DOI: 10.13009/EUCASS2022-4845

European Newspace Vertical Orbital Launcher: Achievements of the H2020 ENVOL Project

Gianluca Liggieri(1), Axel Kolsgaard(2), Romain Ricciardi(3), Frischauf Norbert(4), Diez Eduard(5), Sebastian Imm(6), Sigve Haugsnes(7), Marta Chacón Gutiérrez(8), Dirk Dautzenberg(9), Clas Andersson(10)

(1) Nammo Raufoss AS, Raufoss, Norway, Gianluca.Liggieri@nammo.com
(2) Nammo Raufoss AS, Raufoss, Norway, Axel.Kolsgaard @nammo.com
(3) CT Ingenierie, Guyancourt, France, romain.ricciardi@ctingenierie.com
(4) SpaceTec Partners SPRL, Bruxelles, Belgium, frischauf@spacetecpartners.eu
(5) GTD Sistemas de Informacion SA, Barcelona, Spain, eduard.diez@gtd.eu
(6) Evonik Operations GmbH, Hanau, Germany, sebastian.imm@evonik.com
(7) Andoya Space Center AS, Andenes, Norway, sigve.haugsnes@andoyaspace.no
(8) ISISpace - Innovative Solutions in Space BV, Delft, The Netherlands, m.chacon@isispace.nl
(9) Airborne Composite BV, Den Haag, The Netherlands, d.dautzenberg@airborne.com
(10) GKN Aerospace Sweden AB, Trollhättan, Sweden, clas.andersson@gknaerospace.com

Abstract

ENVOL stands for European NewSpace Vertical Orbital Launcher, and is a three-stage launch vehicle using pump-fed H_2O_2-based hybrid propulsion. ENVOL is a European micro-launcher that is going to provide Europe with its prime commercial, competitive, and green launch service, utilising a true NewSpace approach to offer low-cost, frequent, and flexible access to space to small satellites up to 200 kg. The launch service will enable a just-in-time service approach for space.

1. Introduction

As a result of the technological improvements in the past two decades with respect to the miniaturisation of electronics in general and of spacecraft on-board systems in particular, the space launch market has witnessed a substantial growth in the number of small satellites that are planned to be launched into low-Earth orbits. Meanwhile, due to the influence of NewSpace initiatives, the space market is being pushed towards the commercialisation of a faster and cheaper access to space. However, the growth of this sector is not yet supported by the availability of reliable, cost-effective and dedicated launch vehicles.

To answer these needs, nine European aerospace companies coordinated by Nammo have joined forces in the ENVOL (European Newspace Vertical Orbital Launcher) project, within the framework of the European Union’s Horizon 2020 programme. This three-year project aims to provide Europe with its first commercial, competitive and green launch service, which will follow a true NewSpace approach to offer low-cost, frequent and flexible access to space in low-Earth and Sun-synchronous orbits to small satellites (up to 200 kg) by 2026. The project partners bring together a multidisciplinary set of competences fit to address all the key building blocks needed for the creation of a commercially viable and competitive launch service.

The launch vehicle that will result from the ENVOL project will rely on the green and storable hybrid rocket propulsion technology based on hydrogen peroxide (H_2O_2) as liquid oxidiser, which has been matured by Nammo over the past decade. To reduce costs while improving the launcher’s quality and performance, the overall architecture will be modular and the development will follow a staggered approach. Several demonstrators are foreseen to improve the maturity of critical subsystems and to acquire a high level of launch system maturity. To that end, the composite oxidiser structural tanks, the H_2O_2 turpbopump, as well as the launcher and payload avionics are considered to be technologies of crucial focus. The ground segment will be designed to have the simplest and fewest possible interfaces with the launch vehicle in order to be low-cost, automated, flexible and easily deployable. The design of the payload systems will be based on the varying requisites of different customers, and it will be able to adapt to different mission profiles. For this reason, the avionics and the interconnected subsystems and elements that interface with the payload have to be standardised and modularised. This approach will reduce costs, enhance the availability of the launcher and,

DOI: 10.13009/EUCASS2022-4845

at the same time, provide a customer-centric payload service model that can comply with the requirements of satellites that fall within the ENVOL space mission envelope.

The ENVOL project will also focus on the business and development plans built on industrial expertise, which ensures the competitiveness of its proposed launch service on the space market. Once the project is at a sufficient level of maturity, the ENVOL consortium will transform itself into an organisation capable of attracting investments, while ensuring that the work performed in the project will be transferred into a commercial activity servicing the small satellite launch market in Europe and beyond.

This article will present the ENVOL project, its status and results achieved within its first phase, with a focus on the initial system architecture, the next steps and possible future evolutions.

2. User's Need

Over the past two decades, there have been two leading tendencies in the field of satellite technologies and services: miniaturization and New Space. These trends have driven an important reshaping of the space launch market, which is still ongoing in the space marketplace as of today. Miniaturization, on the one hand, is the result of key technological improvements obtained for all the main satellite on-board systems. New Space mindset and commercialization, on the other hand, emerges from the availability of commercial-off-the-shelf electronic components; the steady growth of satellite market attracting new commercial actors; new thinking in terms of manufacturing closer to serial production; the large influx of capital to this market.

In this context, the majority of satellites has changed drastically in typical dimension, mass, and cost which together with new target orbits has created the need for newly adapted launch services. For both telecommunication and earth observation satellites, which together represent most of the market, a shift has occurred moving away from high-mass, high-cost integral architectures operated in geostationary orbits (GEO) towards distributed architectures relying on a higher number of lower cost and lower mass satellites. The new constellation architecture is more flexible and fault-resilient, and operates in low-earth orbits (LEO), closer to the Earth. Therefore, LEO applications are expected to be dominating the market in the next ten years, as forecasted by ENVOL's market analysis.

The market sector of the smallest and lightest satellites (below 100 kg) is the one that has seen the largest growth in terms of number of satellites launched per year. Nanosats and cubesats can now be manufactured at very low cost, and represent the ideal point of entrance for researchers, students and start-ups in the space sector. Their capabilities are improving year after year, with the most recent prowess demonstrated by the two MarCo cubesats functioning as telecommunication relays in orbit around Mars for the NASA InSight mission.

The second largest sector in rapid growth is that of minisats (range 100 to 500kg), especially the lower half of that spectrum (below 250 kg) as it corresponds to the size chosen for large satellite constellations, notably to supply high speed internet broadband worldwide. The two leading project in this sector is SpaceX Starlink, which is estimated to have as many as 4000 satellites of similar size and orbital requirements.

The growth in these markets will continue considering that about 4000 satellites with less than 25 kg mass and about 1800 satellites between 25kg and 500kg are expected to be launched in the next ten years.

However, as of today, small satellites are launched by large launchers as piggyback of much bigger payloads which usually drive the schedule and the injection orbit. This leads to the lack of size specific, reliable, cost effective dedicated launch vehicles for small satellites.

To answer this need, ENVOL proposes a dedicated low cost solution to launch small payloads up to 200 kg in LEO between 200 and 800km (nominal SSO at 600km), customizing the mission to their needs and with a considerably decreased time to launch, only driven by the payload timeline, and the production cycle of the launch vehicle.

The launch system designed and matured in the ENVOL project will therefore provide:

- Easy access to space: with simplified and dedicated payload interfaces, and controlled schedule;
- Cheap access to space: targeting launch price for the customers lower than 25k€/kg;
- Responsive access to space: in case of shared launch, the standardised and modular payload interfaces, and the automated missionization tool would ensure a quick answer to any payload evolution, and the possibility to easily exchange payloads in the case where one of them would be delayed;
- Green access to space: the use of hydrogen peroxide, a storable green propellant, lowers the environmental impact of space access and increases the safety of launch operations.

The impact of a responsive launch service is a very clear innovation not only in Europe but in the world. Whereas developments are ongoing to realize new commercial launchers, none truly focuses on the customer. Indeed, in both the secondary payload launch market, as well as the smaller launch vehicle market, the customer service model is currently suboptimal. Launch projects are to this date more often than not subject to delays, and the project itself is still very much one where the customer needs to be actively involved, taking away time and money.

One of ENVOL's key objectives is therefore to obtain through discussions with customers a service model for a small launch vehicle – which will drive several aspects of the launch system design as well as all the ground facilities and processes – that enables reliable launch schedules and cost effectiveness for both customer and launch operator.

DOI: 10.13009/EUCASS2022-4845

Introducing standardization and levels of automation in all activities and processes that involve the satellite and customer interfaces will further enable cost effectiveness as well as launch responsiveness.

When a fully customer-oriented launch service is established, this will have a great proliferating impact on European industry. As a simple, and low cost solution, ENVOL would therefore contribute to the growth of innovative and disruptive space use; both in Europe and worldwide. ENVOL will then enable access to space not only for start-ups and small and medium enterprises, but also for scientific, academic and educational projects, with customized needs and limited funds.

Additionally, the possibility to offer “last-minute” piggyback launch enabled by the responsiveness of the proposed launch solution is also of the greatest interest for potential emergency observation needs that are currently being studied, as a response to natural catastrophes or crisis management.

As it is proposing a low-cost, flexible, customized and fully European launch solution, ENVOL is already addressing a completely new market, primarily targeted at dedicated launch for mini-, micro-, nano- and cubesats. ENVOL will be able to function in a wide market, from launching multiple cubesats to replenishing minisats constellations. It is expected that the availability of the ENVOL launch service at a low launch cost will drive the growth of the targeted markets.

As outlined above, ENVOL means to answer the need for available, responsive, reliable, and cost-effective launch solutions for the small satellites market, which has experienced a rapid growth for a few years and this trend is forecasted to continue in years to come. To build the best economically viable solution for that purpose, a strong emphasis is given to the commercial competitiveness of ENVOL and to a close connection with the customers and therefore to the market. One major objective of the project is thus to provide a business and financial plan built on industrial expertise, along with a development plan, for a design approved by the customers to answer their needs. The objective is therefore to attract investors to fund the full development through a commercial entity to be created, ensuring that the work performed in this project transforms into a commercial activity servicing the small satellite launch market in Europe and beyond.

In conclusion, the main objective of ENVOL is to provide Europe its prime commercial, competitive and green launch service, offering low-cost, frequent and flexible access to space to small satellites in the near future.

3. Launch Vehicle System Design

ENVOL is a vertical orbital launch system, using low-cost and green rocket propulsion exploiting hybrid rocket motors. The whole propulsion system will benefit of synergies deriving from the use of the same common propellants: high concentration hydrogen peroxide (H_2O_2) as oxidizer and. hydroxyl-terminated polybutadiene (HTPB) as solid fuel.

In order to achieve the mission targets (about 200kg to orbit), and considering the performance level of H_2O_2-based propulsion, the preferred architecture for the vehicle is that of a 3 stage system (see Figure 1).

Multiple studies have been performed over the years to design a small satellite launch vehicle based on hybrid technology: ESA Q@TS study in partnership with ArianeGroup, SMILE and ALTAIR Horizon 2020 projects, and Nammo’s own North Star activities. All have arrived to similar conclusions, notably regarding the size and characteristics of the 100kN-class hybrid main motor, called Unitary Motor 2 (UM2), to be used both on the first and second stages. This experience gives confidence to the ENVOL consortium for setting up a relatively advanced concept to begin with, but still including the flexibility needed to reach the project objectives optimally.

The chosen initial concept for the launch vehicle can then be described as follows. The two lower stages are using 100 kN-class hybrid motors based on 87.5% concentration hydrogen peroxide (H_2O_2) as liquid oxidizer and HTPB as solid fuel. Those motors will use one turbopump each to feed the H_2O_2 to the hybrid motor(s). The turbopump will be throttleable to contain the acceleration levels if needed and driven by a H_2O_2 monopropellant gas generator in an open cycle. For these two lower stages, a main propulsion module has been defined, composed of one turbopump feeding one UM2 motor. The UM2 hybrid motor design includes 360 degrees lightweight TVC capability using the SuperSonic SplitLine (SSSL) technology and piloting the lower stages. One such propulsion module is powering the second stage of the launcher, while six are powering the first stage. This commonality helps in improving the production and reducing the cost – the only difference then being higher expansion nozzle cones on the motor of the second stage propulsion module. Development and qualification is then planned to be performed only at propulsion module level for both stages 1 and 2.

Commonality does not stop at the propulsion modules and will also concern structural oxidizer tanks, which shall couple oxidizer tank and load-carrying aerostructure functions in one single composite component (to be demonstrated as part of this project with the structural oxidizer tank demonstrator).

The third stage can use the 30kN- thrust class Unitary Motor 1 (UM1) hybrid engine, equipped with the same TVC technology as the larger engine.

In the long term, to increase the launcher capability, the upper stage will be thrusted by one 6kN-class liquid rocket engine. The use of this liquid engine ensures higher performance for the launcher, having a lower mass and higher performance than the hybrid, while keeping the costs as low as possible. Indeed, this engine is based on the same

DOI: 10.13009/EUCASS2022-4845

oxidizer, H_2O_2, as the hybrid motors of the first two stages, and uses readily available RP-1 kerosene as fuel. The commonality with the hybrids allows for a simplification of the GSE and thus reduction of the costs.

In this engine, the feeding system drives the oxidizer by the means of an electric pump while the fuel is pressure-fed. An attitude control system (ACS) is also included on this stage. This ACS is based on multiple H_2O_2 monopropellant thrusters, and fed from the same tank as the liquid engine. The restartability and throttleability of the liquid engine coupled with the ACS will provide high flexibility and a high precision of orbital insertion; features completely new to small payloads.

Vehicle avionics, which will be the focus of an advanced hardware-in-the-loop demonstrator in this project, will target a modern low-cost design with notably the implementation of autonomous flight safety.

In ENVOL's typical mission profile, the first two hybrid stages are burned in quick sequence. The fairing is jettisoned during the 2nd stage burn. A ballistic or coasting phase follows, before the 3rd and upper stage performs the last burn, circularizing the orbit. The payload deployment sequence soon follows, as defined by the missionization process.

In order to meet the required performances, a cluster of 7 hybrid motors for the 1st stage, and the same hybrid motor (one) for the 2nd Stage have been set. This result has then been used to determine several key parameters to size the overall launcher (propellant mass, dry mass, etc.). Dry masses were computed around these propellant masses using structural ratio. External dimensions have been computed (diameter and length of stages). The diameter of the 1st stage has been set up to accommodate the number of engines defined. Moreover, it has been decided that the diameter of the 2nd and 3rd stages will be the same as the fairing diameter, to keep only one conical piece (the stage 1 – stage 2 interstage) and therefore improve the aerodynamic of the launch vehicle. The external diameter of the fairing has been set to 1.5m, in order to accommodate the targeted payloads.

Thanks to a first estimation of the aerodynamic coefficients of the launcher, the preliminary mass budget and the engines performances, an optimization of the trajectory has been completed in order to assess the possible performances of the Launch Vehicle.

This process and these steps have been performed under several iterations in order to converge to a reliable and robust design, for which the performance has been evaluated up to 206kg of payload for an SSO-600km orbit launched from the Andoya in Norway. This ENVOL reference design is considered feasible for ENVOL project and within the requirements and constraints defined by the consortium.

In the frame of system engineering activities of the project and to support the assessment of the performances of the system, the architecture of Launch Vehicle has been defined. To do so, the Model Based System Engineering (MBSE) model was developed under the Capella tool and following the Arcadia method. The main result is the model at physical level, i.e. identification and definition of the elements of the launcher. This modelling has been done down to the equipment level, in order to show the different interfaces between equipment, constraints applied on these equipment, and the functions they have to perform. This enables us to draw budgets (mass, cost, power) and requirements allocation in future phases. Project partners have worked together to define this architecture, each partners providing its expertise on its own sub-system of the Launch Vehicle.

The architecture follows a ground assembly definition, meaning that the architecture shows each sub-system of the Launch Vehicle as part of a ground assembly. The ground assemblies are defined as the assemblies that will reach the Space Port and be assembled together during the Launch Vehicle integration. The main difference between ground assemblies and flight stages is the allocation of the interstages. Indeed, flight stages have their "half interstages", i.e. flight stage 1 owns the aft part of Interstage 1-2. On the contrary, as the entire Interstage 1-2 will be fixed to the 2nd stage structure during ground operations until it is assembled with the 1st stage; therefore Interstage 1-2 belongs to Ground Assembly 2 (A2). Moreover, a ground assembly A4 has been created, which regroups the Payload Adaptor, the Payload Fairing and the Payload Avionics, also for a purpose of ground operations. A4 represents the elements involved in the Payload Integration activities that might require different constraints than other ground operations.

With ground Assemblies A1, A2, A3 and A4 set, the architecture of the subsystems of these assemblies have also been defined. It includes the architecture of the Avionics for each assembly, of the Propulsion Module for each assembly, of the Tank Module for each assembly and of the Structures for each assembly.

It is of course an evolving architecture that will be refined with more details when definition of the sub-systems will be given.

Figure 1. Visualization of the ENVOL launcher.

DOI: 10.13009/EUCASS2022-4845

4. Launch Vehicle Hybrid Propulsion

The technology used in the 1st and 2nd stage of the ENVOL Launch Vehicle main propulsion system is based on the hybrid motor technology currently being developed by Nammo.

The Unitary Motor represents the current status of the hybrid rocket motors concept and is for the moment the most performant motor developed in terms of total impulse delivered. It uses high concentration hydrogen peroxide (87.5% H_2O_2) as oxidizer and HTPB rubber as fuel. Figure 2 shows its working principle.

The incoming oxidizer, in liquid form, enters the motor and it is first decomposed into gaseous oxygen over a catalyst bed. It then goes through the injector and enters the combustion chamber in hot gaseous form, where ignition of the hybrid combustion occurs without any dedicated ignition device due to the high oxidizer heat flux, sufficient to vaporize the solid fuel. The injector creates a vortex flow-field in the chamber which helps to maintain a high heat flux to the fuel surface and in achieving appropriate mixing of the reactants for a high combustion efficiency and high regression rate. The hot product gases are then expelled through a nozzle, generating the thrust.

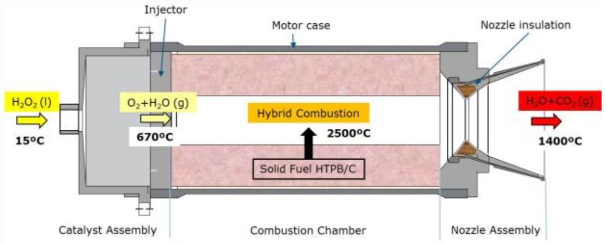


Figure 2. Working principle of the Unitary Motor.

The Unitary Motor has a rich set of positive features for a rocket engine, and more so for a hybrid rocket engine. These features are notably:

- Self-ignition increasing engine start reliability and enabling a multiple restart capability;
- Wide range throttling with limited performance loss;
- Green life cycle and exhaust properties;
- Solid inert fuel and green storable oxidizer;
- High engine combustion efficiency, performance and stability;
- Simplicity of a single circular port and single feedline configuration;
- Rapid and simple thrust termination, achieved simply by stopping the oxidizer flow;
- Low operational costs.

Figure 3. NAMMO’s Nucleus rocket at launch from Andøya in 2018.

ENVOL builds upon the successes of past projects, a flight proven engine and the decades of experience of the involved partners. The ENVOL launcher will rely on an innovate and flight-proven hybrid propulsion technology that has been matured by NAMMO in close collaboration with ESA and which benefit from NAMMO’s mass production knowhow.

On September 27th 2018, the engine technology that will be used for ENVOL reached 107.4 km in altitude on a suborbital test flight from the Andøya Space Center thrusting the Nucleus sounding rocket. To lift a total mass of 820 kg, the 9.5 m single-staged rocket utilised a 30kN scaled-down version of the ENVOL rocket engine. Thus, the technology used for ENVOL is already flight proven and has successfully demonstrated its ability to be used in a safe manner for low-cost and green launches.

4.1 Upscaling of the hybrid motor

The next step in the maturation of the hybrid motor technology after Nucleus was to increase the size of the motor and increase the burning time to a level useful for a micro-launcher such as ENVOL. The following requirements were defined for the new and larger motor:

- The motor design needs to be scalable from trust level 30 kN up to 100 kN
- The burning time needs to be extended from 40 seconds up to 100 seconds.
- The manufacturing processes and the materials need to be the same for all motor sizes.
- The weight of the motor needs to be reduced significantly to improve performance and payload capacity.
- The motor cost needs to be reduced significantly to be acceptable for the private launch marked.

DOI: 10.13009/EUCASS2022-4845

To be able to fulfil the five new requirements, an upscaling of the existing technology demonstrator motor was not possible, and every aspect of the motor design, materials, manufacturing processes and the industrial setup, needed to be improved.

The activities were carried out under a programme of and funded by the European Space Agency – through the Future Launchers Preparatory Programme (FLPP).

In this context, improvements to the motor design have been introduced with the work described in [1] and summarized in this chapter.

Reducing the diameter of the **catalyst** is the best way to reduce both weight and costs, and a limiting factor is the maximum mass flow of hydrogen peroxide the catalyst is able to decompose.

The new catalyst technology development involved materials, structure and design principles, and the target was to find the point for maximum bed loading, combined with very fast start-up, acceptable life time and low pressure drop. After some tests used to calibrate the equipment and improve the first design, the final catalyst was tested with maximum mass flow rate (29 kg/s), after a pre-warming phase of only 15 seconds. After a total of seven full scale catalyst tests, the catalyst design was frozen, since the defined development targets were fulfilled.

With the defined small catalyst diameter, the **injector** diameter was reduced accordingly, and to reach the new requirements, both mass and manufacturing costs needed to be improved even more. The old concept was replaced with a new concept where the amount of material was further reduced. The new design was adapted to be 3D-printed in one simple operation, and the target was to use the printed injector directly without subsequent machining of the surfaces, to avoid costly machining. A test setup was made to test the injector together with the catalyst, and the injector-test was performed with acceptable results. The injector was in good condition after the test, and the injector design was approved.

The previous metallic **motor case** used in the demonstrator is too heavy to be scaled up to a 100 kN motor, and due to thin walls and small tolerances, the manufacturing cost needed to be improved as well. Based on experience from other carbon fibre composite motor cases for solid propellant motors, a dry winding solution was developed for the hybrid motor case, and to keep the cost low, the carbon fibre quality with the highest mechanical properties were avoided. A small reduction of the fibre mechanical properties has a significant impact on material cost, and with the fibre quality used, the motor case weight was acceptable. The target for the motor case design was to reduce the weight as much as possible, and to find a solution were the motor connections to the rocket structure can be produced cost effectively.

The final solution is automatically produced in the same operation as the motor case. In this way, the motor case production cost can be reduced. The motor case was proof tested up to MEOP. To test the motor case behaviour with compressive loads, a 1000 ton press was used as a stiff test fixture, and a 10 ton cylinder compressed the pressurized motor case together, measured by a 100 kN load cell.

The **insulation** process of the hybrid motor was changed due to an effect of the new motor case material, and the target was to develop a process that placed the anisotropic insulation material in a preferred structural direction, to improve the erosion resistance, and to reduce the insulation thickness. The test program for the insulation materials was running in parallel with the motor case activities, and a conservative simplification was used to keep the time schedule. Development of the insulation process and material were done on the motor insulation, the nozzle, and on the exit cone. Different tool concepts were designed, manufactured and tested, and the produced parts were controlled and tested. To evaluate the insulation behaviour during a motor firing, a special insulation material test was developed using the catalyst to decompose hydrogen peroxide, and expose 700°C oxygen rich gas at high speed directly on a selection of insulation materials. Some materials were tested several times using different processes, to see the processing effect. A new machine was designed and manufactured, and the curing cycle was simulated to find the correct parameters for both the heating phase and the cooling phase. The initial tests were performed on the exit cone, and the digital X-ray investigation confirmed good quality after curing. The motor case insulation was produced with the same parameters. The operation was done semi-automatically, but necessary equipment was designed and manufactured for fully automatic production later.

Based on the material properties of both the carbon composite and the insulation material, the insulated motor case design was defined. The insulated motor case was proof tested to be able to compare and contrast the effect of the insulation and to evaluate the material properties. A detailed FEM simulation of the pressure test was also done and the prediction model was compared with the test results. X-Ray inspection after the proof test showed no deviations, and the case was 3D scanned for dimensions, and leak checked.

4.2 Test Results

The materials and manufacturing processes for the 100 kN motor were used to produce the down scaled hybrid motor, and after the motor acceptance and the leak check, the motor was ready for the hot firing test.

After a 10 second pre-warming of the catalyst, using 1.6 kg of hydrogen peroxide, the hybrid motor was run for 40 seconds, with constant oxidizer tank pressure and oxidizer mass flow. Figure *4* to Figure *8* show the motor plume during the test.

DOI: 10.13009/EUCASS2022-4845

The performance has improved slightly compared to the previous design. The motor consumed fuel at a higher rate in the beginning compared to the prediction, and the motor pressure shows that the nozzle starts to erode earlier than expected, but with a more constant rate.

The temperature measured during the test at different motor locations, showed temperature values under the critical limit. The temperature development after the test was also documented, in case of future need of motor restart requirements.

The catalyst start up time was 0.1 second faster than the requirement, and the catalyst performed well through the test.

The performance of the motor was reconstructed without measurements of the fuel geometry inside the motor during firing. The average Isp efficiency was 92%.

A leak test after the firing test was performed, followed by a complete X-ray control of the motor. The motor weight was measured and visual inspection performed, before the motor was cut in pieces and inspected. Remaining fuel was measured to be 2.9%, and insulation thicknesses were compared with the predictions.

The catalyst looked the same compared to previous catalyst tests, and small signs of wear was expected after 117 seconds of accumulated firing. The pressure drop was normal.

The Injector was in good condition, and the pressure drop was a little higher than the CFD prediction.

Visually the motor case was unchanged after the test, and the digital X-ray control found no deviations. The strain gauge measurements on the cylinder section during the motor firing, was in accordance with the strain levels from the proof test, and the strain gauges placed on the front motor skirt, were used to document the effect of the thrust.

The motor case insulation behaved according to expectations. The insulation thickness was measured for the complete motor length. No cracks were detected, and the measured charring and/or erosion of the motor was used to reduce the insulation thickness of the 100 kN motor design. The fuel protects the insulation until it vanish, helping to keep the dimensioning insulation thickness low.

The exit cone was in a very good condition, and process changes have clearly increased the charred/erosion margin. No sign of delamination was observed, but a cracking sound was heard in this area after the test, and cracks were also found, probably due to this cool-down effect.

The nozzle erosion was slightly higher compared to earlier tests, but the X-ray investigation detected no cracks after firing and cooling.

The measured thickness of intact insulation was extrapolated up to the 100 second burn time for the 100 kN motor. The measured charring was also used to update the prediction model for the insulation.

The nozzle was more charred and eroded than the direct neighbouring insulation, and the reduced performance was found to be due to a not optimal processing of the material.

The process for manufacturing the nozzle was evaluated, and some of the parameters were varied during the production of several new parts. The parameter variation was controlled with NDT, and for the next production lot, the defined parameters

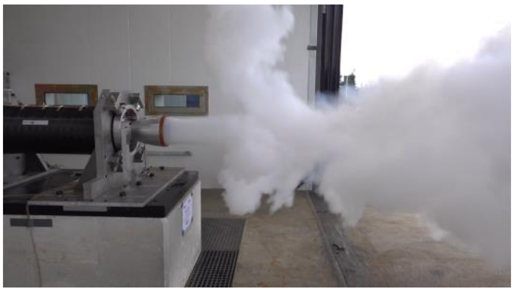


Figure 4. Hot firing test of the new hybrid motor design. Time 0.1 sec. - Monopropellant phase.

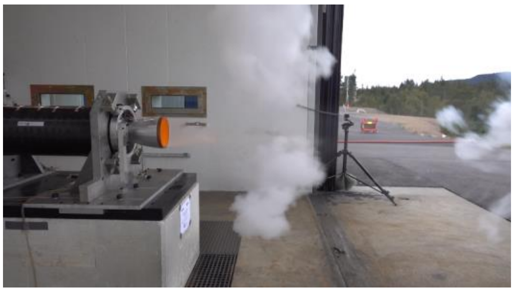


Figure 5. Time 0.2 sec. - Ignition point.

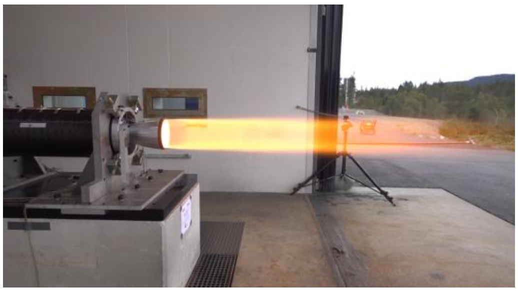


Figure 6. Time 2 sec.

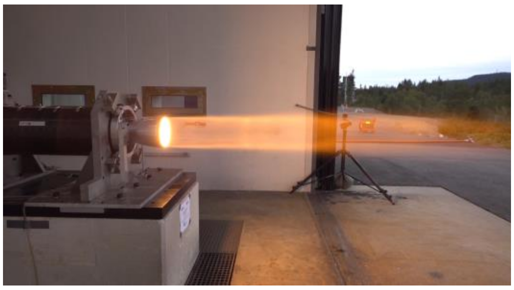


Figure 7. Time 20 sec.

Figure 8. Time 40 sec.

DOI: 10.13009/EUCASS2022-4845

are updated. A small design improvement was also implemented, and a new firing test will finally confirm the improved erosion behaviour of the nozzle.

For the down scaled 30 kN test motor the actual weight savings compared with the 2018 Nucleus rocket design was 62% for the catalyst, 68% for the injector, and 64% for the motor case. Without the propellant, the motor weight saving was 52%, and with the same propellant weight as before, the motor is 31% lighter. For the 100 kN motor these numbers will not be exactly the same, but with three times the size, significant weight savings has been possible.

The final 100 kN motor design is shown in Figure *9*, where all elements can be seen from the outside.

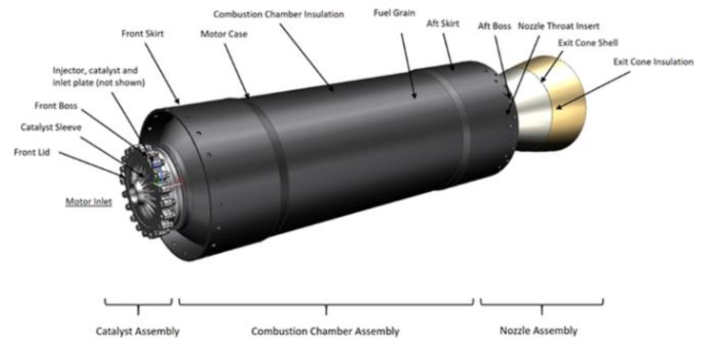
The full size hybrid motor design is justified based on the newly updated prediction models, the firing test results, and the expertise findings.

Manufacturing process prediction models have also been updated, based on the manufacturing trials and the production of the test motor, and are used for the justification of the manufacturing of the hybrid motor in different thrust classes.

The demanding process requirements of scalability of the motor size and high volume production, have pushed the process development towards more effectivity, and a lower investment level.

The motor cost has been improved by using new and more effective processes, and the number of processing steps has also been reduced. The reduction of the catalyst size has reduced the material cost, and going from a complex to more simple operation will be profitable. Relaxed tolerances between components, and easy assembly will also contribute.

For the motor case, the material cost per kg is not inexpensive, but the automatic manufacturing and the effect of the new design solution on other components, resulted in both cost and weight saving compared to the old design.



The new hybrid motor has the following main properties:

Thrust level:	100 kN
Burn duration:	100 sec
Dimensions:	ø724 x 2899 mm
Motor mass:	803 kg
Average thrust:	105 kN
Total Impulse:	10.5 MNs
Fuel:	HTPB (Nammo defined composition)
Oxidizer:	87.5% Hydrogen peroxide, (commercial available)

Figure 9. The UM2-100 kN hybrid motor design.

In conclusion, the motor firing test was considered acceptable. The catalyst and injector performance were good and within the requirements, and the insulation performed well, with good protection and low erosion. The exit showed a very good performance, compared to the previous design. The motor performance was equal or better than the previous design, and the mass and cost significantly lower. Some issues regarding the tested motor were found, both on the motor design and for the manufacturing processes, and the 100 kN motor design was updated to implement these improvements.

5. Launch Vehicle Structures Design

The structure design activities of ENVOL includes the development of the aerostructures, the H_2O_2 tanks and the conceptual design of the 3rd stage.

The design of the H_2O_2 tanks has been the main task for the structure activities as it is one of the most critical elements, being both a vessel and a structure. The design is done with a special focus on the 2nd stage tank that will be produced as a demonstrator in this project. A Function and Value Analysis has been done for the tank of Stage 2. The life cycle phases identified are the following:

- Storage
- Transportation
- Test
- Filling & Draining
- Stand up on Launch Pad
- Utilization (i.e. in flight)

DOI: 10.13009/EUCASS2022-4845

The analysis were used to define the principal and secondary functions to be realised by the tank. Based on this, the constraints, the environment and the acceptance criteria have been defined for these functions. These are used for the sizing of the structural elements and for the identification of external and internal elements to take into account in the design, such as the interfacing elements, the power and data cables running outside of the tank, the possible need for antivortex baffles, etc…

Investigation on possible tank manufacturing concepts has been done and each concept has been analyzeded to understand the pros and cons to the design requirements and in the perspective of material compatibility, cost and mass impacts. In view of this trade-off, the idea/need arose to initiate two derisking tests: compatibility test of Carbon-Fiber-Reinforced Polymer (CFRP)/Epoxy samples with H_2O_2, and bonding test on Fluorinated Ethylene Propylene (FEP) and aluminum liners.

The possible manufacturing flows for each concept were identified, in order to assess the required components and tooling, as well as associated development risks. A first down-selection of these manufacturing concepts has emerged:

- Full aluminium tank
- Aluminum tank overwrapped with composite
- Filament winding tank overwrapped with composite shell
- Composite segmented tank overwrapped with composite shell

To size these concepts, the tank loads have been investigated. To do so, the trajectory of the Launch Vehicle has been analyzed to find the point with the maximal loads occurring when the product of the dynamic pressure and the angle of incidence is at the maximum. The aerodynamic coefficients of the Launch Vehicle at this point have been computed. These coefficients have then been used to compute the loads applied on the different structural sections of the Launch Vehicle. This activity is called the general loads computation and gives the inputs for sizing the different structures, including the tanks.

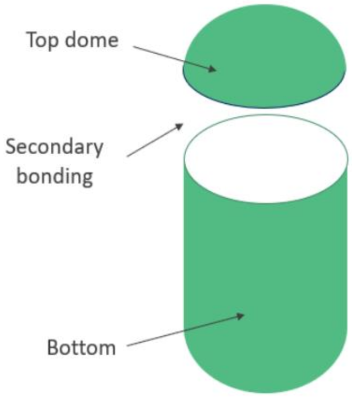


Figure 10. Tank hybrid concept.

Parameterized FEM models of the 4 concepts have been developed to assess the behavior of the tank under the stresses defined. The composite concept models include the layup, i.e. the number, thicknesses and angles of the composite layers. These models are used to perform the sizing and check the structural behavior of each concept. The selected final concept is a hybrid tank with the bottom part being made with Automated Fibre Placement (AFP), a segmented top dome made with Automated Tape Laying (ATL) and an aluminium liner to guarantee the right level of material compatibility for storing H_2O_2.

On top of the tank design activities, a study has been carried out to establish the best solution for the cylindrical and conical structures of the Launch Vehicle (tanks excluded), between metallic, full composite and grid composite. The result of this trade-off, which included not only mass but also maturity and current production means within the consortium, it that full composite is the preferred solution. More detailed design of all the cylindrical and conical structures of the Launch Vehicle are currently ongoing.

The configuration of the 3rd stage, with tanks and equipment arrangement, has been assessed. Defining the 3rd stage early in the project is important as it will allow refining the Launch Vehicle design, and because the 3rd stage mass has a huge impact on the Launch Vehicle performances. Many ideas have been explored and some are still under investigation. The goal is to trade-off between maximizing the space for the payload and minimizing the length of the 3rd stage, in order to minimize its structural mass. The selected configuration will need to offer the advantage of hosting the tank in the close environment of the engine, saving a lot of space.

6. Avionics and Flight Software

6.1 Avionics Architecture

The avionics architecture and the Flight Software (FSW) design are developed in parallel and in co-engineering with the partners working in other launcher subsystems interfacing the avionics, considering the following synergies:

- Physical mass/volume distribution of the equipment, with special attention to harness, seeking to contribute to the optimisation of the tank and structural architectures.
- Propulsion systems interface: the design parameters and performances of the attitude control system thrusters and the thrust control system actuators are a major input to the Control Module.
- Aerodynamic coefficients estimated during the launcher design are a major input to Control Module.

DOI: 10.13009/EUCASS2022-4845

- The mission definition and the Payload requirements contributes to the design of the Guidance Module.
- Ground requirements impact avionics power and data interfaces with the ground equipment during ground operations and checkouts.
- The sensor network interfacing the data acquisition units, is essential for the estimation of the power budget (batteries sizing) and the data budget (bus characterisation).

A requirements and functional analysis lead to the definition of an avionics architecture, which has been refined afterwards with a technology survey to instantiate each of the components identified in the architecture. The trade-off will consider: the level of maturity (availability in the market considering the development plan of ENVOL, technology readiness level, TRL reliability), the cost for budget estimation purposes and physical parameters such as mass, volume and power consumption for Launch Vehicle design purposes, and avionics detailed design in the 2nd loop (data bus budget and power budget).

Several aspects have been studied to converge into a final avionics architecture design:

- For the umbilical connection and harness, the solution adopted is a dedicated connection per stage. This will reduce the mass of the launcher and simplify the launcher integration task and separation mechanism.
- For the safety, a fully autonomous architecture has been chosen in which the safety decisions are taken and executed on-board without interventions of humans in the loop.
- For the navigation sensors, the choice is to have dedicated but not redundant sensors for safety. This allows to focus on an independent set of sensors to feed the safety chain and at the same time comply with the requirement of having no redundancies.

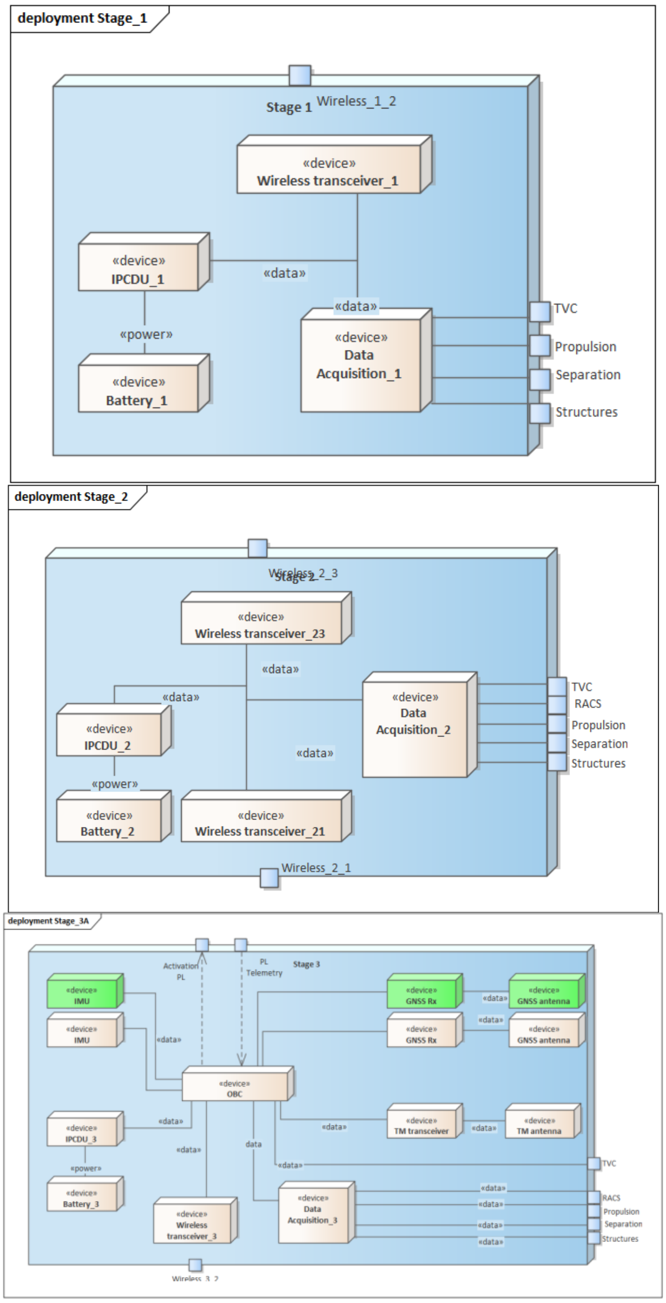


Figure 11. Avionics architecture.

About On-Board Computer (OBC) redundancies, even though a general design constraint no redundancies are conceived for Flight Computer, its high cost and the required performances for the autonomous on-board safety, turned into the consideration of other possible solutions based on segregation and redundancies. Cost is considered as the main decision variable. Thus, based on the cost of space-qualified OBCs, the non-dedicated and non-redundant option seems to be the best candidate to reduce total cost.

Based on all the previous trade-off the adopted solution seeks an innovative approach to the avionics architecture, presenting cutting-edge solutions for the key aspects listed hereafter:

- Safety functions are operated autonomously by the FSW and on-board the vehicle. The conservative decision chain, including the intervention of range officers, is substituted by a software module that autonomously evaluates the health status of the vehicle and the mission and commands a safety decision.
- Umbilical connections during pre-launch phases at the ASC are placed at each vehicle stage. This proposal, together with the use of optical wire-less communication between the stages, allows to avoid having inter-

DOI: 10.13009/EUCASS2022-4845

stage harness, reducing the weight of the avionics and avoiding the necessity of a system to cut the wire at stage separation, and the galvanic problematic attached.
- No redundancies are contemplated but the segregation of navigation sensors (Global Navigation Satellite System (GNSS) and Inertial Measurement Unit (IMU)) will be dedicated to Safety functions.

Figure 11 shows the resulting avionics architecture design for each stage of the launcher. With the presented architecture a technology survey has been carried out to instantiate each of the components identified.

6.2 Flight Software

The FSW is responsible of the control and supervision of the launcher. The FSW is in charge of functions as: Guidance, Navigation and Control (GNC); Flight management; Safety-FDIR and Telemetry. In the frame of ENVOL, the following FSW applications will be targeted in the applicative layer (level 3) specifically:
- GNC: to implement a control subsystem with the objective of designing and validating the ENVOL nominal mission and trajectory.
- On-board flight Safety (OBFS): the project aims to assess the reliability, availability and security of on-boarding the ground safety on launcher avionics, looking forward doting the launcher of an autonomous flight safety
- Flight Manager (FM): responsible for the management and distribution of all information in the FSW, as well as the awareness of the flight phase and status of all FSW applications

ENVOL aims to assess an economic viability and potential further interest on the system, by reducing the associated mission costs in terms of lower infrastructure requirements and shorter campaign costs along with a reduction of testing and validation requirement and reduction of campaign durations to achieve higher launching rates.

The applicative layer (Level 3) of the FSW for ENVOL is designed pursuing those drivers contributing to achieve the common high level requirements. Therefore the design axes are:
- Missionization: flexibility and responsiveness in front of different mission configurations and FSW updates, seeking the launch of ENVOL from different Spaceports.
- Improvement of Reliability, Availability, Maintainability and Safety (RAMS).
- Automatization, seeking the reduction of operations and infrastructures costs through embedded systems.

A modular FSW has been developed to allow to test different combinations of the methodologies with the objective of selecting the best trade-off for the ENVOL mission. Hereafter the design and technologies used on each software component are described.

The Flight Manager is based in finite-state machine and has the following main functions:
- Managing the configuration of GNC and Safety modules.
- Sending signals for the execution of mission timeline events to the launcher (stage separation, propulsion ignition and cut-off, and flight termination).

The flight Manager uses parallel states to allow the simultaneous management of every field of interest. Intelligent state transitions are used to allow for soft adaptations of the nominal timeline in presence of perturbations.

The Navigation component uses hybridization of GNSS and IMU allowing to provide reliable navigation solution without transient errors. Classical launchers used only high performances and expensive IMUs, the addition of GNSS data allow to reduce the drift of the IMU measures and the use of less expensive components.

Multiple Kalman filter are implemented to adapt to mission phase requirements:
- Indirect Kalman Filter (IKF)
- Extended Kalman Filter (EKF)
- Unscented Kalman Filter (UKF)

For the guidance, different flight phases have been identified and different guidance modes are implemented for each phase according to Table 1.

The Pitch Program (PP) mode is an open loop algorithm based on time tabulated attitudes. This requires low computational effort to the OBC.

The Unified Powered Flight Guidance (UPFG) mode is a close loop state-of-the-art algorithm widely used in the launcher industry. Originally developed for Space Shuttle it is still used in today launchers.

The Convex Optimization option has been studied but it has been discarded due to its low TRL and low real-time performance.

The flight is divided into several manoeuvres, so that different guiders and targets can be configured by a Manoeuvre Planner.

DOI: 10.13009/EUCASS2022-4845

Table 1. Guidance modes.

FLIGHT PHASE		**GUIDER**
Thrusted	Endo-atmospheric	Pitch Program (PP)
	Exo-atmospheric	Unified Powered Flight Guidance (UPFG)
Ballistic	Stages release	Free COAST mode
	Orbital manoeuvers	Free COAST mode
		Slew COAST mode
		BBQ COAST mode

For control, following the same approach as in the guidance, different flight phases have been identified and different control modes are implemented for each phase according to Table 2.

The parameters that define each controller are scheduled (by time, velocity or mass) due to the fast flight condition changes (atmosphere, mass) impacting the controller's design.

Controller and actuator types are selected by a configurable Manoeuvre Planner.

The safety component is divided in two parts:

Safety diagnosis: Diagnoses the status of the mission and the vehicle through:

- Impact Predictor (point/area): Predicts the impact point/area of the launcher in the event of propulsion cut-off.
- Vehicle Health Status: makes a diagnosis of the status of the vehicle based on the health status provided by the telemetry of the different units and sensor measurements.

Safety evaluator: This module is in charge of making the safety decisions based on the diagnosis done by the previous module. Design considerations of this module are:

- Fuzzy Logic based decision-making.
- Modular architecture for mission phase adaptability.
- Configurability of restrictiveness to allow safety requirements missionisation.

Table 2. Control Modes.

FLIGHT PHASE		**Pitch/Yaw**		**Roll**	
		Actuator	Controller	Actuator	Controller
Stage 1	Endo-atmospheric	TVC	PID/Hinf	TVC	P *(angular rate)*
Stage 2	Endo-atmospheric	TVC	PID/Hinf	RCS	P *(angular rate)*
	Exo-atmospheric	TVC	PID	RCS	P *(angular rate)*
Stage 3	Thrusted	TVC	PID	RACS	P *(angular rate)*
	Coasting	RACS	PID	RACS	P *(angular rate)* PID *(3 axis)*

7. Demonstrators

With the design of the Launch Vehicle being consolidated, the last part of the project is going to focus on four ambitious launch vehicle demonstrators that will advance the maturity of critical launcher technologies, to ensure market readiness and competitiveness. These concern the main critical technologies for the launch vehicle such as the composite oxidizer structural tanks and the H_2O_2 turbopump, the launcher avionics and the payload avionics.

The structural oxidizer tank demonstrator will reflect ENVOL's 2nd stage tank. It will be manufactured in scale 1:1 and it will be pressure tested before the end of the project.

A pump demonstrator able to provide the right pressure and mass flow to one hybrid motor will be designed and manufactured. The pump will be tested with water to gather data about its capacity, performance and functionality, which is crucial information for maturing the design of the selected components in the turbo-pump. Moreover, additional information about cavitation margins and material compatibility with H_2O_2 will be available after the test campaign.

A modular payload service avionics system will be designed, introducing a high level of standardization and modularity. This will trigger the manufacturing and testing of a demonstrator built on this design.

All the avionics subsystems are developed, designed and validated following the HW in the loop approach (HWIL). The HWIL test bench simulates the avionics of the launcher and its environment, in order to provide a system allowing the execution for testing purposes. Nominal and degraded FSW tests will be executed on this platform. In addition, the injection of failures allows testing the robustness of the FSW. With the HWIL solution, the different simulated models running on a real-time target machine are connected to the target OBC. The sensors, actuators, environment, vehicle and dynamics, the avionics of the launcher and its environment are modelled in the simulator, with performance and operational characteristics obtained from testing or from the component manufacturer.

All the components of the HWIL approach are orchestrated by a dedicated machine, that manages the simulation and testing procedures (configuration, test definition, results exploitation, graphic interface,…)

DOI: 10.13009/EUCASS2022-4845

8. Conclusions

ENVOL is a three-stage launch vehicle that is going to provide Europe with its prime commercial, competitive, and green launch service, utilising a true NewSpace approach to offer low-cost, frequent, and flexible access to space to small satellites up to 200 kg. ENVOL will provide a launch service, which will enable a just-in-time service approach for space.

The launch vehicle will rely on the green and storable hybrid rocket propulsion technology based on hydrogen peroxide (H_2O_2) as liquid oxidiser. In particular, the two lower stages will need motors of 100kN thrust class.

To be able to make the motor scalable the current 30kN, the design, the materials and the manufacturing processes have been developed based on predictions, functional tests of components, and manufacturing trials.

The final design was tested in a down-scaled static firing test, and the test confirmed that the hybrid motor performance was improved, and the new requirements regarding weight and cost were fulfilled.

Different tank concepts have been analysed to assess the behavior of the tank under the stresses defined. The selected final concept is a hybrid tank with the bottom part being made with Automated Fibre Placement (AFP), a segmented top dome made with Automated Tape Laying (ATL) and an aluminium liner to guarantee the right level of material compatibility for storing H_2O_2. Moreover, a study has been carried out to establish the best solution for the cylindrical and conical structures of the launch vehicle (tanks excluded), and a full composite concept has been identified as the preferred solution after a trade-off between, among others, mass, maturity and production means.

In general, the launcher overall architecture will be based on modularity to reduce costs and improve quality and production. Moreover, the development of four demonstrators for as many subsystems is planned to raise the launch system maturity. These concern the main critical technologies for the launch vehicle such as the composite oxidizer structural tanks and the H2O2 turpbopump, as well as the launcher avionics and payload avionics.

The design phase is still being completed with the consolidation of the main subsystems (propulsion, structural tank, avionics) and of their status is presented.

9. References

[1] A. Kolsgaard, J.S. Hegre, B.E. Hansen, R.B. Molland, D.O. Aashammer, M. Faenza, B. Decotignie. 2022. Development and testing of a scalable 100 kN hybrid motor for sounding rocket and micro launcher applications. In: *8th Edition of the Space Propulsion Conference*.