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Getting Ready for Space: Nammo's Development of a 30 kN Hybrid Rocket Based Technology Demonstrator

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Abstract

In the framework of ESA FLPP, Nammo is working on the development of the Unitary Motor (UM), a 30 kN hybrid rocket motor based on 87.5% H2O2 - HTPB, and the Nucleus, a sounding rocket propelled by UM and to be launched from Andøya Space Center to reach over 100 km altitude. The Nucleus is conceived as a demonstrator of the hybrid technology and its possibility of being upscaled whilst maintaining competitive performance. UM went through two development phases, successfully concluded in early 2017 with great propulsive performance demonstrated. The development of the Nucleus is ongoing and static test campaign is planned to be completed during fall 2017. This article provides the status of Nammo's activities on its large scale hybrid in order to get ready for Space.

1. Introduction

The space market sees nowadays an evolution towards nano- and micro-satellites, that are more and more performant for all kind of purposes. The need for a dedicated launch service for these satellites is becoming quite clear to everybody in the space community ([1], [2]). The challenge lies in their limited launch mass, which represents the low-end of the satellite mass range for which no institutional launchers have been developed. In response to this need, several commercial space companies have already claimed that they will soon be ready to offer to the market their own version of such a new launch service, i.e. Virgin Galactic's LauncherOne, Rocket Lab's Electron, to name but the most matured ones, with dozen others at different level of development.

The Norwegian initiative, or NorthStar, with Nammo, Andøya Space Center (ASC) and the Norwegian Space Center (NSC) as main contributors, is moving along a path leading to a solution which will provide this emerging market a dedicated launch service, the first of its kind in Europe.

ASC, in Northern Norway, operates a launch site for sounding rockets and scientific balloons. The site has been operative since 1962 and has launched around 1200 sounding rockets. It has a close cooperation with ESA, NASA, German Aerospace Center (DLR) and the Japan Aerospace Exploration Agency (JAXA) on scientific sounding rocket campaigns. ASC has offered launch services based on rockets up to 10 tons, but has a capacity of up to 20 tons. They construct their own payloads and payload sections and offer space education through their subsidiary NAROM (Norwegian Centre for Space-related Education). Andøya Space Center does not manufacture rocket motors and therefore depends on acquiring rocket motors on the open market or on their customers to provide their own rocket motors. Increasing difficulties in acquiring suitable rocket motors for their customers has made them approach Nammo, as being rocket motor manufacturer, for a solution to this need.

In 2008, ASC and Nammo, with NSC support, conceived the vision to cooperate on the realization of a family of rockets based on hybrid rocket propulsion, thanks to its appealing features, such as simplicity, low cost, safety and fast responsiveness. The family of rockets created was called the NorthStar Rocket Family.

The NorthStar Rocket Family is based on a modular concept of Nammo's hybrid rocket motors clustered together. The initiative is conceived for maturing the propulsive technology and enhancing the system complexity according to a step by step approach that keeps both risks and costs as low as possible. The first market to be addressed is the sounding rockets one, where microgravity flights remain an active and appealing sector for scientific and technological application of reasonably sized rocket motors. Ultimately, the operational flight experience and technology matured on this market can be implemented as well for a future affordable dedicated space transportation system for small to very small satellites.

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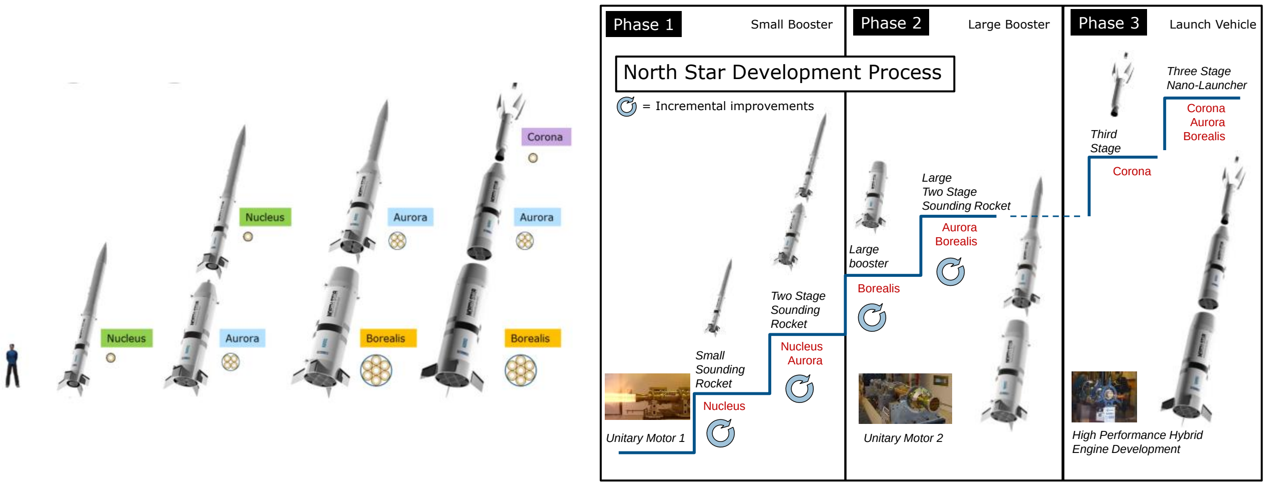

Figure 1.1: The North Star rocket family (left) and its development logic (right).

For full details about the NorthStar initiative, the reader is referred to [3], [4] and [5].

Two main factors have motivated the Norwegian space activities: first of all in order to stimulate growth and innovation in Norway's high-tech economy; secondly the geographic factors. Norway is an elongated country, reaching far to the north, with a sea area more than six times larger than its land area. With a scattered population, rugged topography, long distances to cover and harsh climatic conditions, space is an attractive place to monitor its own territory from. In addition, Norway's economy includes heavy elements of natural-resource extraction and maritime transport. There is a priority towards the use of navigation, communication and earth observation satellites to address needs related to ship traffic, fisheries, agriculture, offshore petroleum and search and rescue in the north.

All these priorities and the will to exploit the geographic and territorial advantages of Norway have led to considerable investments in space infrastructure. Norwegian infrastructures are located in Svalbard and in northern Norway (Figure 1.2), in addition to Antarctica, and this has made Norway an attractive space partner for international cooperation.
As a coastal island far from major settlements, Andøya's launch location is a competitive advantage for launching rockets: there is a vast sea area, no air restrictions and it is situated at high latitude, away from most international airline corridors, with a year-around access, which makes it the ideal place for launching into polar or Sun-Synchronous Orbits. Moreover Andøya Space Center is located at 2 degrees north of the Arctic Circle in northern Norway, making it ideally situated for scientific research in the auroral oval. With the SvalSat satellite station in Svalbard and the TrollSat station on Antarctica, Norway can offer launch, orbit insertion and multiple download and control points of a nanosatellite from Norwegian territory. It can offer an around-the-globe service.

Figure 1.2: Space infrastructures in Norway.

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1.1 Hybrid Rocket Technology at Nammo's

The conception of the NorthStar Rocket Family is based on the know-how which Nammo has acquired since 2003 on hybrid rocket propulsion technology. Nammo Raufoss began working on hybrid motors strong of its consolidated experience from solid motor design and production for defense (Exocet, NSM) and space applications (FE/FA Ariane 5 boosters).

Several research and technology programs have been completed since, either nationally or in cooperation with partners like Lockheed-Martin, ESA, SAAB Dynamics, and ONERA to name a few ([6], [7], [8], [9] and [10]). Nammo started its development on lab scale motors investigating initially different kind of oxidizers (N_2O, GOX, LOX, H_2O_2) and fuels (HTPB, HDPE, plus additives). Since 2008, high concentration hydrogen peroxide and HTPB has been the core which Nammo has built its strong expertise around, a combination which is both friendly to the environment and cost effective. The motors developed at Nammo combine the environmental friendliness and cost effectiveness of a H_2O_2-HTPB hybrid rocket motor, with a high regression rate and an excellent overall combustion efficiency (up to 98%).

2010 saw the beginning of the support, still lasting today, from the Norwegian Space Center and the European Space Agency in developing Nammo's hybrid propulsion technology. Firstly within ESA TRL Improvement program and lately in ESA FLPP (Future Launchers Preparatory Program), Nammo has performed more than 100 small-scale successful hybrid rocket tests exploring many different motor and flow configurations, and has afterward moved to upscaling the technology, in order to demonstrate the feasibility of using hybrid propulsion for sounding rocket and nano-launcher applications.

In order to support the development of the hybrid technology Nammo has invested in 2014 in the construction of a state-of-the-art test facility for green propulsion, with the capacity to test the first stage of a nano-launcher with a sea level thrust up to 500kN [11].

FLPP aims at fostering new promising technologies for future European access to space. The objective of the Future Launchers Preparatory Programme (FLPP) is to determine and ensure how Europe maintains and strengthens its independent access in space into the mid to long-term. The Programme has been investing in development of technological and industrial capabilities in all main space transportation areas since 2003, including in the propulsion field [12].

2. The Unitary Motor

With the support of ESA FLPP, Nammo is developing the Unitary Motor (UM1), which represents the first building block to design a clustered architecture potentially applicable both to the sounding rocket and the nano-launcher market.

The Motor belongs to the 30 kN thrust class and is based on a novel concept of hybrid rocket engine technology developed by Nammo. It uses high concentration hydrogen peroxide (87.5% H_2O_2) as oxidizer and hydroxyl-terminated polybutadiene (HTPB) rubber as fuel.

It was 2014 when Nammo successfully tested the battleship configuration for a burning time of up to 25 seconds. The upscaling factor with respect to the previous phase of lab-scale testing was above 20 and the performances achieved have been beyond expectations, in terms of stability, efficiency and high regression rate. This achievement promoted the go-ahead towards flight weight optimization of the UM1.

Figure 2.1 shows the working principle of UM1. The incoming liquid oxidizer, with a mass flow of about 11 kg/s, is decomposed passing through a catalyst into hot steam and gaseous oxygen at a typical temperature of 670°C. It is then injected into the combustion chamber in hot gaseous form, where ignition of the hybrid combustion occurs instantly without any dedicated ignition device due to the sole high temperature which is sufficient to vaporize the solid fuel. The vortex flow-field in the chamber generated by the injector helps in maintaining a high heat flux towards the fuel surface and in achieving appropriate mixing of the reactants. Ultimately, this allows sustaining high combustion efficiency. The hot combustion gases are then expelled through a standard nozzle, generating close to 30 kN of thrust.

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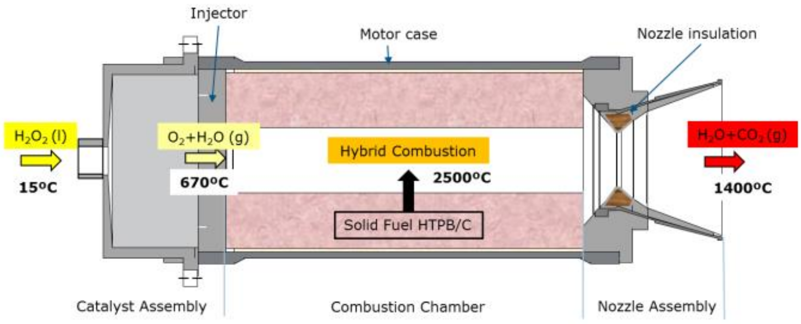

Figure 2.1: Schematic Showing the Working Principle of the Unitary Motor.

Compared with solid rocket motors, the hybrid technology developed by Nammo has a rich set of attractive features, which are:

- self-ignition (no dedicated igniter needed) increasing engine start reliability and enabling and unlimited restart capability;
- wide range throttling with limited performance losses;
- green life cycle and exhaust properties;
- solid inert fuel and high-density green storable oxidizer;
- high engine combustion efficiency, performance and stability;
- simplicity of a single circular port and single feedline configuration;
- low development and operational costs.

Most of these properties are shared with the inherent properties of other hybrid propulsion technologies, but some of them are unique for the H2O2 based technology perfected by Nammo. Some of these features are as well common with liquid rocket engines, but compared with liquid engines, the architecture of the Unitary Motor is much simpler and the same features are obtained for a fraction of the cost.

2.1 Development Logic

As previously mentioned, in the last years Nammo has been developing its hybrid technology with the support of ESA and the FLPP program. The primary objective of the FLPP hybrid demonstration is to increase the TRL of hybrid propulsion while demonstrating it at a significant scale; that is at a thrust level above 100 kN.
As illustrated in Figure 4, the program started with lab-scale motors which notably investigated combustion processes and the use of different fuel additives. After the completion of more than 100 lab-scale motor tests across many projects, Nammo was ready for upscaling. This upscaling occurred within FLPP Hybrid Phase 1, which was completed after the first two firings of the Heavy-Wall Unitary Motor (HWUM) in autumn 2014.
Phase 2 of the project continued the HWUM test campaign until completion, and then moved on to the design and manufacturing of the next motor evolution, the Flight-Weight Unitary Motor (FWUM). Phase 2 was concluded in spring 2017 by the FWUM Post Test Review after a successful test campaign which confirmed the performance of the HWUM on a flight optimized design.
Phase 3 focuses on two different further utilizations of the FWUM, displayed in Figure 4: the Cluster Demonstrator, a bundle of 4 FWUMs expected to deliver a sea-level thrust of the order of 120 kN; and the Nucleus demonstrator, a flying vehicle that will lead to a flight test of the FWUM and of Nammo's hybrid rocket technology. The rocket is planned to be launched from Andøya's Space Center in Northern Norway and to reach an altitude above 100 km. This flight has to be considered as a technology demonstration of the propulsive system (motor and feed system) in a representative environment: all the main motor parameters in flight will be measured and thus the performance assessed. More details will be provided on the Nucleus in the last section of the article.

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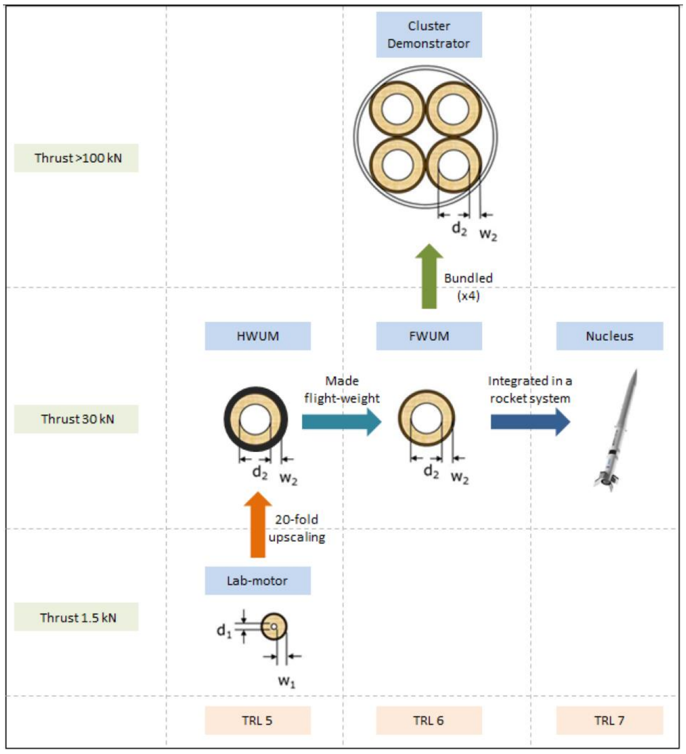

Figure 2.2: Development logic of Nammo's hybrid propulsion technology within ESA FLPP.

2.1.1 Motor Evolution

The FWUM is an evolution of the HWUM in terms of mass, with 3 times less dry mass, but not only: it is also an evolution in terms of capability. Through discussions with actors of the sounding rocket industry on the UM and Nucleus sounding rocket payload and altitude capabilities, the preference for a larger total impulse capability of 1000 kNs was expressed on numerous occasions. This need furthermore coincided with the fact that a 1000 kNs impulse UM would have an outer diameter of 14 inches, which is the standard sounding rocket payload diameter in use in Europe and at Andøya Space Center in northern Norway.
The decision was then taken by Nammo and ESA to increase the UM outer diameter to 14 inches, applying this change directly on the FWUM. Within the demonstration program, this evolution means not a higher thrust level for the motor, but a longer burn time, which was increased from 25 seconds to more than 35 seconds.
From the analysis of the HWUM firing test data, the project actors were able to conclude that this increase in motor capability and diameter was feasible and to be pursued within the framework of the FLPP hybrid demonstration program.
Table 1 shows an overview of the differences between the HWUM and the FWUM, while Figure 2.3 and Figure 2.4 show the two motors during testing at Nammo Raufoss premises.

Table 1. Differences between FWUM and HWUM

	HWUM	**FWUM**
Total impulse at ground level	700-750 kNs	1000 kNs
Outer diameter	334 mm	356 mm (14 in)
Burn duration	25 s	>35 s
Motor dry mass	> 280 kg	< 100 kg
Consumed fuel mass	< 50 kg	> 60 kg
Consumed oxidizer mass	270 kg	400 kg

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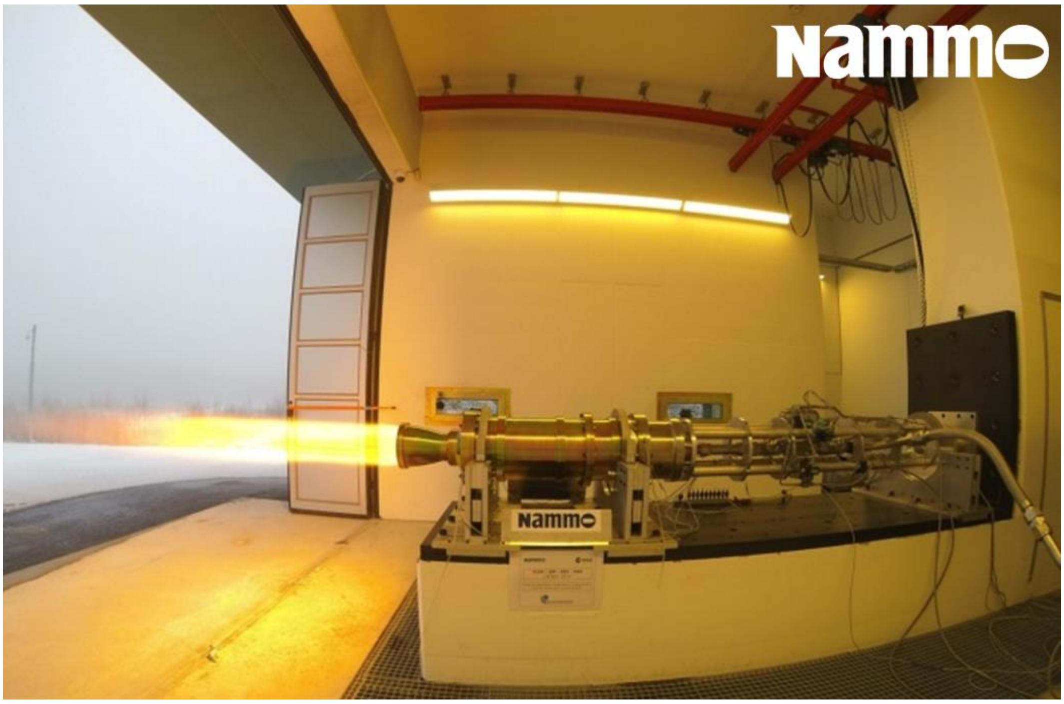

Figure 2.3. HWUM during static testing.

Figure 2.4. FWUM during static testing.

2.2 Test Campaign

2.2.1 Heavy Wall

Within FLPP Phase 1, the HWUM was designed, manufactured and first fired during the sole year 2014. The HWUM campaign then continued in FLPP Phase 2.
The HWUM ground tests were concluded with the delivery of a very satisfactory motor design yielding the performance desired for the next stage in the program.

The reader is referred to ref. [13] for a complete overview about the results of this test campaign.

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2.2.2 Flight Weight

The design of the FWUM occurred within the first 8 months of 2015, with the completion of its Preliminary Design Review in June 2015 and its Manufacturing Readiness Review in September 2015. The manufacturing phase then followed on during the fall of 2015, leading to the first catalyst tests at the end of November 2015.
During the FWUM test campaign, and after a preparatory phase of GSE (Ground Support Equipment) validation with water tests, both monopropellant and hybrid tests were performed.

The former consisted of catalyst functional tests whose results have been already presented in the past: the reader is referred to ref. [14] for a complete overview on the results of this part of the campaign.
Since the last monopropellant test, the project has worked on preparing for the hybrid firing. Several tests have been performed with the targeted goal of ramping up the burn duration towards the same duration achieved during the HW campaign.
In performing this part of the campaign an additional achievement has been demonstrated: the capability of Nammo's engine to stop and restart, feature very appealing for hybrid rocket based propulsion systems. One of the hybrid firings, with a targeted cumulated burning time of 15s, has been split in two pulses: a first one lasting 5 s and a second one, lasting 10 s. The second pulse has been performed 2 hours and 35 minutes after the first pulse. Ignition, stability and performance of the engine confirmed very satisfactory in the stop-restart tests as well, as shown by the thrust curves in Figure 2.5.

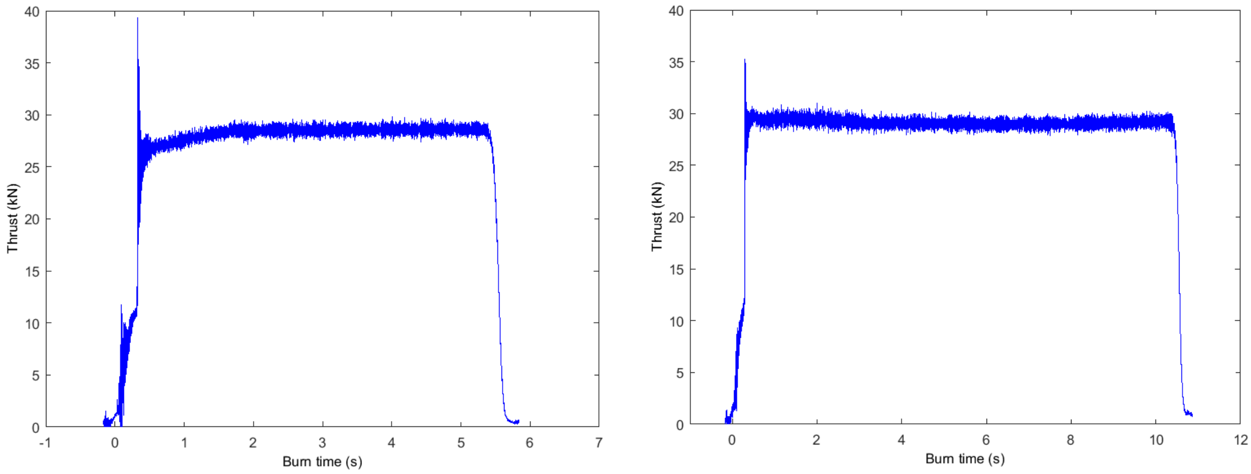

Figure 2.5. Unfiltered thrust curve recorded during hybrid firing with stop and restart: first pulse on the left, second pulse on the right.

At the end of this static test campaign, burning time duration of 25 s was demonstrated and the performance confirmed at the expected level. It is remarked that 25s is the maximum duration allowed and tested during the HWUM test campaign. It was therefore an important milestone to achieve again the same burning time duration, but this time on the flight weight configuration.
The flight weight UM demonstrated great and stable performances for the full burn duration, delivering a specific impulse in line with the expectation and a stable thrust in the order of 28 kN. Figure 2.6 shows typical frames of the motor during testing while Figure 2.7 shows the thrust curve as recorded during the test. One can really appreciate the stability and neatness of the produced thrust, thus suggesting a well performing motor.

This firing is currently the longest 30 kN firing performed by Nammo which demonstrated a long and stable burn time of the FWUM without any major issue encountered. This result together with a delivered overall average motor efficiency of the order of 95% clears the way to proceed to longer firings as part of the Nucleus ground test campaign.

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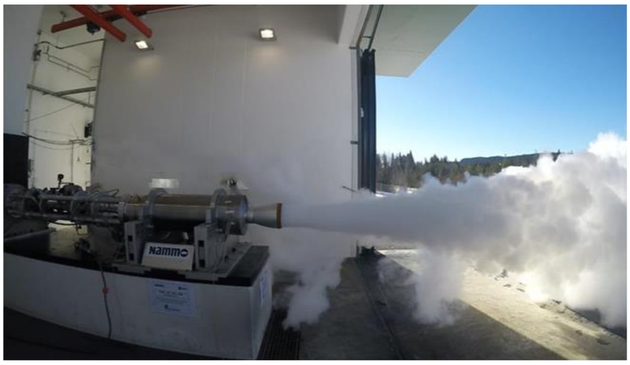

a) start-up: condensed phase

b) start-up: monopropellant phase and early ignition

c) Steady-state firing

d) shut-off and purge

Figure 2.6. FLPP-UM-016-HRE during the various stage of the firing

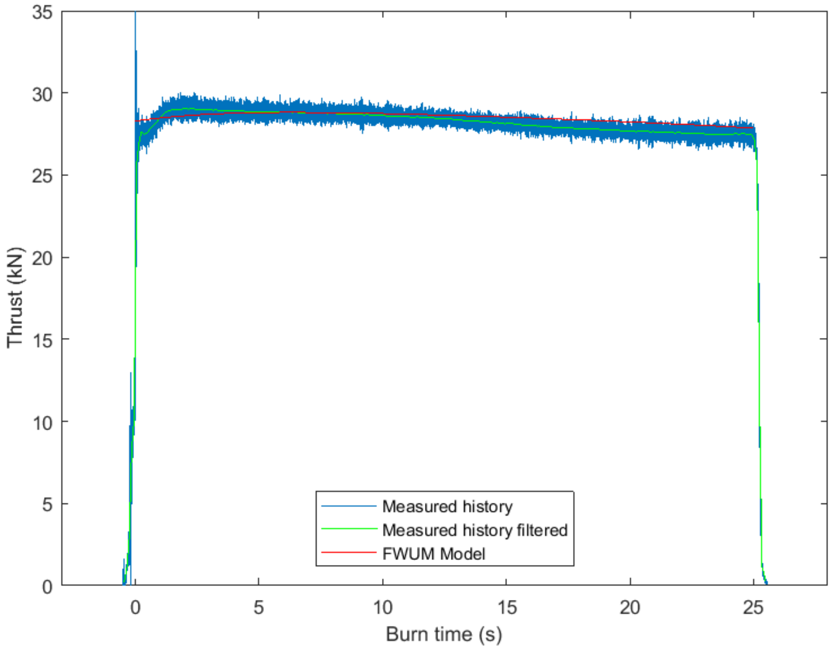

Figure 2.7. Experimental unfiltered thrust curve in comparison with model prediction.

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3. Nucleus

With both a Cluster Demonstrator and a Flight Demonstrator (the Nucleus rocket) on the Nammo roadmap of future hybrid activities, the Nucleus is currently the one on which most focus is placed. That is primarily because of the pressing sounding rocket market needs, with ASC ready to propose those vehicles on the commercial market as soon as available.
As already mentioned, the Nucleus is the prototype sounding rocket developed by Nammo, with the flight weight UM1 as propulsive unit. This vehicle will be a flight demonstrator for Nammo's hybrid rocket technology, and will include the entire life cycle at system level, with tanks and valves, electronics, launch pad GSE and operations, etc. It will be used to demonstrate at full scale the Concept of Operations (CONOPS) associated with rocket launches based on hydrogen peroxide powered hybrid rockets.

The design activities started in Nammo Raufoss and ASC in November 2015 with the three actors, ESA, Nammo and ACS working closely together. Manufacturing Readiness Review (MRR) with ESA has been successfully passed in December 2016 and manufacturing is now ongoing and well underway.

3.1 Specifications

Table 2 summarizes the main features of the Nucleus rocket according to specifications.

Table 2. Nucleus specifications.

Parameter	Specification
Motorization	One FWUM fitted with a flight nozzle (AR 8.5)
Apogee altitude (with 82° launch rail elevation)	> 100 km
Body outer diameter	356 mm
Total length	9 m
Total mass	820 kg (of which 70kg for the ASC payload)
Hybrid motor burn time	>35 s
Total impulse	> 1000 kNs
Average delivered specific impulse in flight	> 250 s
Peak acceleration	7 Gs
Oxidizer tank material	Aluminum
Helium tank material	Carbon-composite
Airframe structures	Aluminum

3.2 Architecture

The Nucleus is a single stage spin-stabilized sounding rocket. In order to reduce the complexity and the cost of this prototype, no active control of the rocket is foreseen during the flight and no recovery is planned.
Nucleus architecture can be divided in 4 main sections, as shown in Figure 3.1: the FWUM, the oxidizer feeding section, the pressurizer feeding section and the payload.
The main components of the rocket can be separated in 4 categories, depending on their role:

- Propulsion;
- Structure;
- Aerodynamics;
- Instrumentation and telemetry.

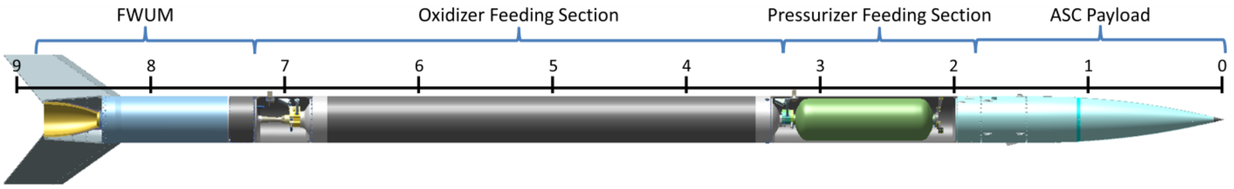

Figure 3.1. Simplified CAD model of the Nucleus Prototype Rocket.

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Except for the payload section, developed by Andøya Space Center, and the fins, developed by DLR Stuttgart, the rest of the rocket has been entirely designed within Nammo and all the manufacturing is either carried out in house or outsourced to local companies in the Raufoss industrial park.
As the “scientific” payload of this launch is the propulsion system itself, the payload sections are limited to what is necessary for the flight: housekeeping (battery, accelerometers and magnetometers,…), telemetry system (transmitter and antennas) and nose cone. Several types of sensors are located along the rocket and especially in the FWUM section (pressure probes, thermocouples and accelerometers) and signals are carried to the nose cone where they are handled by ASC payload.

The propulsion is covered by the FWUM section, where one FWUM is fitted with a flight adapted nozzle to maximize the flight performances. A boat-tail is mounted around the nozzle in order to reduce the base drag and provide interface for the attachment of the DLR fins, responsible of the stability of the rocket. The motor housings carry the loads: thrust, G forces, dynamic pressure and aero-heating. The motor is operated in blow down using helium as pressurizing gas.

3.2.1 Tanks and Valves

The Oxidizer Feeding Section mainly consists of the structural oxidizer tank filled with about 400 kg H2O2. The design and qualification of the tank is carried out by Nammo with the support of a Norwegian company experienced in friction stir welding for the manufacturing.
A Propellant Management Device (PDM) has been developed in order to limit the formation of free surface vortex in the liquid due to spin and to avoid premature ingestion of gas in the motor.
Nammo has also developed a customized oxidizer valve assembly with different functions embedded in one single body in order to significantly decrease mass and size of the fluid system. The assembly performs the filling/draining of the oxidizer tank, as well as the catalyst priming and the firing of the motor, all in one structure.
A cavitating venturi is used to calibrate the mass flow rate given to the FWUM.
Figure 3.2 shows a schematic representation of the main items included in the Oxidizer Feeding Section.

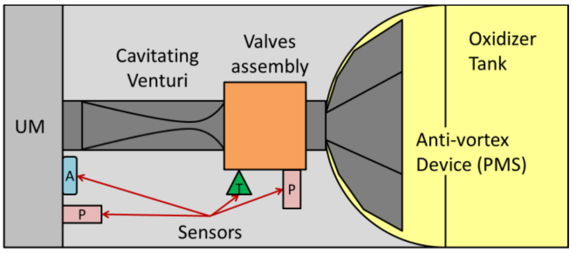

Figure 3.2. Sketch of the Oxidizer Feeding Section.

The Pressurizer Feeding Section has a structure similar to the Oxidizer one: a composite non-structural cylinder filled with Helium at 400 bars, a purpose-built and multifunction valve assembly designed for the pressure level and all the operations needed (filling/draining of the cylinder, pressurization of the oxidizer tank and flow regulation) and a flow restrictor to ensure a good pressurization level in the oxidizer tank all throughout the propulsive phase. Helium is selected as pressurizing gas due to its low mass.
In this section, the loads are carried by a dedicated aluminium airframe structure around the pressurizer tank.
Figure 3.3 shows a schematic representation of the main items included in the Pressurizer Feeding Section.

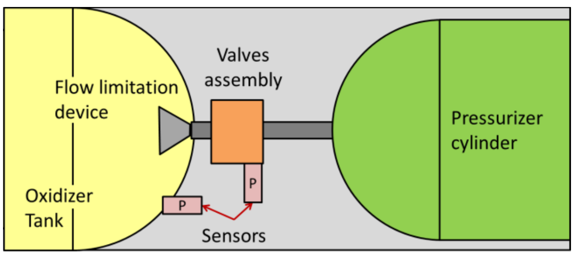

Figure 3.3. Sketch of the Pressurizer Feeding Section.

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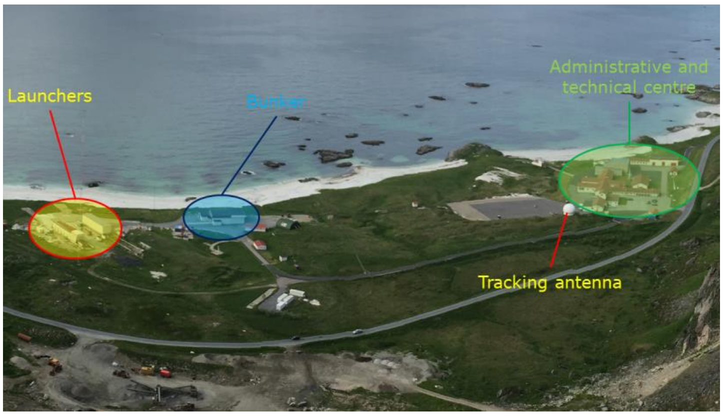
In order to further reduce the dry mass of the rocket, the actuators for both valve assemblies are installed on the launch rail and planned to remain on the ground at rocket take-off.

3.3 Ground Support Equipment

ASC has launched over 1200 sounding rocket since its foundation in 1962, but so far only one hybrid rocket. The launch pad has thus to be adjusted to accommodate this technology. The Nucleus will be launched from the main launch pad, the U3 launcher, capable of launching all kind of sounding rockets, from Improved Orion to Black Brant XII. The upgrades of the U3 facility concern mainly the safe handling and storing of H2O2, for which dedicated ground support equipment is designed and installed. This GSE will be used to fill the oxidizer tank and the pressurizer cylinder, to control and operate the rocket system from the bunker while on ground and to ensure the safety in the launch area.
Figure 3.4 shows an overview of ASC site and launch pad.



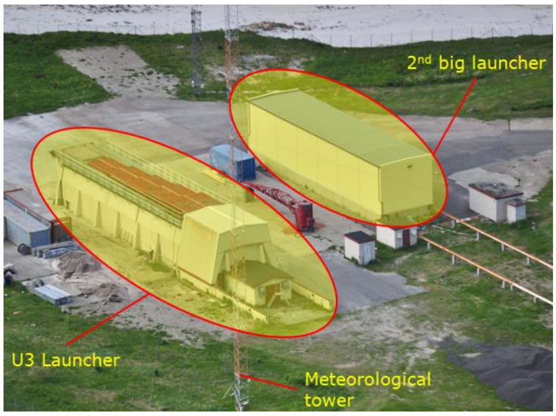


Figure 3.4. Global view of ASC (left) and zoom on the launch pad area (right).

3.3.1 Launch Pad

In order to accommodate the Nucleus rocket on the U3 launcher some extra hardware has been developed by Nammo: it consists of a set of two retractable launch lugs and a guiding rail specifically designed for guaranteeing the simultaneous release of the rocket at take-off. The guiding rail is connected to the U3 launch rail and the Nucleus is suspended on it through the mentioned lugs (Figure 3.5). At rocket release, the lugs design guarantees them to retract inside the rocket body in order to minimize aerodynamic drag.
Figure 3.6 shows a schematic representation of the lugs design and connection to the guiding rail.

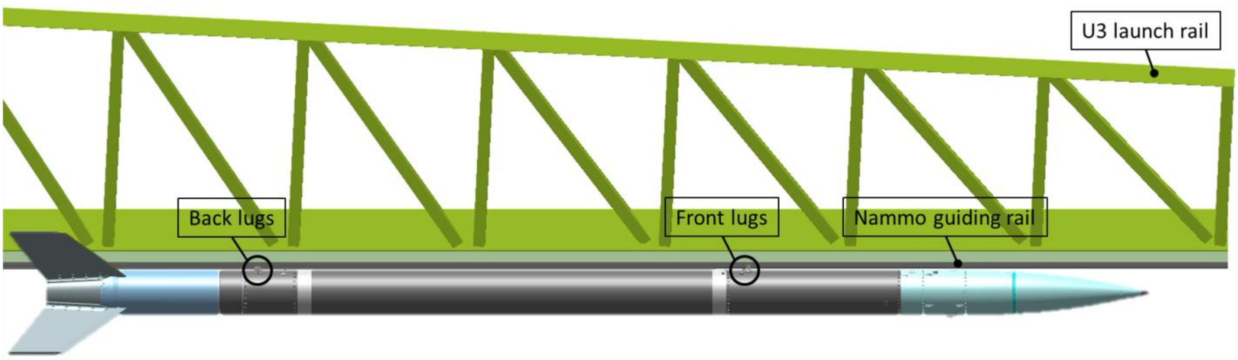


Figure 3.5. CAD model of the Nucleus suspended on the U3 .

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Figure 3.6. CAD model of the Nucleus suspended on the U3.

3.4 Flight Performance

Trajectory analysis and safety assessment are performed by Nammo in collaboration with Andøya Space Center.

A numerical tool for rocket design was developed by Nammo to help the design process. This tool allows the user to define all parameter of interest (size of the motor, oxidizer total mass, Helium initial pressure, etc.) and gives the corresponding rocket preliminary design. This design can then be used as input to the second part of the code that is a flight simulator. It includes physical models for the motor operation, for the aerodynamic forces acting on the rocket and for the resulting trajectory. The expected trajectory calculated with this tool is shown in Figure 3.7.

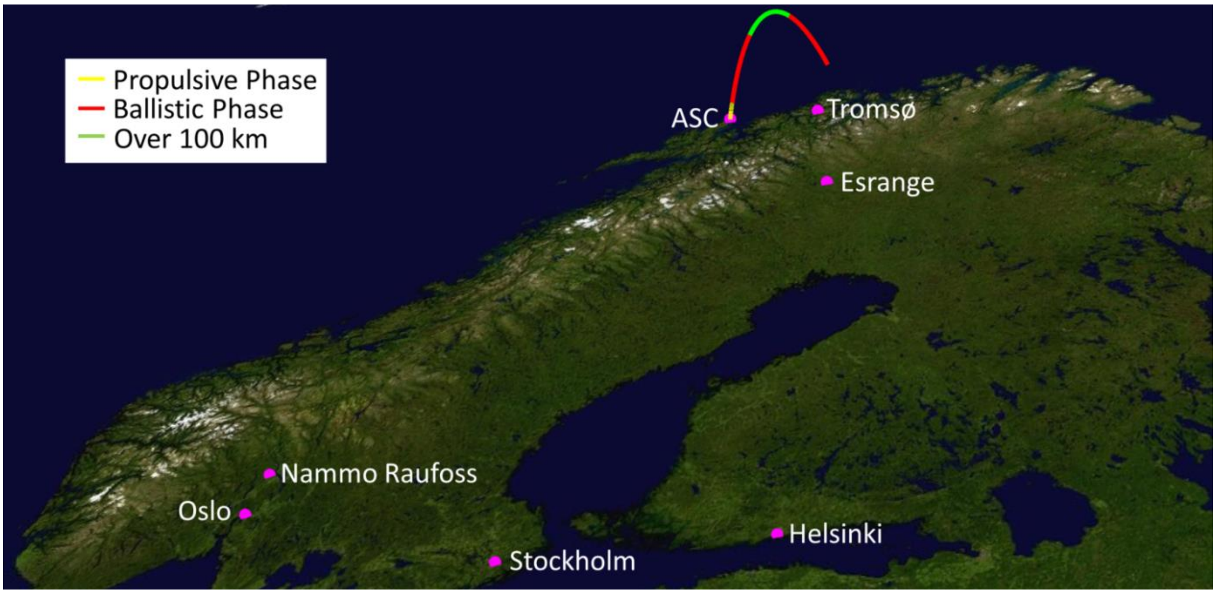

Figure 3.7. Simulated trajectory of Nucleus flight.

3.5 Ground Testing

Before being cleared to launch the Nucleus, the full propulsion system is being validated through an ongoing ground test phase in Nammo's Test facility in Raufoss ([11]).
This test campaign has two main goals:

- test the FWUM functioning in blow-down and for the full burn duration (>35 s);
- introduce all the flight components (tanks, valves, sensors) in the test assembly in order to qualify filling, testing and draining operations on ground before flight.

These goals are being pursued progressively adding step by step complexity to the test assembly. Several hybrid tests will be needed in the next months to reach the ground system test objectives and proceed to rocket final assembly and flight.

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4. Conclusions

Between 2014 and 2017, Nammo has upscaled and matured its hybrid technology to a scale and technology readiness level relevant for sounding rockets and nano-launcher applications. Those developments have so far culminated with the design, the manufacture and the testing of the Unitary Motor 1, a 30 kN class hybrid motor which showed all along the test campaigns exceptional performances and behaviour. In parallel to the motor development, Nammo has worked on the design and the manufacturing of the Nucleus, a single stage sounding rocket, seen as a demonstration platform for the Unitary Motor 1. The design has been finalized, manufacturing is ongoing and the project is currently occupied with the ground testing of the full propulsion system, with a flight that has the goal to bring Nammo's technology above 100 km altitude.

Ultimately, the work done so far by Nammo demonstrates its capability of mastering the hybrid technology with a dedicated work oriented towards continuous improvement; moreover it paves the way with the support of Andøya Space Center, the Norwegian Space Center and ESA for the use of its hybrid technology for heavy-lift sounding rockets and potentially nano-launcher application, as part of the Norwegian initiative, where the Nucleus represents the first and smallest building block of the NorthStar rocket family.

Acknowledgments

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References

[1] http://www.parabolicarc.com/2016/10/03/plethora-small-sat-launchers/. Messier D., "A Plethora of Small Satellite Launchers". Article on parabolicarc.com, October 2016.

[2] http://spacenews.com/launch-woes-diminish-demand-for-small-satellites/. Foust J., "Launch Woes Diminish Demand for Small Satellites". Article on spacenews.com, February 2017.

[3] Haemmerli B., Boiron A. J. and Verberne O., "The Norwegian Initiative for a Satellite Nano-launcher". Proceedings of the 29th AIAA/USU Conference on Small Satellites, Logan, Utah, August 2016.

[4] Verberne O., Boiron J.B., Faenza M.G. and Haemmerli B., "Development of the North Star Sounding Rocket: Getting Ready for the First Demonstration Launch". Proceedings of the 51st AIAA Joint Propulsion Conference, Orlando, Florida, July 2015.

[5] Verberne O., "The North Star Rocket Family". Proceedings of the 12th ReInventing Space Conference, London, Great Britain, November 2014.

[6] Verberne, O., Rønningen J. E. and Boiron A., "Development and Testing of Hydrogen Peroxide Hybrid Rocket Motors at Nammo Raufoss". Proceedings of AIAA 50th Joint Propulsion Conference, Cleveland, Ohio, July 2014.

[7] Anthoine, J., Lestrade, J-Y, Verberne, C.J., Boiron, A.J., Figus, C & Khimeche, G, "Experimental Demonstration of the Vacuum Specific Impulse of a Hybrid Rocket Engine". Proceedings of AIAA 50th Joint Propulsion Conference, Cleveland, Ohio, July 2014.

[8] Rønningen J.-E. and Husdal J., "Nammo Hybrid Rocket Propulsion TRL Improvement Program". Proceedings of the 48th Joint Propulsion Conference, Atlanta, Georgia, August 2012.

[9] Rønningen J.-E. and Husdal J., "Test Results from Small-Scale Hybrid Rocket Testing". Proceedings of the 3rd Space Propulsion Conference, Bordeaux, France, May 2012.

[10] Rønningen J.-E., "The HTR Program – An Overview of the Rocket System and Program Achievements". Proceedings of the 18th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Visby, Sweden, June 2007.

[11] Verberne O., Boiron A.J. and Vesterås T., "Green Propulsion Rocket Test Stand". Proceedings of the 4th Space Propulsion Conference, Cologne, Germany, May 2014.

[12] Underhill, K., Caruana, J-N, De Rosa, M. & Schoroth, W. (2016). Status of FLPP Propulsion Demonstrators – Technology Maturation, Application Perspectives. Proceedings of the Space Propulsion Conference 2016, Rome, Italy, May 2016.

[13] Boiron J.B, Faenza M.G, Haemmerli B and Verberne O., "Hybrid Rocket Motor Upscaling and Development Test Campaign at Nammo Raufoss". Proceedings of the 51st AIAA Joint Propulsion Conference, Orlando, FL, July 2015.

[14] Boiron, A.J, Faenza M. G., Haemmerli B., Verberne O., Vesterås T., Caruana J.N., Schoroth W., "Demonstration of 30kN-Thrust Hybrid Rocket Propulsion at Nammo Raufoss within ESA FLPP". Proceedings of Space Propulsion 2016, Rome, Italy, May 2016.