propellant to ensure good operation of the RACS. The principle materials used in the RACS are therefore aluminium alloys offering the highest compatibility with H2O2.

Filters (PF1 and PF2) are located on the H2O2 tubing, between the tank and the thrusters, in order to protect the downstream components from particles and other contaminants that could be found in the sub-system. To ensure safety on the ground, an isolation valve (PV1) completely separates the propellant from the thrusters until priming. This function is ensured by a pyro-valve. Another pyro-valve (PV2) is used at the end of the mission to finalize the system passivation at End Of Life (EOL). On the ground, the RACS is filled and leak tested through three dedicated Service Valves (SVs: FDV, FVV and LTP), being the fluidic interfaces with the external equipment.

Two pressure probes and thermistors and/or thermocouples are finally used to monitor the evolution of the system during its use.

The data obtained are used to monitor the system while on the ground, notably due to propellant decomposition (see chapter 5) and as well for the post-flight analysis. During the mission, the system is fully controlled by the on board computer solely through outputs from the performance model that is as well part of the delivery along with the hardware.

The propellant used is Hydrogen Peroxide, nominally at 87.5% concentration (per mass); the rest being water and some stabilizer elements (see chapter 5). Nitrogen (N2) is used as pressurizer.

2.2. Project Organization

All the components mentioned in section 2.1 are represented in Figure 6. Nammo is the design authority, being in charge of the development of the full RACS. It is as well the design authority of most of the components. The Thrusters, the TCB, the ATC, the Tank and the Tubing Kit are developed by Nammo Raufoss, while the three Service Valves and the FCV are developed by Nammo Ireland.

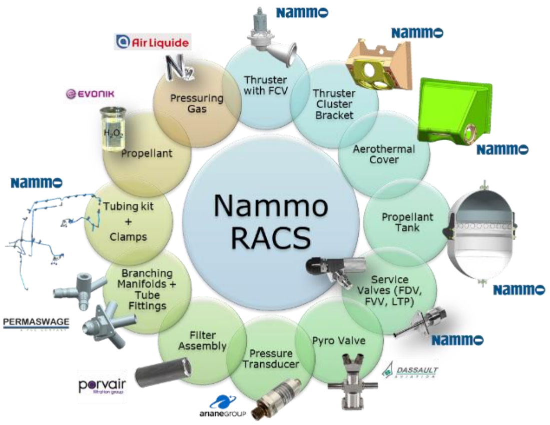

Figure 6: Summary of the RACS Sub-System Main Components

Among the components not developed by Nammo, the Pyro-Valves (Dassault Aviation) and the Pressure Transducers (ArianeGroup) are considered Component-Of-The-Shelf (COTS); both having flight heritage on board launchers. The filter assembly is being developed by a sub-contractor of Nammo, Porvair, which has extensive experience with propellant filter design. This development is carried out according to the specificities of the RACS. Finally, some custom-made fittings are made by PCC-Permaswage, notably for the manifolds separating the flows between the two side of the system and between each thruster in the TCMs.

In addition to the hardware of the RACS, Nammo is also responsible for two software models of the sub-system. A Thermal Mathematical Model (TMM) is being developed. It will be integrated in the general TMM of VEGA-C and used to update the thermal interfaces during specific missions and for post processing of the data collected.

In parallel, and more importantly, a Performance Mathematical Model (PMM) is as well being developed by Nammo. This PMM will be the sole interface between the propulsion hardware, and the On-Board Computer of the AVUM giving the firing orders.

The Ground Support Equipment (GSE) is under AVIO's design authority, with the exception of the Ground Half Coupling (GHC) of the SVs and the thruster nozzle plugs for leakage testing that are part of Nammo's perimeter. This GSE includes then delivery and any potential storage of H2O2, the filling and pressurizing equipment as well as any safety aspects related to the use of the RACS and of its propellant. This work is a full part of the development, and Nammo is to provide all required input as design authority and based on its extensive experience with H2O2.

Nammo will deliver to AVIO sub-assemblies and components with acceptance status at these levels. The final assembly, as well as the acceptance of the entire RACS, will then be performed by AVIO following User Manual and Acceptance Specification written by Nammo.

2.3. Main Design Parameters of the RACS

The RACS shall be operational from the moment it is primed (opening of PV1 just after lift-off) until the deorbiting manoeuvre of the AVUM after delivery of the payload(s). This notably means that the required performance are verified both at Sea Level (SL) and in hard vacuum (Vac.). As the propellant is being fed to the thruster in a blow-down fashion, the pressure set by the N2 changes between Beginning Of Life (BOL) and EOL. This change is quite significant and leads to a change of thrust performance during the mission.

The RACS shall be able to perform long duration steady state firing (SSF), for important attitude compensation (roll control during boosting phase of the P120C for example) or for small delta-V modification (distancing after stage separation or payload delivery, collision avoidance manoeuvre, etc.). At the same time, it shall be able to perform very short pulse mode firings (PMF), in order to achieve the precision objectives of the VEGA-C mission (orbit insertion, payload delivery) as well as minute attitude modification. The smallest impulse to be delivered by the RACS, the Minimum Impulse Bit (MIB), is performed over a duration of 20 ms, while the longest SSF is up to 120s. This wide range of objectives lead to the need for a very versatile design, especially of the thruster.

The AVUM is already qualified with the architecture of the hydrazine version of the RACS. In order for the change to H2O2 to be as cost effective as possible, it is therefore required to keep the qualification status of the full system as high as possible.

This implies notably keeping as much as possible of the already defined architecture. As such, the introduction of the RACS shall lead to no modification of the interface structures and of the other sub-systems of the AVUM. This means notably that the already defined mechanical interfaces for the hydrazine version need to be reused. As well, the organization of the RACS in the AVUM, shall be within the allowable volume defined from the current system (in transparent brown in Figure 7) and design checks are to be performed, wherever infringements of this allowable volume are needed, notably due to H2O2 RACS specificities.

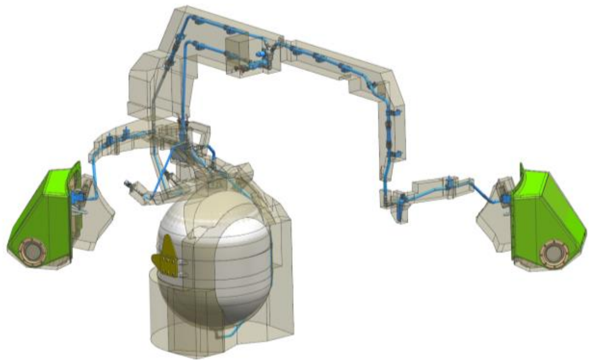

Figure 7: Visualisation of the RACS in the AVUM with its Allowable Volume

In order to fit the required launch flexibility (weather holds, postponement), the RACS shall be ready for launch for longer duration, even though the operating time itself is limited to one day. This means that the RACS shall tolerate to be filled with propellant and pressurized (hence sealed) during this extended period on the ground. The natural decomposition rate (see chapter 5) of the propellant during this period has then two main effects.

On the one hand, it reduces the propellant concentration, and therefore the maximal performance achievable, notably in terms of specific impulse (Isp.). As such, the ground conditions, notably the temperature, the compatibility of the materials and the filled storage duration need to be properly set to guarantee the performance. With a nominal filling concentration of 87.5%, a maximum drop of 2.5%, over a filled duration of 4 months, is allowed to meet the mission objectives.

On the other hand, the decomposition leads to the release of oxygen gas. Prior to pressurization, the gas can be evacuated from the sub-system. This then requires the tank to be oriented in a vertical position (North-South, NS) with the propellant on top (as shown in Figure 5). The oxygen is then evacuated through the FDV. However, once the RACS is pressurized and sealed (up to 25 days), any new oxygen gas will remain in the system and contribute to increasing the pressure. The Maximum Expected Operating Pressure (MEOP), against which all structural components need to be proofed, is therefore higher than the BOL pressure needed for the mission. The outgassing gas is removed from the system during the priming phase.

Finally, as the RACS is filled and pressurized on the ground, and shall remain such while potential other manual operations are taking place around the sub-system, the safety of the workers shall be ensured at all time. H2O2 being not toxic, the working condition around the system can be somewhat lighter than with hydrazine (see chapter 5). This being said, H2O2 remains a high oxidizer that need proper safety procedures and equipment. From the RACS point of view, this means that the sub-system shall be with proper safety factors against burst, as well as being tolerant to two mechanical failures (Fail Safe/Fail Safe design; FS/FS). This includes then the presence of 3 safety barriers between the tank stored propellant and the ground environment.

Table 1 gives then an overview of the design objectives linked with what stated above.

Table 1: Overview of Main Design objectives

Characteristics	Value
Envelope constraints	
Dimensions	Fitted to the AVUM
Dry Mass	< 42 Kg
Propellant feeding	Single Tank Blow-Down
Tank Orientation	NS/Propellant on top
Fluids	
Propellant	H2O2
H2O2 Concentration	85.0 – 88 %. Nominally 87.5%
Pressurizer	N2 Grade B
Performances	
Total Impulse	>79000 Ns
Vac. Thrust BOL	>200 N
Vac. Thrust EOL	>100 N
SL Thrust BOL	>140 N
Vac. Isp SSF	>150s for firing duration 1-120s
Vac. Isp PMF	>120s for firing duration 20-1000 ms
MIB	2.1 – 3.9 Ns
Pressure Ratings	
MEOP	32 barA
BOL	26 barA
EOL	9.5 barA
Temperature Ranges	
Propellant on Ground	16-33°C
Propellant in Tank mission	15-40°C
Propellant upstream FCV	15-80°C
Safety Aspects	
Safety Rule	FS/FS upstream PV1 (3 safety barriers)
Proof Pressure	>1.5xMEOP
Burst Pressure	>2xMEOP for Tank >2.5xMEOP other.
Life cycle	
Shelf Life Components	8 years
Shelf Life RACS	3 years
H2O2 filled duration	1 day - 4 months
Pressurized duration	1-25 days
Operating Time	1 day

2.4. System Performances

As both the systems and the main components are under development in parallel, all the results mentioned in this chapter are obtained either from simulations or from preliminary Testing. A margin policy is therefore applied on those results to take into account the degree of maturity of the different components and shall therefore be taken as preliminary results at "Preliminary Design Review (PDR) level".

<u>H2O2 Decomposition and Pressure Budget</u>

As mentioned previously, the effect of the H2O2 decomposition are a lowering of the concentration during the 4 months the system is filled, and an increase of the pressure during the 25 days pressurized. The two main parameters driving this decomposition are then the temperature of the propellant and the compatibility class of the contact material (see chapter 5).

Figure 8 provides then an overview of the simulation performed with different scenarios. In order to ensure the Isp requirements, a minimal concentration of 85% is to be guaranteed, which corresponds to a maximal drop of 2-3% from the delivered nominal concentration of 87-88% (green and red lines). Case "i" is done with the lowest ground temperature of 16°C (see Table 1), while case "iv" is with the highest temperature of 33°C. Case "ii" is then taken at a temperature of 23°C and give results compliant with the performance requirements, especially knowing that the tank material is closer to the "class 0.5" with low decomposition than the "class 1 (see chapter 5). It has therefore been agreed with AVIO to consider a temperature of 23°C as baseline for future development.

Figure 9 shows then the expected pressure increase during the pressurized time. The nominal case "ii" lead to a maximal expected pressure increase of 6 bar, which is used for the definition of the MEOP. The additional pressure brought by this gas is removed from the system during priming.

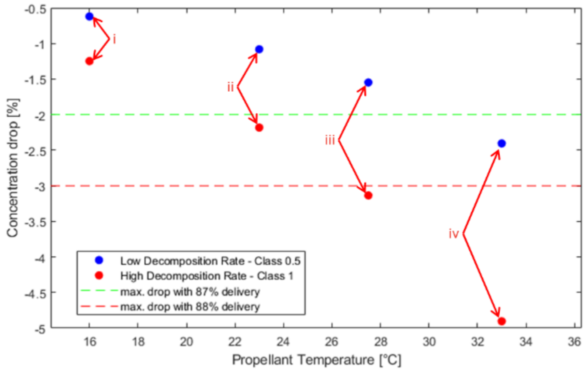

Figure 8: H2O2 Concentration Drop during the 4 Months Filled Duration in Different Scenarios

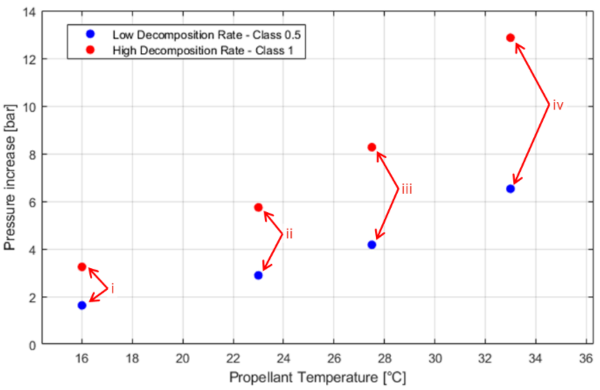

Figure 9: Pressure Increase in the RACS during the 25 Days Pressurized Duration in Different Scenarios

Figure 9 can as well be used to present the problematic of the orientation of the tank during the 4 months filled period. Indeed, with a NS orientation and the propellant on top, the gas released by the decomposition during the filling time can be directly removed from the system through the FDV. Another configuration would have led this gas to remain in the system, leading to an even bigger pressure increase, between 14 (Class 0.5) and 28 (Class 1) bar, or more than 100% of the BOL pressure.

The system pressure is dictated by the allowable volume, giving an upper limit for the gas volume, and the performance requirement at EOL, giving the lower limit to the amount of gas in the system. The pressure budget is therefore based on those two requirements, adding to it the temperature evolution during the mission, the potential leaks of gas during the pressurized time and then checking that the available pressure at BOL is compliant with the BOL performances. In order to achieve the 100N EOL thrust, a pressure of 9.5 barA is required, which corresponds then to the 26 barA BOL pressure. In order to achieve the 140N SL BOL thrust only 24 barA of feed pressure is required. The vacuum BOL requirement (200 N vac.) is requiring less pressure.

EcosimPro System Simulations

The performances of the RACS are currently assessed through an EcosimPro simulation model, shown in Figure 10. The performance of each components are then mainly taken from component testing (see chapter 3) or, when no test data available, standard value, from the supplier or catalogues, are used. In specific, the thruster component is built to represent as closely as possible the performance (FCV opening time, transient flow, Isp,…) of the test object, the PoC3 thruster (see chapter 3.1).

The model is then used to confirm the budgeted values, substitute unavailable test data and build the PMM to be delivered.

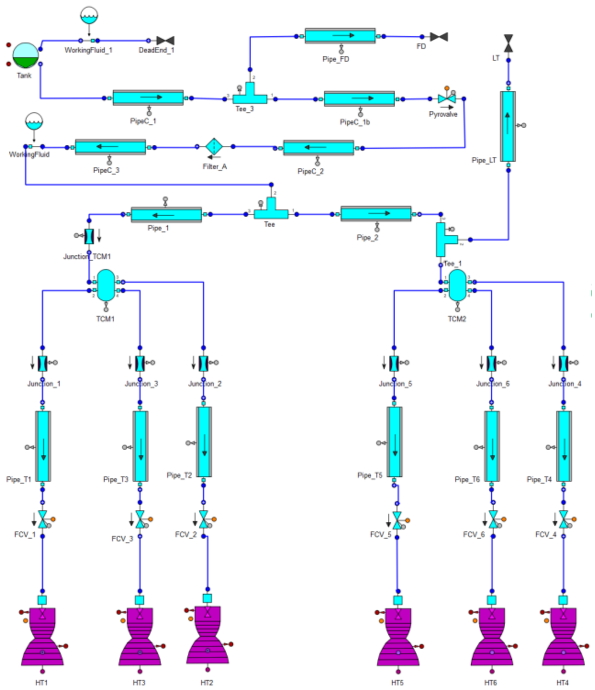

Figure 10: EcosimPro Model Built For RACS Sub-System Simulations

It is continuously compared with test results for increasing the confidence in the models and update the equations. Comparison with thruster test is shown in Figure 11 for SSF and Figure 12 for PMF.

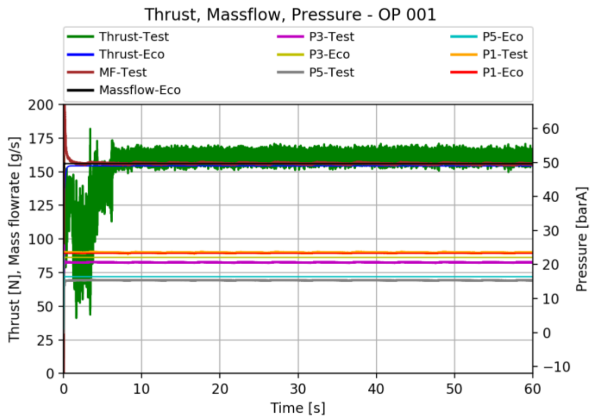

Figure 11: Comparison of Test Results of the PoC3 Thruster with the RACS EcosimPro Model during SSF

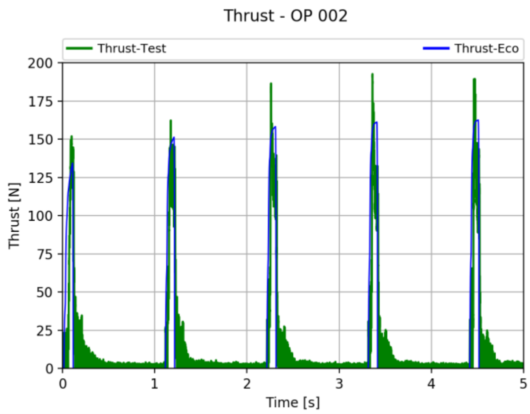

Figure 12: Comparison of Test Results of the PoC3 Thruster with the RACS EcosimPro Model during PMF

The model will be used to see different duty cycles, in order to investigate the margins the system has against all possible worst-case situations. Figure 13 gives then an overview of such simulation, showing that the requirements are met with some margins. As mentioned previously, the EOL performances are the harder to achieve.

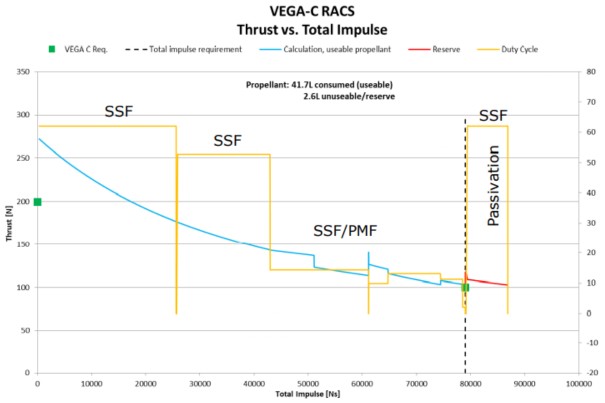

Figure 13: Example Of RACS Use During An Artificial Mission Profile Achieved With The Model.

Investigation of Water Hammer Effects

Water hammer effects are quite strong in such a system. The priming pressure wave is somewhat damped by the presence of a gas: the pad pressure downstream the PV1 or supplemented with the outgassing from H2O2 decomposition. The operational water hammer from the closing of the FCV is however more intense, both due to higher amplitude and as it is with high repetition during the mission (>4000 cycles). This pressure surge is due to the very fast closing of the FCV, taking around 3 ms to stop completely the flow. The same EcosimPro models is then used to simulate those effects and compared with test results. As shown in Figure 14, the modelling is not sufficiently accurate at this time and further development is ongoing.

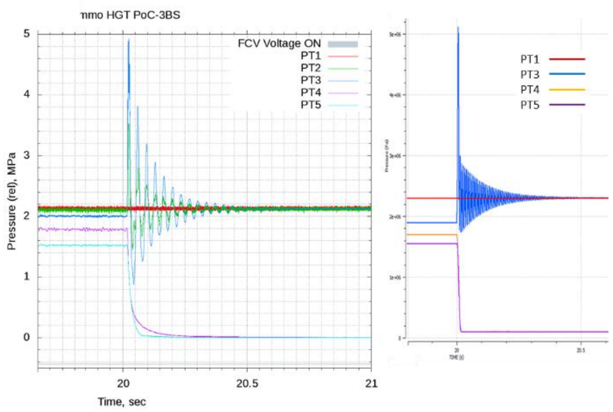

Figure 14: Comparison of Water Hammer from Tested FCV Closing (Left) and EcosimPro Simulation (Right)

In order to understand better the physics of the water hammer, Nammo is planning for dedicated testing points. Indeed, the amplitude, frequency and attenuation of the pressure wave is highly affected by several factors, sometimes difficult to simulatr accurately, such as: the geometry of the line, presence of gas bubble, reducing the speed of sound, as well as the stiffness of the assembly. While the data on closing of the FCV can effectively be obtained during thruster testing, the configuration (tube assembly, presence or not of components,…) is pre-defined, as the priority is to obtain thruster data.

The pressure surge for priming is difficult to repeat multiple times as a PV is single use and quite costly. This as well make difficult to build a good model.

As such, Nammo has designed and manufactured a "pyrovalve replicator" (PVR), with much of the characteristics of the PV (opening time, flow configuration,…) allowing to test the pressure surge effects in an effective way. The design of the PVR is shown in Figure 15: a weight is accelerated by gravity and impact a piston to open suddenly the flow path. The height and mass of the weight can easily be adjusted to fit different opening time with a nominal opening time of less than 7 ms.

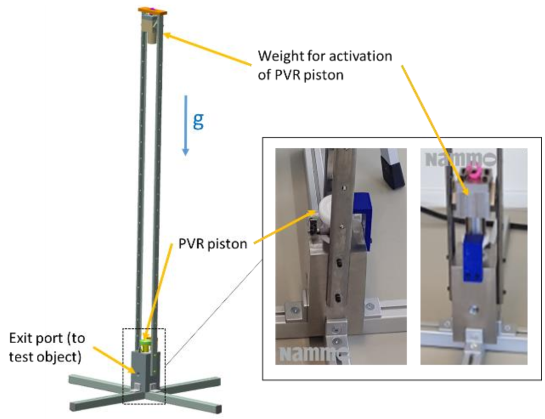

Figure 15: Design of the PVR

Different component configuration can then be tested downstream the PVR with dedicate pressure sensors to characterize the pressure waves. Internal pad pressure or vacuum can be set in the test object. The P&ID (Piping and Instrumentation Diagram) for those tests is shown in Figure 16.

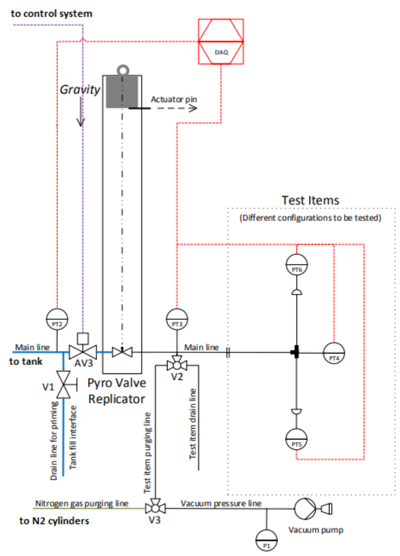

Figure 16: P&ID of the PVR Test Setup

3. COMPONENTS DESIGN AND MATURATION

3.1. Monopropellant Thruster

The thruster design is the component having received the highest focus in preliminary design, having gone through series of designs and evolution to improve the performances for the required operating conditions (see Figure 29 and [3]). The current design (pre component PDR) of the thruster for RACS is shown in Figure 17.

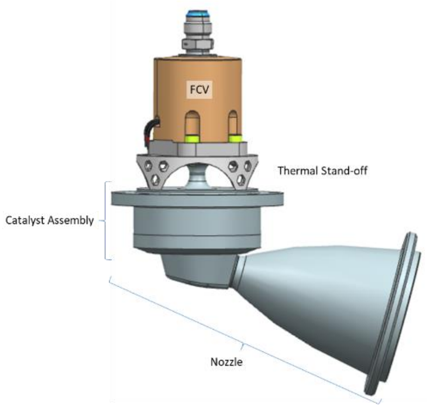

Figure 17: Pre-PDR Design of the RACS Thruster

The most important characteristics of this thruster are presented in Table 2, showing that all performance objectives are met at the worst concentration of H2O2 at 85%.

Table 2: Overview of Main Thruster Characteristics

Characteristics	Value
Envelope	
Length (horizontally)	160 mm
Heigh (vertically)	168 mm
Mass (incl. FCV)	1.48 kg
Materials	
FCV	Stainless Steel
Catalyst Assy and Nozzle	Inconel
Catalytic Bed	Silver-based
Temperature Range	
Propellant	15-80°C
Catalytic bed	670°C
Performance characteristics	
Nozzle Area Ratio	40
H2O2 concentration	85-88%; 85% used
Nominal Flow Rate	153/70 g/s (BOL/EOL)
Nominal Isp,vac SSF	155 s
Nominal Isp,vac PMF	128 s (MIB)
Nominal Thrust,Vac.	239/106 N (BOL/EOL)
Nominal Thrust, SL	148 N (BOL)
Total impulse delivered	>45'000 Ns
Pressure Drop (FCV inlet to combustion chamber)	<6.2 barA
Life Cycle	
FCV opening/closing (wet)	>4000
FCV opening/closing (dry)	>1000
Qualification factor	4

Nammo is currently testing a pre-Engineering Model (EM) thruster, the PoC-3 Upgrade, with the test set-up shown in Figure 18. The goal of the test campaign is to verify all major requirements before entering into PDR.

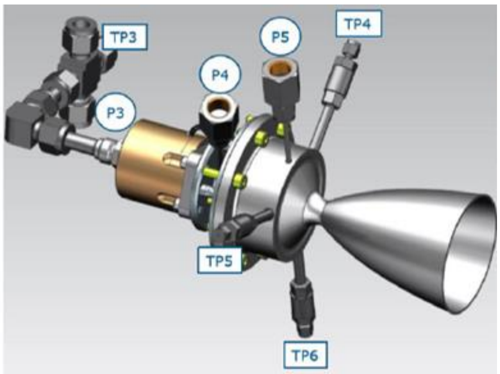

Figure 18: Test Set-up of the PoC3 Upgrade Thruster

While the PoC3 thruster has a straight nozzle, the rest of the geometry is similar to the RACS thruster, notably the catalytic bed and the inner volume of the thruster that allow for the very short pulses, while surviving the full life cycle.

An atmospheric test campaign has been performed at Nammo Raufoss test centre during spring 2020, in the newly built dedicated green propellant test facility, with test cells for thruster, tank and system testing (see Figure 19 for the thruster test cell).

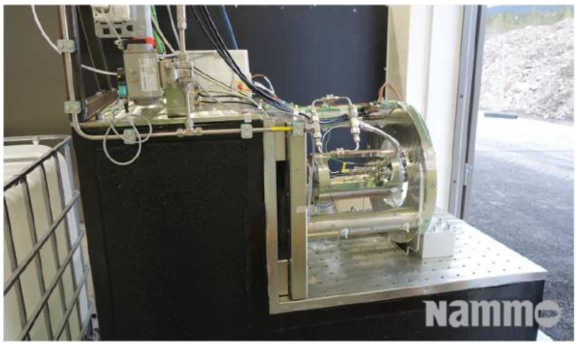

Figure 19: The Poc3 Upgrade Thruster Installed on the Test Bench at Nammo Raufoss Test Centre

This extensive test campaign was performed on a single test object, with more than 4000 activations and a total impulse delivered higher than 200'000 Ns without sign of degradation of the hardware.

The performance presented in Table 2 have been obtained from this test campaign and taken as basis for the system simulation presented in chapter 2.4. Test results from one operating point (OP5) are given in Figure 20, showing that both SL and vacuum extrapolated values meet the expected performance in nominal conditions. It is to be noted that the atmospheric test campaign was plagued with unsteady plume detachment, as can be indicated by the fluctuating performance for this OP. This has been identified as an issue with the nozzle contour design that was too much optimized for vacuum conditions. New designs are being proposed for the RACS thruster in order to fix this issue and ensure stable plume separation at SL. Further development and testing to solve this is then expected before finalizing the EM Thruster design.

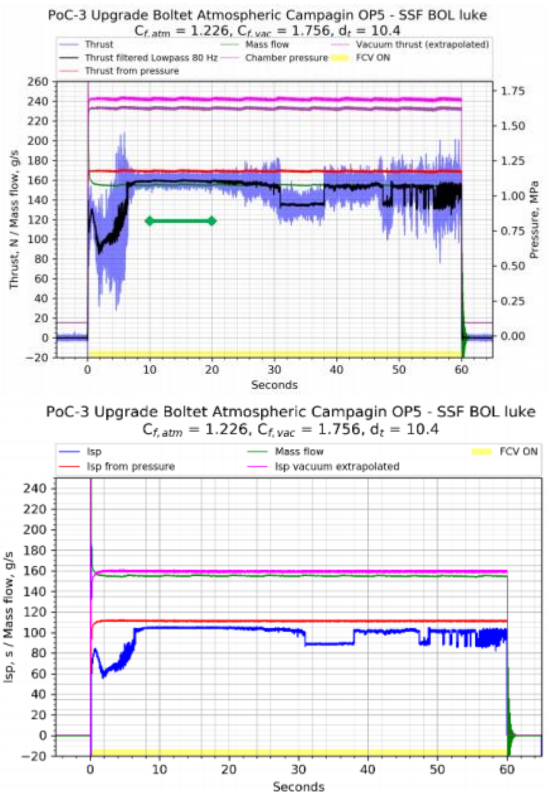

Figure 20: PoC3 Upgrade Atmospheric Test Results. OP5. The Performance Dents Are Due To Unsteady Plume Detachments To Be Fixed.

A similar extensive test campaign was planned to be performed on the PoC-3 Upgrade in the vacuum chamber of DLR Lampoldshausen in autumn 2020. However, due to the Covid-19 pandemic, the campaign had to be postponed and is now planned for March-April 2021. The goal of the vacuum test campaign is to confirm the performance extrapolated from atmospheric conditions as well as giving all needed data for thermal simulation of the thruster; data that are difficult to obtain in atmospheric condition due to the presence of air convection.

3.2. Flow Control Valve

The FCV is developed by Nammo Ireland Ltd., based on already qualified valve design for other mono- or bi-propellant thrusters. The materials of the FCV were tested and demonstrated compatible with H2O2 and the design was then adapted to the requirements of the RACS, specifically actuation speed and power consumption. The Nammo FCV is a mono-stable, all-welded, non-sliding-fit design, and is fitted with a large capacity filter to protect against system contamination. The FCV uses a moving armature suspended on spring-flexures to prevent frictional contact between any parts. A polymer seal is attached to the armature and the armature is displaced by a magnetic flux generated by a solenoid coil, opening the flow path. When electrical power is removed, the armature is returned to the closed position by a spring. The sealing between the FCV and the Thruster is accomplished with an O-ring.

A picture of the valve during EM testing is given in Figure 21. As a valve is always needed for thruster testing, it is normal for the valve to be in advance of the thruster design. The EM FCV has gone through all required development testing and is therefore already close to qualification status.

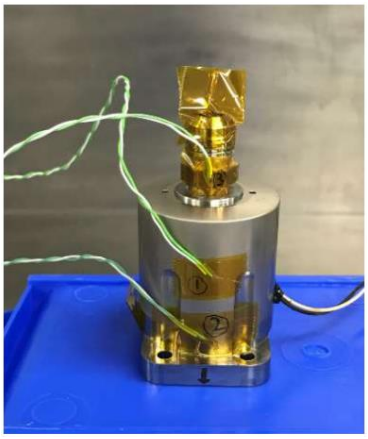

Figure 21: FCV during EM Test Campaign at Nammo Ireland Ltd, 2020.

The main characteristics of the FCV are summarized in Table 3.

Table 3: Overview of Main FCV Characteristics

Characteristics	Value
Envelope	
Body Diameter	42 mm
Heigh (vertically)	74 mm
Mass	0.48 kg
Pressure Rating	
Proof Pressure	48 barA (1.5xMEOP)
Minimal Design Burst	80 barA (2.5xMEOP)
Leak Rating	
Internal (Main Seal)	<1x10^{-4} mbar.l/s
External (Through O-ring)	<1x10^{-5} mbar.l/s
Performance Characteristics	
Nominal Voltage	24-26 V transient 24-32 V Steady State
Opening Response Time	<20 ms
Closing Response Time	<20 ms
Physical Movement Time	~3 ms
Power Consumption	<50W
Minimal Force Margin	1.59
Filtration Rating	
Propellant throughput	>245 kg H2O2
Particle Filter	25 µm absolute

3.3. Propellant Tank

The RACS propellant tank is a PED type design utilizing a diaphragm membrane separating the propellant from the pressurizing gas (see Figure 22). The tank shells are manufactured in a carefully selected aluminium alloy in the 6000 series that meets H2O2 compatibility requirements (see chapter 2.4 and 5) and structural strength requirements. The diaphragm is made of Viton® based elastomer; material chosen for its compatibility with H2O2. The diaphragm shall as well withstand high pressure, aging, cycling and vibration due to the specific orientation of the tank.

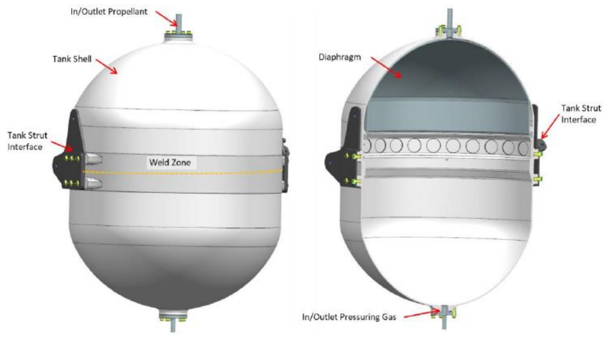

Figure 22: Pre-PDR Design of the Propellant Tank

The Tank has a semi elliptical shape with a cylindrical mid-section to fit the allowable volume provided by AVIO. The division between gas and propellant is made to respect the blow-down ratio presented in chapter 2.4.

The two halves of the shell are manufactured using a cold impact extrusion method. This manufacturing method is a heritage and space qualified method of Nammo Raufoss, notably used for the manufacturing of the FE/FA motors of Ariane 5, and on the DR motor for Ariane 6.

The Tank is assembled in a clean room (see Figure 23) before welding. The weld, on the equator of the tank, is performed by self-supported Friction Stir Welding (FSW); a welding method allowing to keep higher material properties in the weld zone than traditional welding method. In order to simplify and reduce the costs of manufacturing, and the damage risks, the tank plugs are machined separately. They are then connected to the domes through screwed connections, fitted with three independent O-rings to ensure the safety requirements.

Figure 23: PoC2.1 Tank under Assembly in Nammo Raufoss Newly Built Clean-Room

The main characteristics of the RACS propellant tank are then presented in Table 4.

Table 4: Overview of Main Tank Characteristics

Characteristics	Value
Envelope	
Length	672 mm
Diameter	467 mm
Mass (incl. strut interface)	<14 kg (TBC)
Propellant Volume	45.5 L
Pressurizer Volume	27.5 L
Materials	
Shells	AA6082
Diaphragm	Viton®
Propellant Compatibility	< Class 1
Pressure Rating	
MEOP	32 barA
Proof Pressure	48 barA (1.5xMEOP)
Minimal Design Burst	64 barA (2.0xMEOP)
Leak Rating	
Internal (diaphragm)	$<1x10^{-2}$ mbar.l/s At 1 barA
External	$<1x10^{-6}$ mbar.l/s at MEOP
Performance Characteristics	
Expulsion efficiency	>99%
Nominal flow rate	460 g/s
Pressure drop	<0.15 bar
Life Cycle	
Fill, Pressurized and drain	>10 cycles

Nammo is currently testing a pre-EM tank, the PoC2.1, before entering into PDR (see Figure 24). The goal of the test campaign is to increase the maturity of the technology by performing extensive functional testing, pressure cycling and structural resistance. The test results would then feed the design of the EM tank. The PoC2.1 tank has a slightly different design than what is required for the RACS, due to change of requirement between PoC2.1 design and manufacturing and RACS Sub-System PDR. This is the main reason the mass is written as TBC in Table 4, the PoC2.1 Tank having a slightly lower volume, with a MEOP of 28 barA and safety factors of 1.25/1.5 respectively for proof and burst. The mass of the PoC2.1 is 13.3 kg.

Figure 24: PoC2.1 Tank during Proof Pressure Testing at Nammo Raufoss Green Propellant Test Center

3.4. Tubing Kit

The manufacturing of the H2O2 tubing sections is done by Nammo from standard supply of straight tubes in Aluminium 6061. This alloy has been selected for its compatibility with H2O2, its mechanical properties as well as being a qualified material for Permaswage connection technology.

Nammo has invested in a CNC (Computer Numerically Controlled) tube bending machine as well as 3D scanning technology in order to offer the most flexible and reliable design of the tubing. Preliminary tubing sections have been manufactured and inspected with this equipment, as shown in Figure 25 and Figure 26.

Figure 25: CNC Tube Bending Machine (Left) and machine controller (right). A Prototype Tube Section with Complicated Bends is Being Produced

Figure 26: 3D scanner under use (left) and measurement overview on the control PC (right)

4. DEVELOPMENT STATUS

The RACS development program (see overview in Figure 27) has passed its first programmatic milestone in September 2020 with the RACS sub-system PDR, following a contract signature in March 2019. In parallel, and as mentioned in previous chapters, Nammo has worked on maturation work on the different principal components, most notably the thruster PoC3, the tank PoC2.1 and the tubing elements (water hammer and tubing manufacturing). Within 2021, the different sub-assemblies and components of RACS will go through their PDR.

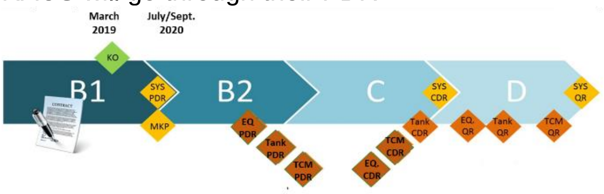

Figure 27: Development logic for the RACS

This will start with the Tubing & Equipment (Filter, SVs, PVs, Sensors) and followed with the Tank. The PDR for the TCM is then schedule at last to give time for performing the postponed vacuum test campaign at DLR Lampoldshausen. It is then expected for the project to be finished with Phase B2 by the end of 2021.

Following the PDRs, EM components will be manufactured for extensive EM testing. This will notably include a first prototype RACS sub-system to increase the maturity of the system simulations as well as measuring in-situ pressure drops and water hammer effects. In addition, this test campaign will allow performing the procedures that need to be developed by Nammo. The different assembly steps currently planned will be performed on an AVUM representative mock-up and the filling, pressurizing and abort procedures tried live. As the tests can be performed without thruster (FCVs only), this system test campaign is planned for end of 2021, potentially before the TCM PDR.

In the following years, the different CDR and QR will be performed with a planned qualification date of the system in 2023. As this would be in delay with respect to the original plan, all parties are actively working toward compressing this plan.

5. SPECIFICITIES OF HYDROGEN PEROXIDE

H2O2 at 87.5% concentration is available in industrial quantities. The main European producer is Evonik with its trademark product Propulse875™. Nammo Raufoss notably has a storage of 20 tonnes at his green propellant test site. This availability ensure fast development of the associated technologies, low cost and high maturity.

This maturity is most important when it comes to safety. Even though this is a non-toxic and green propellant, it remains a high oxidizer that need to be handled with care. Simple Personal Protective Equipment (PPE) covering the skin and the face of the operator is sufficient. In case of accidental contact with the skin, or in case of spillage, simple dilution with water is required. The diluted H2O2 can then be drained through normal means with water waste or in the soil without any damage to the ecosystem. Adapting an area for use with H2O2 consist then mainly in installing proper water access and drainage as well as in avoiding any combustible and flammable materials. Active work is being performed with AVIO and ESA to ensure those safety measures are in place at the launch site.

Figure 28: Nammo PPE for H2O2

As mentioned all through this paper, H2O2 decomposes naturally into oxygen gas and water:

$$2 \cdot H_2O_{2(l)} \rightarrow 2 \cdot H_2O_{(l)} + O_{2(g)} \qquad \text{Eq. 1}$$

On a catalytic material, this reaction happens very fast and lead to the release of high energy: This is the working principle of the RACS thrusters.

However, this reaction happens as well naturally, as the mixture water-H2O2 is metastable. As such, 87.5% H2O2 is always delivered with chemical stabilizer to keep the reaction rate low.
The decomposition rate of this product follow then an Arrhenius law as shown in Eq.2:

$$r_{T1} = r_{T0} \cdot A^{\frac{T1-T0}{10}}; A{\sim}2.2 \qquad \text{Eq. 2}$$

The temperature is shown to be the most impacting factor, the rate approximately doubling every 10°C. The other parameter is then the nominal rate given at the temperature T0 of 20°C in the standards. This value is measured for each materials in contact with the propellant as a given “compatibility class”. Class 1 is then defined as a rate of 0.001 g. of oxygen produced, per square centimetre of material in contact, per 24 hours. Class 0.5 is then half of this rate. These rates, adapted then to the temperature of the propellant are the one discussed previously in this paper. The change of rate with temperature is however not linear, stopping almost completely at around 3°C, which would then be the ideal temperature for long storage in small quantities, like in the RACS tank. In a storage tank, as at Nammo Raufoss test centre, the amount is such that renewing the H2O2 because of too low concentration is only needed after 4-5 years. The gas is then simply vented in the storage room through a filter and the decomposition is in any case so slow that there is no risk of increase concentration of H2O2 vapour or oxygen gas in the air.

Besides this decomposition, H2O2 is very stable. This has notably been tested by Nammo, with pyroshock tests having been performed on H2O2 samples (see [5]) without any reactions. Further testing will be performed as part of the RACS qualification to ensure all aspects are qualified for its use on board VEGA-C. For further read on specificities of H2O2, the reader is referred to paper 494 of the proceeding.

6. CONCLUSION

The green direction taken by ESA for the future European launchers, and planned notably for VEGA-E with AVIO, has been anticipated with the introduction of Nammo’s Hydrogen Peroxide RACS technology directly for VEGA-C.

The RACS requires then to be fitted to the already qualified AVUM+ stage. In order to introduce this new technology in a cost effective way, the RACS need to take the baseline architecture of the hydrazine RACS, while introducing all needed elements specific for the H2O2 and keeping the required performances.

Nammo is the design authority for the full RACS as well as of most of the components and of the performance models. On the component side, the focus has been put so far on the thruster and the tank for which prototypes have been manufactured and heavily tested.

The development project has reached Sub-System PDR and is planning the PDRs for the components by the end of year, in parallel with further testing, notably of the thruster in vacuum. Qualification is then planned for 2023 with all actors working together to shorten the time.

7. REFERENCES

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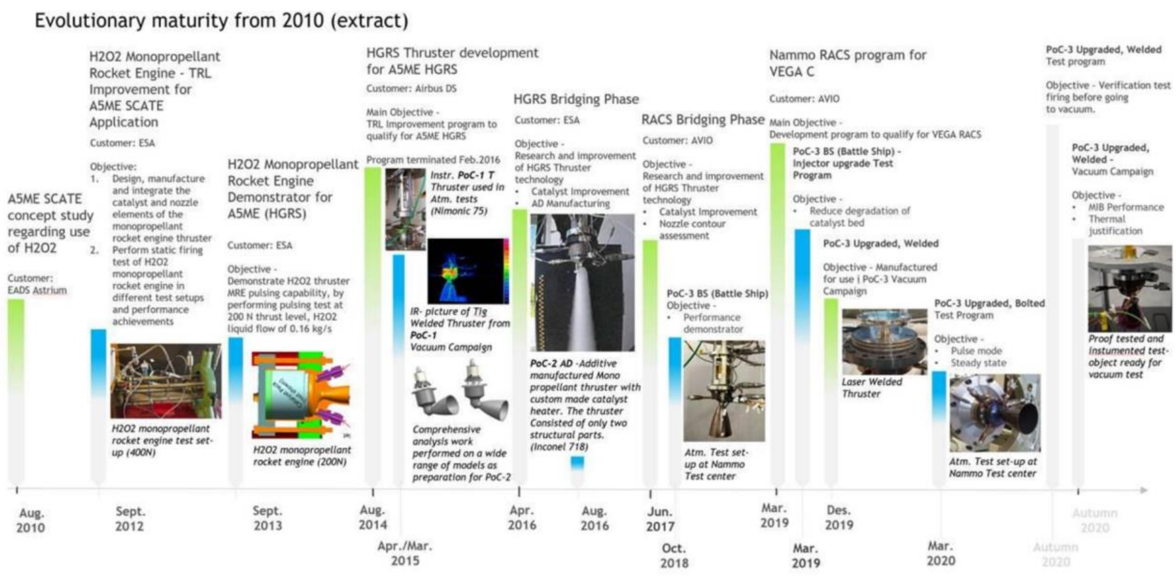

Figure 29: Historic Overview of the RACS Thruster Development