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HYPROGEO Hybrid Propulsion: Latest project achievements

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KEYWORDS:

HYPROGEO, Spacecraft propulsion, Hybrid propulsion, green propulsion, H2020, hydrogen peroxide, High Test Peroxide (HTP), polyethylene, long duration firing, cost reduction, stable thrust, isochoric combustion chamber, catalytic decomposition, long endurance nozzle, propulsion module, transfer module, kick-stage, satellite propulsion.

ABSTRACT:

Independent access to space is a key component of the European Space Policy. The competition is increasing in this area both for the full launching systems and the key subsystems. Cost effectiveness becomes the main driving factor.

This paper describes the advancements [2] performed in HYPROGEO [1], a 3-years cooperative R&D project funded by the European Commission's Horizon 2020 program. HYPROGEO is a consortium of 14 European partners managed by Airbus Defence and Space Toulouse, bringing together complementary profiles from large space industry, SMEs till research institutes.



Figure 1: European Commission Horizon 2020

HYPROGEO's ambition is to develop the key technologies enabling a propulsion module based on hybrid chemical propulsion. This application is very challenging as it has to overcome the limitations of classical hybrid engines with the objectives of long duration burns, constant thrust below 1kN, specific impulse comparable to bi-liquid propulsion). The project shall also provide solutions to the classical issues linked to bi-liquid engines (toxicity, architecture complexity and cost) and electric propulsion (cost and transfer duration).



Figure 2: HYPROGEO vision

The impact of the project is secured by the composition of the consortium led by Airbus Defence and Space with the main European actors of the hybrid: it contributes to the consolidation of the European industrial supply chain for Hydrogen Peroxide and Hybrid propulsion, inherently green and safer than liquid chemical propulsion (moreover impacted by the threat of a limitation of use by REACH European regulation).



Figure 3: HYPROGEO consortium

The main challenges concern the feasibility of managing near-anhydrous hydrogen peroxide (H_2O_2 or HTP), sustaining long duration burns with constant thrust, and integrate the hybrid propulsion within operational spacecraft and confirm the economic and technical effectiveness.

Therefore, the main technical objectives of HYPROGEO are centred on four building blocks:

- Combustion chamber: to develop and test innovative isochoric architecture to produce the constant thrust during several hours.
- High endurance nozzle: to develop a lightweight nozzle capable of withstanding the thermal load and specific erosion caused by the long term exposure of the reaction products.
- HTP: produce at industrial scale up to 98% concentration HTP, aiming theoretical ISP equal to state-of-the-art NTO/MMH apogee engines.
- Catalytic injector: the challenge is to ensure compatibility to the HTP and rapid ignition.

These four elements influence the performance of the system; scientific achievements in these technological domains and TRL level increase are required in order to propose the development of an operational system.

This paper describes the potential satellite & space transportation applications when using hybrid propulsion and the associated technical challenges in the development of key technologies for a novel isochoric hybrid propulsion system in the kilonewton class, compatible with long duration firings.

This investigation called HYPROGEO is a 3-years cooperative R&D project funded by the European Commission's Horizon 2020 programme and managed by Airbus Defence and Space, Toulouse [1]. HYPROGEO is a consortium of 12 European partners, bringing together complementary profiles from Space industry till research institutes.



Figure 4: HYPROGEO logo

1 CONTEXT AND INTRODUCTION

1.1 Context

The emerging trend towards the electric propulsion (EP) has a profound impact on the spacecraft industry with an ever increasing interest for Telecommunication Satellites platform (Airbus Defence and Space Eurostar NEO, Boeing 702SP, OHB Electra, Thales Alenia Space Spacebus Neo, etc.)

The EP is efficient with a very high Specific Impulse (ISP) but with very low thrust (<1N) and expensive by inducing additional design and operational constraints, such as longer transfer phase (months instead of days, thus requiring more ground operation monitoring), higher electrical power demand during critical phases, etc. As a consequence, use of a complementary high-thrust propulsion system for the transfer phase is a key advantage if it can offer similar performances to existing mature but not environmentally-friendly chemical propulsions technologies at a reduced cost. This is where older concepts can re-emerge and become attractive, when combined with new technologies.

In particular, the hybrid chemical propulsion has been known for more than 60 years. Despite its known advantage with respect to pure solid rocket and bi-liquid propulsion systems, it suffers from specific issues (unburnt fuel, combustion oscillation and thrust stability issues, etc.), that have limited the development of large thrust applications and remained at most typically sounding rockets).

	Compared to solid system	Compared to bi-liquid system
Smarter	Stop-Restart Thrust modulation	Architecture Simplicity Reduced mass of liquid
Performant	Better Isp Performance	Theoretical equivalent Isp Better ρ .Isp
Safer	Zero TNT equivalent	Reduced firing hazard
Greener with H_2O_2	No highly toxic combustion products as with solid engines	No highly toxic storable liquid (MMH, NTO, Hydrazine) + REACH threat

Figure 5: Hybrid propulsion strengths

However, changing perspectives, and targeting low to moderate thrust applications with limited operational duration opens a whole new

application range for which the hybrid propulsion system can offer the potential of an inherently safe, mechanically simple alternative with lower life cycle costs compared to solids and liquids.

The ambition of HYPROGEO is thus to fully take advantage of those specific operational requirements better suited to this technology (i.e. high ISP, medium thrust, and long duration firings) to target the optimization and exploitation of hybrid chemical propulsion to satellite transfer modules or upper stages.

HYPROGEO, an H2020 project [1], relates to the topic COMPET-2-2014 of the work program: Independent access to space. This program highlights three main strategic orientations:

- The vital dimension of an autonomous access to space capability in Europe,
- The need for breakthrough technologies providing reliable and cost-effective launch and transfer solutions, fully complementary with on-going development activities: the optimization of the hybrid technology to the proposed transfer phase mission is very innovative,
- The economic dimension: the quest for cheaper launch solutions is a critical driving factor for the competitiveness of the European space-industry and its enabling effect on satellite applications and services. The confirmation of a significant reduction in recurring costs is the main expected impact of the project.

1.2 Key Performance Targets: the reference mission

Our technical objective is to demonstrate that hybrid chemical propulsion can become a credible solution for operational space missions. One of the main targeted applications of the hybrid engine for which the key technologies shall be developed is the apogee engine of a geostationary satellite.

Hybrid propulsion is a good candidate if the achieved performance and reliability is similar to one of today's reference system (i.e. bi-propellant engine) with a lower price. Price and dry mass

shall all be smaller or equal than this reference. The main features of the reference mission, derived from the Airbus Defence and Space 400N bi-propellant engine (using MMH with N₂O₄, MON-1 or MON-3) are:

- Typical mass of the satellite: 5000 kg,
- Required Delta V: 1500 – 2000 m/s for the transfer (and 800 m/s in addition to station-keeping during the satellite lifetime),
- Number of burns and duration: 3-6 firings,
- Duration of each firing: 30'-60',
- Effective specific impulse: 318-321 seconds,
- Thrust: 400-500 N,
- Total efficiency: 91.5% (combustion >96%, nozzle efficiency > 95%)

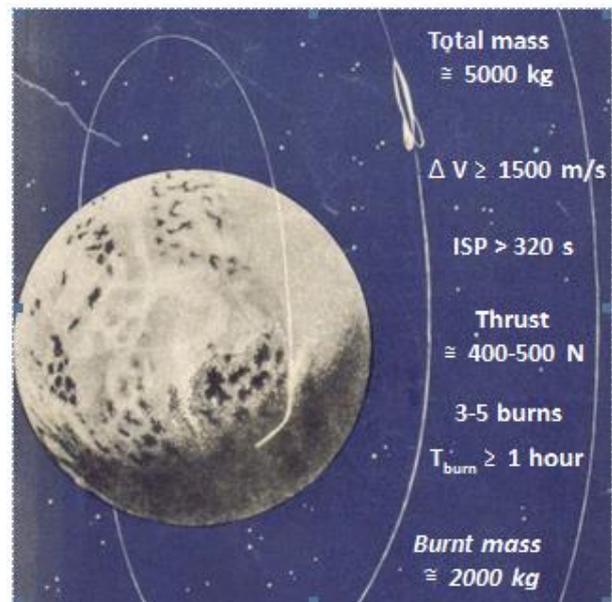


Figure 6: The reference mission

1.3 Specific Challenges & Scientific Objectives

Taking into account the requirements of the reference missions and the objectives at system level [2], the main challenges of HYPROGEO are described in Table 1.

Table 1: Scientific and technical challenges

	<i>Technical challenges</i>	<i>Benefits and impacts on performance</i>
<p><u>1st Challenge:</u> Achieve high specific impulse (ISP): (target > 320 s)</p>	<ul style="list-style-type: none"> ▪ Fuel selection compatible with space applications and providing the highest theoretical ISP. ▪ Combustion efficiency with low regression rate. ▪ Optimization of catalyser and increase of H₂O₂ concentration. 	<ul style="list-style-type: none"> ▪ Increase of payload mass and/or launch mass ▪ Reduction of dry mass. ▪ $\Delta V/M$ optimization. ▪ Reduce duration of transfer. ▪ Recurring costs. ▪ Green technology
<p><u>2nd Challenge:</u> Sustain long duration burn with medium thrust (> 400 N)</p>	<ul style="list-style-type: none"> ▪ Duration of burns (long firings /medium thrust). ▪ Thrust stability. ▪ Thermal management (nozzle and combustion chamber). ▪ Geometrical arrangement of the fuel for long duration burns and constant performance with time. Compatibility with oxidizers. 	<ul style="list-style-type: none"> ▪ Cost of operations. ▪ Optimization of orbit transfers. ▪ Lifetime and reliability of subsystems
<p><u>3rd Challenge :</u> Demonstrate the feasibility of using High concentration hydrogen peroxide (H₂O₂)</p>	<ul style="list-style-type: none"> ▪ High concentration issues (production, storage, decomposition, safety of operations). ▪ Compatibility with material and subsystems (lifetime of tanks). 	<ul style="list-style-type: none"> ▪ Safety of operations. ▪ Vehicle integrity during flight ▪ Green propellant. ▪ Cost.
<p><u>4th Challenge:</u> Integrate the hybrid propulsion within operational spacecrafts and confirm the economic and technical effectiveness</p>	<ul style="list-style-type: none"> ▪ Confirmation of cost impact and reduction of design complexity. ▪ Accommodation of the hybrid propulsion modules within the spacecraft. ▪ Geometrical arrangement of tanks. ▪ Reaction control thrusters ▪ Trade-off between upper stage and apogee engine scenarios. 	<ul style="list-style-type: none"> ▪ Impact on satellite architecture, manufacturing and launch operations. ▪ Reduction of cost ▪ Enable innovative system design options: concept of autonomous transfer module. ▪ New architecture of satellite with detachable apogee engine. ▪ Separation of propulsion functions between transfer and station keeping. ▪ Reduced cost of the overall propulsion system.

1.4 TRL Level

Although the chemical hybrid concept has been studied in the past for launcher application, the key technologies the present study proposes to develop to achieve the required long stabilized thrust burns for the transfer phase are true innovation as reported in the following table that indicates their current TRL level and the targeted one at the project completion.

	TRL at project start	Target TRL
Isochore combustion chamber	TRL 1/2: innovative concept never designed nor tested.	TRL 4
High endurance nozzle	TRL 4: existing material but never tested/validated under long high temperature duration chemically reactive environment.	TRL 5
Catalytic injector for high H ₂ O ₂ concentration	TRL 2: Potential catalytic bed for high H ₂ O ₂ concentration > 87.5% identified but their feasibility range not yet tested.	TRL 4
high concentration H ₂ O ₂	TRL 2/3: no industrial process for large scale production. New product formulations to be developed and tested.	TRL 4
Full engine	TRL 2: never design nor tested yet	TRL 5

Table 2: The HYPROGEO technologies TRL levels

Through the work performed, it is expected at the end of HYPROGEO to reach TRL 5 (Technology validation from “high-fidelity” laboratory integration of the hybrid engine components tested in a simulated operational environment).

1.5 Justification of the Project Orientations

By focusing on R&D activities on key hybrid propulsion components, HYPROGEO proposes to increase the European excellence on a technology which is a critical asset to develop an efficient, reliable, cost-effective propulsion system for the spacecraft transfer phase that nicely complements ongoing efforts on electrical propulsion in order to strengthen Europe’s leading edge position in the highly competitive Telecom satellite market.

By simplifying the propulsion system architecture, reducing the operational and system cost, and by reducing the transfer phase duration, this technology offers a key advantage with respect to competing launch service and satellite suppliers.

It will also position European research centres and space industry as global leaders in cost effective, environmentally-friendly, non-toxic, and efficient engine technology. This pioneering activity is not supported today by space agencies (national or European): they focus their current effort on new platform developments (such as NEOSAT), in particular based on electric propulsion.

However the proposed activity is a necessary step to build European knowledge and competence into a technology that will be further matured within EC or ESA programs dedicated to technologies development (some US operators, such as Scaled Composites, invest a lot on it).

2 CONCEPT & APPROACH

2.1 Overall Approach

In order to meet the high level objectives, the work approach proposed for the HYPROGEO project combines activities at two complementary levels:

- System level and missions, because it has impacts on the mission profile, on the overall architecture of the transfer module, on ground and in-flight operational constrains, etc.
- Critical components and critical technologies used in the system, because further innovative solutions are to be explored and validated,

The main proposed activities at system level are:

- Identification of the technical challenges for cost-efficient independent access to space and adaptation of hybrid propulsion technologies for orbit transfer. This system study will provide guidelines for the R&D activities (definition of driving factors and specification of performance indicators),
- Technical coordination of R&D activities in critical technologies, consolidation and evaluation of R&D results and performance assessment,
- Definition of the testing strategy,
- Build the exploitation plan, based on market analysis, competitive positioning, cost modelling and cost-benefits analysis and shape the development roadmap.

Advanced research activities on critical parts and technologies address four main domains: Combustion chamber, High endurance nozzle, Catalytic injector, Production, storage and use of high concentration hydrogen peroxide. Those are key drivers to achieve a reliable and efficient spacecraft transfer system.

HYPROGEO WBS is organized with two levels:

- The high level Work Packages: WP 1, WP 2, WP 3, WP 4, WP 5, WP 6 and WP7. Level 1 forms contain an overview of the work and a consolidation of level 2 tasks,

- The task level: WP 12 is the subtask 2 of the WP 1. HYPROGEO description of work is thus detailed up to level 2

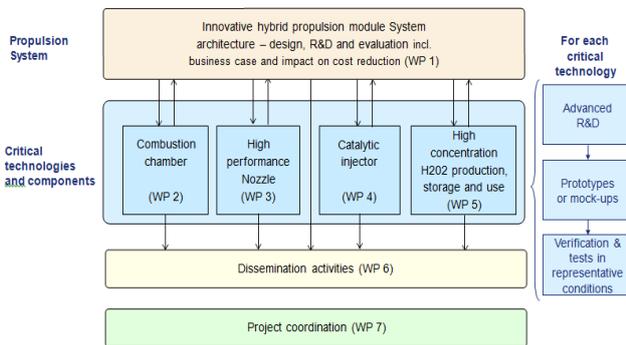


Figure 7: Overall work Logic

For each critical technology, similar work logic is proposed:

- Advanced R&D,
- Design and development of prototypes and breadboard
- Tests in representative environments

The work strategy is planned to last 3 years as shown on the road-map below:

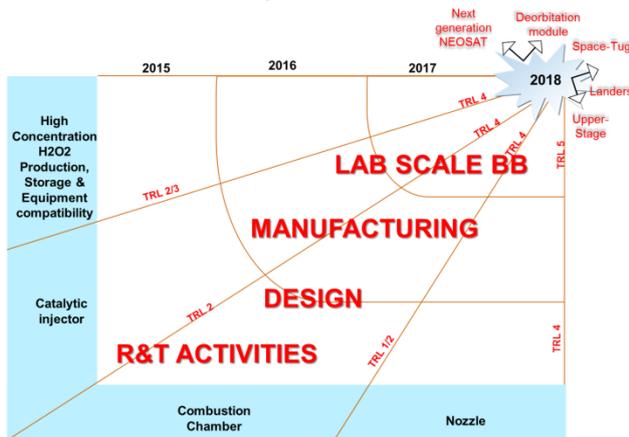


Figure 8: HYPROGEO Road-Map

The study also includes appropriate coordination and dissemination activities.

2.2 Exploitation Strategy

The exploitation plan has two dimensions (global and individual) and depends on the participant profile:

- For the Space industry players, either prime contractor (Airbus Defence and Space) or provider of systems and subsystems (Nammo, DELTACAT Ltd). HYPROGEO results will increase their leading position in all propulsion technologies (from system to equipment). In particular, the reached

maturity levels on the key technologies will foster development studies of innovative cost-effective spacecraft architectures (new apogee engines, upper stages or even disruptive architectures) to response to the highly competitive satcom market in the worldwide competition. For instance, NAMMO will reuse the results of the R&D and manufacturing activities on the C/C- SiC high endurance nozzle that will be used in their rocket development program,

- Other industrial actors, such as Evonik, the European leader of H₂O₂, will improve its competitive position in the European specialty chemicals industry to become an important supplier of environmentally benign propellants to the European space industry. The developed process design for high concentrated peroxide will help Evonik to implement a full scale production unit and supply the space industry. This is a major component of a future independent EU supply chain,

- The research and scientific organizations involved in HYPROGEO (ONERA, UPD, IOA, IVKDF, UOS) will benefit from the HYPROGEO project by transposing the new know-how gained in rocket applications to the design of an innovative combustion chamber for long duration burns of a transfer module. The results will allow them to position themselves as complementary cutting- edge partner for future projects related to hybrid propulsion applied to space applications. Dissemination activities and publication on peer review journals and international conferences, dedicated seminars to University students, dedicated seminars to High School students and publication on newspaper will reinforce their position with the international research community,

- For Spacetec, a consultancy company, the knowledge accumulated during the project will be valuable for future commercial contracts within the framework of the firm's ongoing contractual relationship with the EC or ESA.

In a more global perspective, the exploitation is clearly related to the preparation of development roadmaps integrating the hybrid chemical propulsion as a key component of the future propulsion programs in Europe (ESA, EU or national agencies). The complementary dimension with electric propulsion will enable cost-effective or even disruptive approaches for new generation of spacecrafts and satellites.

This is clearly the main justification of a H2020 program: the increased TRL level contributes to enable these new programs.

2.3 Communication Strategy

Spacetec disseminates the HYPROGEO project research results through various channels that include professional audiences, research forums and end user groups. Furthermore, Spacetec will be responsible for organizing a workshop during the project, in order to present to the general public the research results from the project. Dissemination is also done via publications of scientific papers in international conferences and peer- review journals, presentations at conferences and workshops.

Following table describes the dissemination plan:

Web site and social media:	A web site has been created for the public dissemination activities, in coherence with the dissemination rules. HYPROGEO proposes also an innovative approach of dissemination. In complement of the web site, social media, and in particular the professional social media such as LinkedIn and blogs will also be used in order to animate the community of interested users and stakeholders.
Project workshops:	Spacetec will organize the final workshop.
Workshops, conferences and scientific partners:	Scientific and industrial partners present scientific papers regarding the Project outcomes.
Other media:	- TV documentary and outtakes for HYPROGEO website.

Table 3: HYPROGEO dissemination strategy

3 HYPROGEO TEAM

3.1 Team Overview

Beyond the individual participants, HYPROGEO consortium has been built in order to achieve the project objectives and enable the expected impact with the following strategy:

- A consortium with a true European dimension with 14 partners from 7 countries: Belgium, France, Italy, Poland, Germany, Norway, United Kingdom,
- A project bringing together complementary profiles:
 - Space industry or large industry: Airbus Defence and Space, Nammo, Evonik;
 - Small and Medium Enterprises: DELTACAT Ltd, Spacetec;
 - Research organizations: ONERA, Von Karman institute, University of Padova, Polish Institute of Aviation, University of Strathclyde.
- A project with the relevant expertise needed to:
 - Study & design innovative space systems;
 - Perform advanced R&D activities in key technical areas;
 - Implement the relevant tests with specific facilities;
 - Drive the technological research with cost-benefits criteria

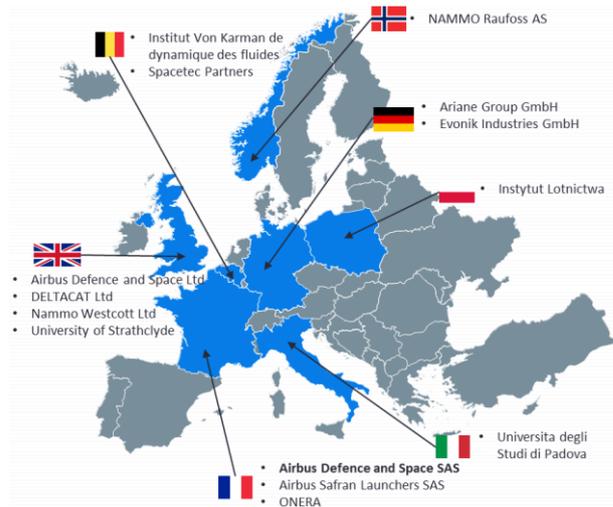


Figure 9: The European Dimension of Hyprogeo

- A project Committed to the scientific and operational exploitation of results and with the direct involvement of potential users: HYPROGEO industrial partners are either in charge of designing and developing space infrastructures and launchers or capacities supporting these activities. They are the first users of projects results. There are also indirect benefits for their customers, both at institutional and commercial levels and for the overall competitiveness of the European space industry.

3.2 Skills & Know-how

HYPROGEO consortium has all the skills required to perform this ambitious project, with a very good complementarity between the participants:

- Design of space systems (launchers and satellites);
- Propulsion and mechanical engineering;
- Mission and system analysis, trajectory design and optimization, Technology road mapping;
- Operation of space systems;
- Space propulsion and propulsion system for satellites;
- Modelling of propulsion systems;
- Strategy and competitiveness, cost – benefits analysis;
- Experience of FP7/H2020 or coordination of previous FP7/H2020 projects;
- Operation of large testing facilities;
- Expertise in High Test Peroxide.

The skills and know-how within the consortium is an asset for the quality of the R&D activities and the management of risks during the project.

3.3 Individual Participants

Table 4: HYPROGEO Partner Presentation

	Name	Country	Summary description
1	Airbus Defence and Space SAS (Airbus FR)	France	Airbus Defence and Space, 100% owned by Airbus Group is a worldwide leader in the space domain. Airbus Defence and Space is composed of four pillars business divisions: Space Systems, CIS, Electronics and Military aircrafts.
2	ONERA	France	Onera is involved in chemical space propulsion development since a very long time, with a recognized know-how on solid and hybrid propulsion concepts based on theoretical, experimental and numerical approaches. In particular, the Propulsion Laboratory Unit is equipped with several static firing test benches simulating solid and hybrid chemical propulsion engines.
3	Nammo Raufoss (NAMMO)	Norway	The Nammo Group is an aerospace and defence group specializing in high end products. Nammo has 2.200 employees and is present in 9 countries with 21 production Sites. Nammo Raufoss is situated in Norway and is the largest site of the Nammo Group. The Missile Products Division supplies rockets to separate the stages of Ariane 5, has its activities in Raufoss. The last 10 years, extensive development has gone into hybrid rocket motor technology.
4	Spacetec Partners (STP)	Belgium	SpaceTec Partners (STP) is a strategy, management and communications consultancy firm, focused on the space sector. STP is a unique boutique consultancy as its team combines years of consulting craftsmanship with in-depth expertise of the space industry and policy.
5	Evonik Industries AG Evonik RE GmbH (EVONIK)	Germany	Evonik is one of the world's leading specialty chemicals companies. Profitable growth and sustained value creation form the heart of our strategy. Around 80 percent of sales come from leading market positions, which we plan to expand further. We concentrate on high- growth megatrends, especially health, nutrition, resource efficiency and globalization.
6	DELTACAT Ltd	UK	DELTACAT Ltd is a world leader in developing small, demonstration-scale rocket thrusters with high performance and at low cost. DELTACAT Ltd designs, builds and tests very high performance thrusters that rely on hydrogen peroxide. Thrust levels of between 5 and 500 Newtons are DELTACAT's special focus of interest. DELTACAT's Managing Director is well known in Europe and the US for its work in this area.
7	University di Padova (UDP)	Italy	University of Padua is one of the most advanced experts in the world in the development of hybrid rocket based on paraffin wax. University of Padua have designed developed and flown the largest Hybrid rocket in Europe based on paraffin wax. University of Padua has experience both on experimental testing and numerical simulation of Hybrid Rocket Motor.
8	von Karman Institute for Fluid Dynamics (IVKDF)	Belgium	The von Karman Institute for Fluid Dynamics (IVKDF) is an international, non-profit, education and research institute devoted to the field of fluid dynamics. The Aeronautics & Aerospace has a long experience in the field covering atmospheric entry of space vehicles and the qualification of thermal protection materials under high thermal flux.

	<i>Name</i>	<i>Country</i>	<i>Summary description</i>
9	Airbus Defence and Space GmbH (Airbus DE)	Germany	Airbus Defence and Space GmbH is the German legal entity of Airbus Defence and Space. The Business Division "Propulsion & Equipment" is integrated inside Airbus Defence and Space in Space Systems and in this segment in Operations. Propulsion and Equipment is responsible for a great part of Airbus Defence and Space's launcher propulsion and for all in-orbit propulsion activities.
10 11	Ariane Group SAS & GmbH	France & Germany	ArianeGroup, formerly Airbus Safran Launchers, is a joint venture of the European aerospace company Airbus and the French group Safran, with its three core businesses: aerospace (orbital propulsion systems and equipment), defence and security with the objective of development and subsequent production of Ariane 6.
12	Airbus Defence and Space Ltd (Airbus UK)	UK	Airbus Defence and Space Ltd, 100% owned by Airbus Group is a Worldwide leader in the space domain. The Propulsion Engineering Team is deeply involved in all the programs (Scientific, Earth Observation and Telecommunication) in order to design and develop propulsion sub-systems using standard and innovative solutions. Propulsion concept design, system engineering, analysis, integration, test and in orbit support is centred at Airbus Defence and Space Stevenage.
13	Institute of Aviation (IOA)	Poland	IoA is the main design, research and development centre for the Polish aviation industry. The laboratory works on new, green propellants to space applications, as well as liquid, solid and hybrid propulsion. It has the possibility to produce highly concentrated H ₂ O ₂ in HTP standards (>90%).
14	Nammo Westcott Limited (previously MOOG ISP)	UK	Nammo Westcott is a leading provider of thrusters and space propulsion system components. The Nammo Westcott site is involved in design, development, build and testing of both R&D thrusters as well as commercially produced thrusters. Recent projects Nammo Westcott has been involved with include development and hot fire testing of thrusters from 1N to 1.1 kN.
15	University of Strathclyde (UOS)	United Kingdom	Founded in 1796 to create a second university in Glasgow, Anderson's Institution (today the University of Strathclyde) was founded "for the good of mankind and the improvement of science" and in 1800 became the birthplace of modern engineering education. The university has four faculties, the largest of which is the Engineering faculty which is the top ranked engineering faculty in Scotland.



Figure 10: HYPROGEO participants

4 HYPROGEO TECHNICAL OBJECTIVES

The quest for an independent and cheaper launch and space transportation solutions is a critical driving factor for the competitiveness of the European space-industry and its enabling effect on satellite applications and services. The confirmation of a significant reduction in recurring costs is the main expected outcome of the project.

The technical objectives of the project are to demonstrate that hybrid chemical propulsion, where a solid-state fuel is burned in contact with a liquid oxidant, can become a credible solution for operational space missions. One of the main targeted applications of the hybrid engine is a transfer propulsion system of a geostationary satellite. Hybrid propulsion is a good candidate if the achieved performance and reliability are similar to one of today's reference systems with a target price -30% lower.

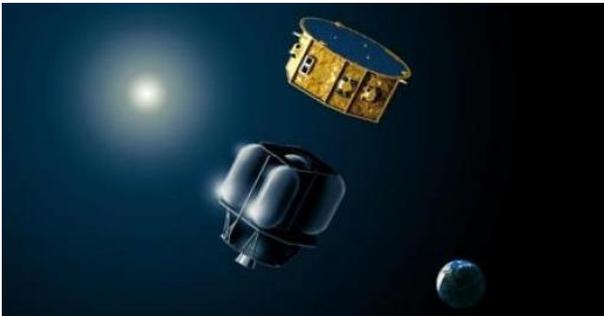


Figure 11: Example of kick-stage propulsion module. Credit: Airbus Defence and Space

By changing perspectives and targeting moderate thrust applications with limited operational duration opens a whole new application range for the hybrid propulsion system that can offer the potential of an inherently safe, mechanically simple alternative with lower life cycle costs compared to solids or liquids on their own.

The proof of concept of such engine concept (combination of propellants, specific impulse, thrust, regression rate) has been widely demonstrated (e.g. [4], [5], [6], [7], [8]) and led to the choice of polyethylene and hydrogen peroxide as preferred propellants for the considered application. The main innovative aspect and technical challenge of this project is the need for continuous hour long duration firings with medium thrust level instead of the standard launcher configuration using very high thrust and impulse delivered in a few minutes.

The target of HYPROGEO project is thus the development of a hybrid engine test bench featuring those key components and to perform tests in representative conditions.

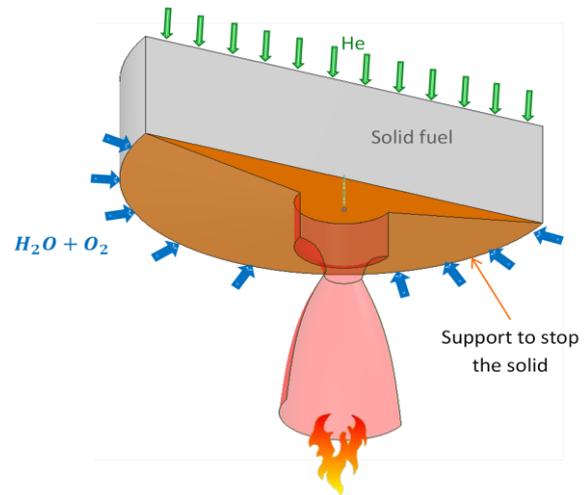


Figure 12: Principle of an implementation of an isochoric chamber with axial fuel combustion and radial oxidizer injection

The main operational objectives and work packages breakdown of HYPROGEO project are:

1. To study a new cost-effective propulsion subsystem for access to space using hybrid chemical propulsion technology and confirm the benefits as a complementary and cost-effective alternative to classical bi-liquid chemical engines and all-electric propulsion (WP1);
2. To provide significant scientific progress and increase the European excellence and know-how in critical technologies and components of an operational hybrid propulsion system:
WP2: isochoric combustion chamber;
WP3: high endurance nozzle;
WP4: high duty catalytic injector;
WP5: production and use of HTP.
3. Ensure dissemination of scientific results and internal & external communication, including general public (WP6).
4. Cooperative scientific achievements in all these technological domains are required in order to eventually propose the development of an operational system. A dedicated project management (technical & financial) is then integrated in the project as WP7.

HYPROGEO's main area of interest is a transfer module, both for transfer to the GEO orbit and as upper stage of a LEO launcher. When combined to current or future European launchers and to the emerging EP technology on satellites, module will increase the flexibility of the missions achieved by these launchers, improving then the competitiveness of the European access to space.

5 TECHNOLOGICAL DEVELOPMENT PLAN

To succeed in this long journey, the overall objectives have been cascaded to each work package (thruster subassembly development). Main objectives were then broke down each year, with the first year focused on:

- WP1 (system-level studies):
 - Selection of the preferred application based on technical and market evaluation
 - Definition of the main requirements of the main hybrid engine & associated subassemblies in term of targeted thrust level and efficiency, firing durations, accommodation constrains, number of re-ignition/cycles, etc.
- Consolidation of the overall test strategy implemented throughout the project
- WP2: Trade-off between several innovative hybrid engine combustion chamber concepts based on analytical, experimental and simulation data
- WP2,3,4,5: First characterization tests on key component technologies
- WP6: Definition and implementation of a communication and dissemination strategy

For the second period, the activities consolidated the development performed at component to integrate them at subassembly level and prepare the development of the final demonstrator, with the following main objectives:

- WP1: Feed an in-depth market analysis & technological roadmap. Update of the verification plan based on this results and key component technologies test results
- WP2: Combustion flow optimization (injection position definition to improve combustion efficiency, fuel regression uniformity, and limit the heat flux at the walls). Characterization of the fuel regression rate and demonstration of the combustion concept feasibility and ignitability through a subscale engine test
- WP3: Experimental evaluation of the nozzle erosion and design & manufacturing process optimization
- WP4: Identification of the maximal usable HTP concentration & catalytic injector design and test
- WP5: HTP storage stability & optimization of the crystallization production process
- WP6: Update of the communication & dissemination support
- WP7: Technical meetings organization & EU interface

For the third and last period, the work performed focused on the demonstration of the integrated technologies with the tests of the final demonstrators and confirmation of the technological achievements, with following main objectives:

- WP1: Finalization of market analysis, prepare a cost assessment & technological development roadmap
- WP2: Design, manufacturing and test of the demonstrator combustion chamber and integration of the complete demonstrator
- WP3: Design, manufacturing and test of the low-erosion nozzle to be integrated on the hybrid engine
- WP4: Design, manufacturing and test of the catalytic injector on the demonstrator engine
- WP4: Design, manufacturing and test of the monopropellant HTP auxiliary thruster
- WP5: 98% HTP production for the test campaigns, supply chain evaluation and basic engineering of the full scale production plant
- WP6: Update communication & dissemination support through a new edit of the project movie
- WP7: Technical meetings organization & EU interface

6 OVERVIEW OF THE PROJECT PROGRESS IN YEAR 1

In order to achieve the objectives defined in the frame of HYPROGEO project, the following activities have already been performed during this first year period together with the associated main achievements, scientific and technical results.

All these activities have been performed as planned by WP13 and coordinated by WP14 technical coordination & project management team in order to ensure coherency and compliance to WP12 requirements related to WP11 preferred mission.

6.1 WP1: System-level studies

6.1.1 Performed activities

A system level study has been performed to define the most promising applications for the foreseen hybrid engine and derive the targeted technical requirements.

6.1.2 Exploitable results & impact

Definition of a preferred application as an independent kick-stage module compatible with full or partial geostationary transfer of geostationary satellites, optimally complemented by a low-thrust phase provided by the satellite electric propulsion system itself after separation from the kick-stage, as assessed in [3] to maximize the payload mass in orbit while keeping acceptable transfer durations.

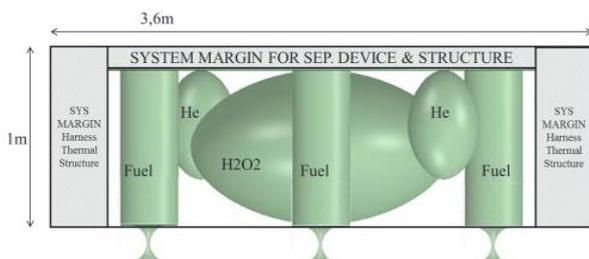


Figure 13: Preliminary accommodation of a propulsion module for accelerated GTO transfers

6.2 WP2: Combustion chamber

6.2.1 Performed activities

R&D activities to support the trade-off between several innovative hybrid engine combustion chamber concepts.

6.2.2 Exploitable results & impact

Numerical simulations of the piston concept, as detailed in [9] leading to a swirled outer radial injection.

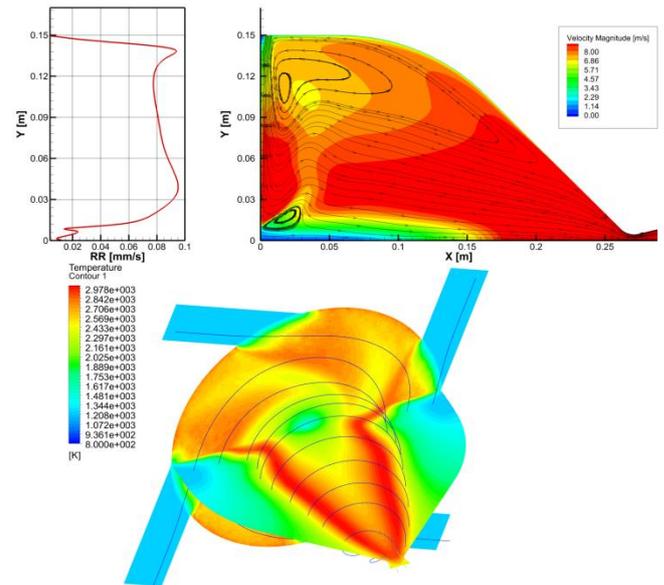


Figure 14: Various numerical simulations of the isochoric combustion chamber with computed fuel regression rate profile © UNIPD

Development & experimental tests of various concepts have been performed on a dedicated test-bench [11]. Identification of design drivers: regression rate, location of swirl oxidizer injectors, fuel behaviour under thermo-mechanical loads ...

A selection of a family of preferred combustion chamber concepts was performed, based on the numerical analyses and experimental firing results.



Figure 15: Post-test inspection of several concepts of isochoric combustion chambers © Onera

6.3 WP3: High endurance nozzle

6.3.1 Performed activities

Identification of operating conditions & optimization of the nozzle inner shape.

Manufacturing tests of the nozzle and characterisation of the nozzle materials.

6.3.2 Exploitable results & impact

Initial geometry of the nozzle defined through coupled fluid/solid numerical simulations.

Collaborative definition of the nozzle diameter at the combustion chamber interface and throat diameter with related sub-assemblies and performance objectives aimed for the final breadboard to be tested at the end of the project.

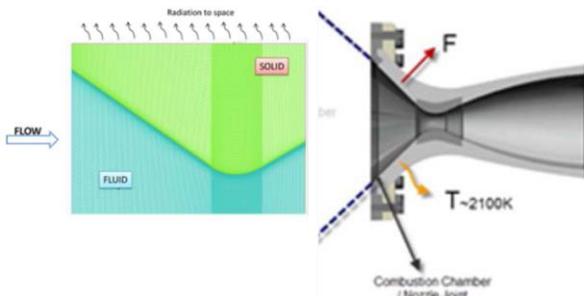


Figure 16: Numerical simulations of the nozzle for convergent-divergent profile optimization © UNIPD

Verification test firings performed to characterize C/C-SiC nozzle insert erosion (January 2016).

Preliminary results in [12] shows that no erosion was observed in the throat of the nozzle insert indicating that the need for an additional coating of the surface might not be necessary. To be backed up with additional more representative firings scheduled for April 2016.



Figure 17: Pre- & Post-firing inspection of a CC-SiC nozzle breadboard © Nammo

6.4 WP4: Catalytic bed

6.4.1 Performed activities

Design & manufacturing of a dedicated PX1 characterization catalytic bed followed by an experimental campaign in February 2016 [10].

6.4.2 Exploitable results & impact

Preliminary results demonstrate that PX1 catalyst is compatible with PROPULSE 980 HTP for long duration firing: More than 10min long firing duration was achieved, **for the first time in Europe**, using 45kg of 98% HTP without any significant PX1 catalyst bed degradation.

PX1 & PROPULSE 980 HTP have thus been selected as baseline catalyst and oxidizer for the hybrid engine concept & ACT thruster.



Figure 18: Long duration firing test of the PX1 characterization catalytic bed. © Deltacat Ltd - IoA

6.5 WP5: Near-anhydrous hydrogen peroxide

6.5.1 Performed activities

Definition and validation of the stabilizer package for 98% HTP to insure safe handling, long storage shelf, and high performance.

Experimental validation and optimization of the PROPULSE 980 HTP production process.

Identification of material candidates for an HTP based propulsion system compatibility tests with PROPULSE 980 HTP.

6.5.2 Exploitable results & impact

PROPULSE 980 HTP product: Material safety data sheet produced.

PROPULSE 980 HTP stabilizer package identical to standard 87.5% HTP: ensure chemical compatibility with PX1 catalyst.

Demonstration of transportability of PROPULSE 980 HTP.

Standard transportation procedures used for delivery of PROPULSE 980 HTP to IOA institute for PX1 characterization bed test campaign.

Identification of the best parameters of the crystallization based production process.

Production & delivery of 45kg of PROPULSE 980 HTP to IOA institute for PX1 characterization bed test campaign.



Figure 19: PROPULSE 980 HTP crystallization process. © Evonik

Nitinol, AlMgSc alloy 5028, Inconel 718 (ALM), & TFM / PFA based flexible membrane compatibility tests on going.

Nitinol has been found to be not compatible with HTP. However, preliminary results for AlMgSc alloy 5028 after 2 week exposure to PROPULSE 980 HTP are positive.



Figure 20: Material compatibility tests with HTP © Airbus DS GmbH

6.6 WP6: Dissemination & communication

6.6.1 Performed activities

Development of the HYPROGEO visual identity & website.

6.6.2 Exploitable results & impact

Videos & interviews of each experimental test campaigns.

Online publication of HYPROGEO project website: www.hyprogeo.eu, including Member's area for file sharing, public news and photo gallery and a kids' corner as hands-on experiments "fly your own hybrid rocket" will be organized in various European locations.

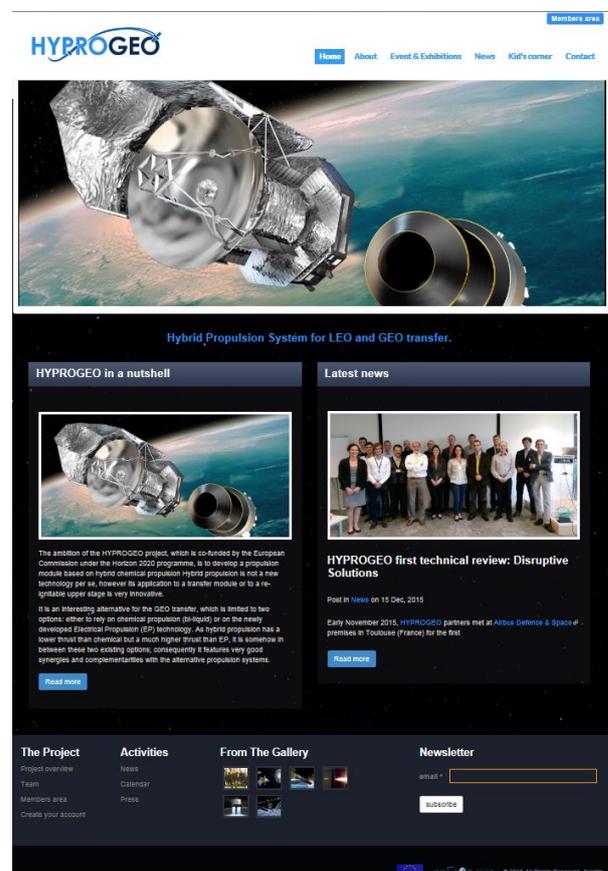


Figure 21: www.hyprogeo.eu website homepage

7 OVERVIEW OF THE PROJECT PROGRESS IN YEAR 2

7.1 WP1: System-level studies

Following the preferred application definition in year 1 and the specification of the required hybrid engine, the technical coordination of the project updated the definition of the test strategy and the verification plan in order to demonstrate feasibility and investigate the critical design parameters that will be required for the final demonstrator.

The need has been identified of an intermediate engine dedicated to combustion chamber concept validation and regression rate measurement. This facility will be used to confirm the CFD simulations of the combustion chamber and define the sizing parameters of the injection influencing the combustion and fuel regression [13].

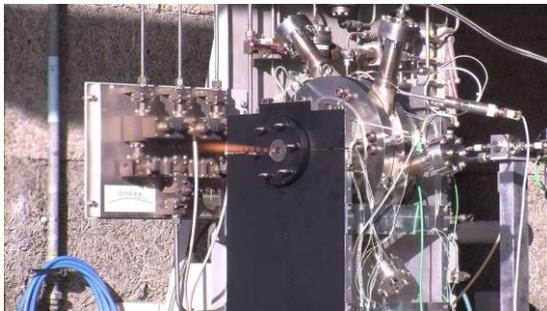


Figure 22: Intermediate MHYCAS engine hotfiring test – Credit: Onera

7.2 WP2: Combustion chamber

R&D activities were performed to support the design and sizing of the final breadboard engine, with the choice of the combustion chamber material (Inconel 625 for its highest strength at high temperature), the development and experimental tests on a dedicated test-bench (MHYCAS engine). Main exploitable were the successful regression rate law correlation from WP26 test results with determination of design-drivers and parameters of major influence [13].

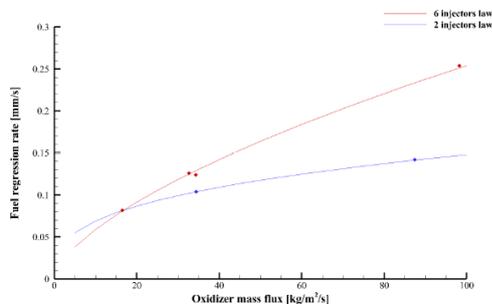


Figure 23: Regression rate law correlation from WP26 test results © Onera

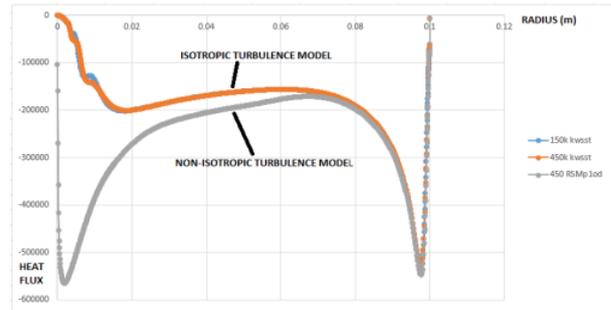


Figure 24: Correlation of CFD computations with WP26 test results to optimize the combustion chamber geometry, fuel regression uniformity and wall heat fluxes © Onera

7.3 WP3: High endurance nozzle

Definition of nozzle internal profile based on CFD computations.

Optimization of the manufacturing process

Definition of the overall geometry and interface with the combustion chamber for the final BB.

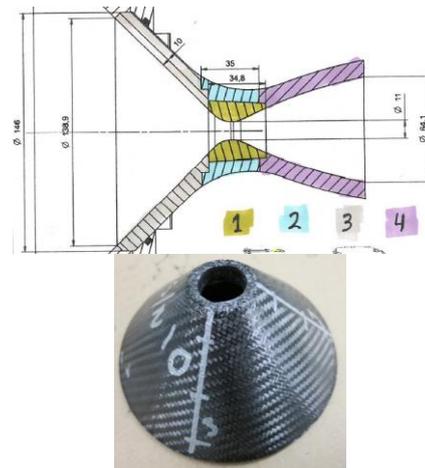


Figure 25: Design description of the different parts of the CC-SiC nozzle © Nammo

7.4 WP4: Catalytic bed

After validation of the compatibility of the 98% HTP with the PX1 catalyst during the test of the characterization bed at loA, year 2 activities were focused on the design of the monopropellant 10N ACT thruster and the hybrid thruster catalytic injectors (design, manufacturing and test of the 200mm inner diameter injector for the MHYCAS thruster in stainless steel 316 and design of the 250mm Inconel one for the final demonstrator).

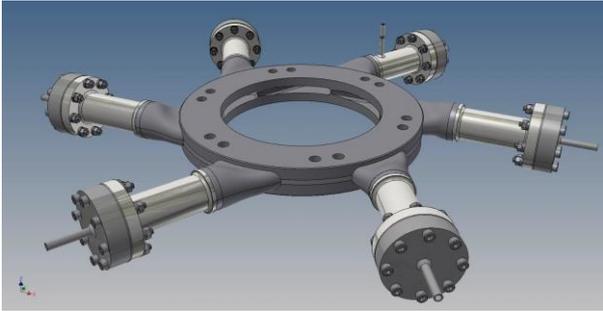


Figure 26: Design description of the catalytic injector and integration on MHYCAS hybrid thruster test facility © Deltacat

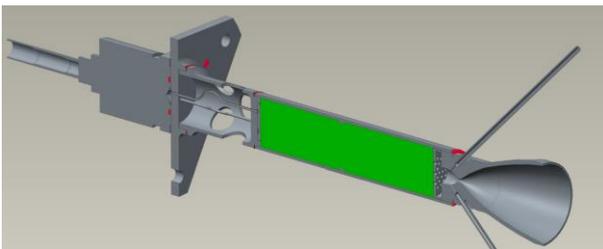


Figure 27: Design description of the ACT thruster © Nammo

3D printed injector ducts were successfully integrated and tested within the catalytic injector of WP26 breadboard engine during the whole campaign of 22 hotfire tests.

7.5 WP5: Near-anhydrous hydrogen peroxide

Final specification of the PROPULSE 980 HTP has been defined, as compatibility of PROPULSE 980 HTP with PX1 has been demonstrated.

The major activity of this work package was the optimization of the PROPULSE 980 HTP production process, with the construction of the aluminium pilot plant



Figure 28: PROPULSE 980 aluminium reactor for HTP crystallization production plant. © Evonik

7.6 WP6: Dissemination & communication

Development of the HYPROGEO visual identity & website.

Scientific communication in conference papers, with several papers and posters presented at the Space Propulsion'16 conference in Rome.

Videos & interviews of each experimental test campaigns, with a first public edit of the project video for the Mid-Term review, shared on YouTube.



Figure 29: HYPROGEO Mid-Term video

8 OVERVIEW OF THE PROJECT PROGRESS IN YEAR 3

8.1 WP1: System-level studies

Main activities performed in WP1 during year 3:

- Implementation of WP26 extension to anticipate validation of the fuel feeding system
- Management of the integrated test campaign preparation and planning to respect the H2020 project deadline
- Evaluation of the technical achievements for a system level perspective
- Cost Benefit Analysis, business and exploitation plan and recommendations for future roadmaps

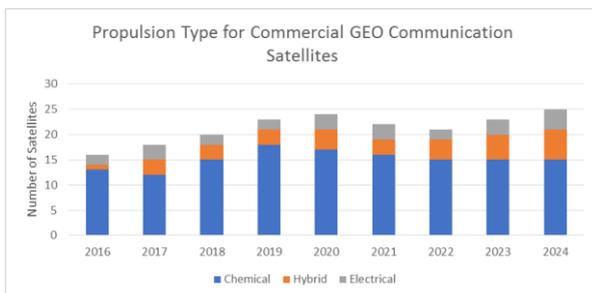


Figure 30: Market analysis of the HYPROGEO kick-stage

8.2 WP2: Combustion chamber

Main activities performed in WP2 during year 3:

- Combustion chamber CFD analysis to predict the swirled flow behaviour and internal thermal environment

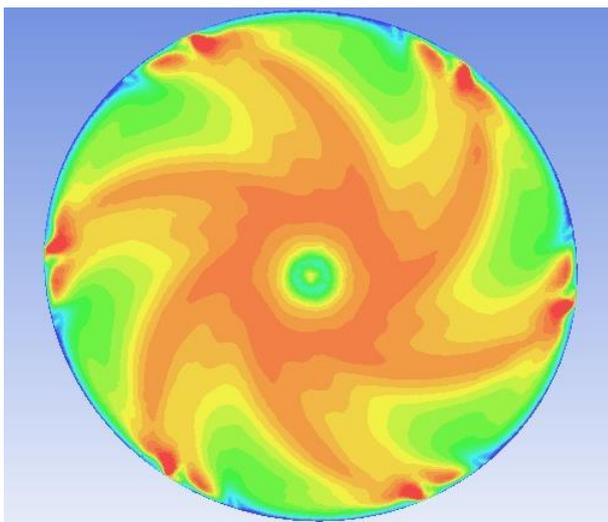


Figure 31: adimensional regression rate on fuel surface (red max, blue min) of the MYCHAS engine geometry © UNIPD

- Combustion chamber design and thermomechanical strength justification

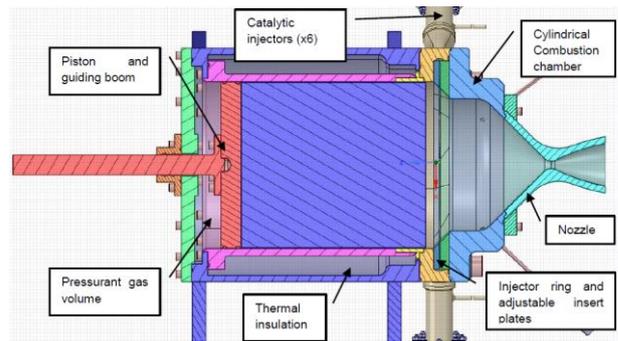


Figure 32: SuperMHYCAS demonstrator design description

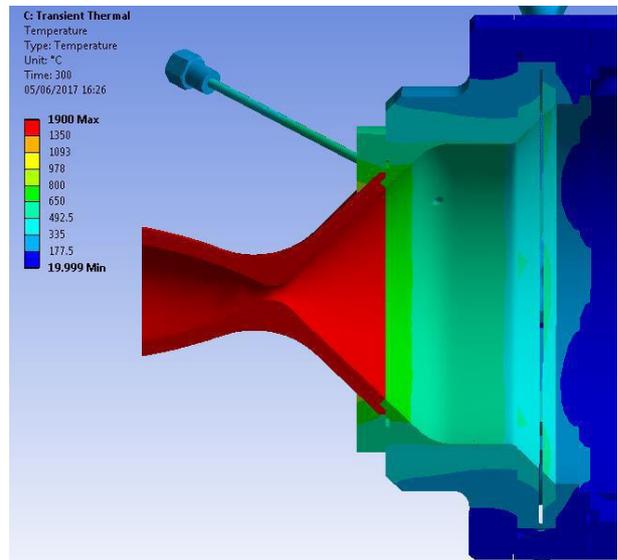
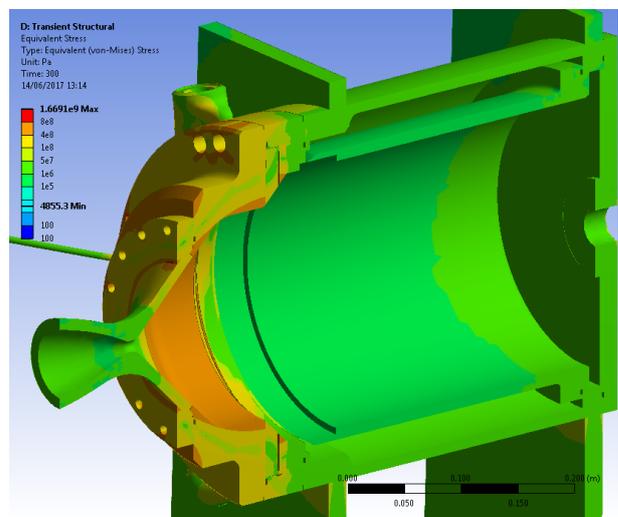


Figure 33: Thermomechanical analysis of the hybrid engine combustion chamber © Airbus

- Experimental validation of the fuel feeding system on the small-scale breadboard
- Manufacturing of the combustion chamber
- Integrated tests of the combustion chamber and the catalytic injectors [15]

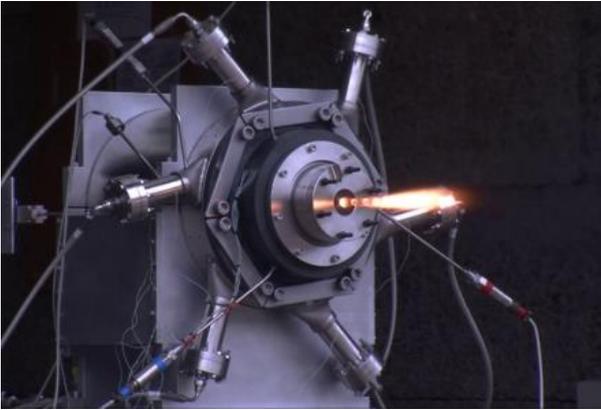


Figure 34: SuperMHYCAS long duration hotfiring test campaign © Onera

8.3 WP3: High endurance nozzle

Year 3 was focused on the manufacturing of 2 CC-SiC nozzles for the test campaign of the hybrid engine demonstrator.

The first one is dedicated for long duration firings at ambient conditions with the objective to demonstrate the low erosion and long-term endurance of the material to the high pressure, thermal load and oxidizing environment.

The second is adapted in its diverging area to the primary vacuum in Onera test chamber.

As Nammo detected a porosity issue of the material which lead to a leak rate above acceptable levels, these parts have not currently been integrated on the demonstrator, and are being reworked to solve the issue.



Figure 35: Design description of the different parts of the CC-SiC nozzle © Nammo

8.4 WP4: Catalytic bed

Main activities performed in WP2 during year 3:

- Manufacturing of a catalytic injector for the hybrid demonstrator engine compatible with long-duration firings & tests on the integrated engine.

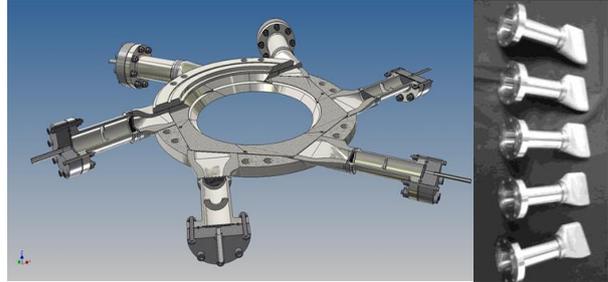


Figure 36: Design description of the catalytic injector and integration on superMHYCAS hybrid engine demonstrator © Deltacat

3D printed injector ducts in Inconel 625 were successfully integrated and tested within the catalytic injector of the superMHYCAS engine during the whole campaign of 11 hotfire tests, with a cumulated firing time over 1000s [14].

- Design and manufacturing of an ACT thruster with a low-loaded catalytic bed and Hotfire
- Testing in the vacuum test facility.

In total the thruster saw 2 hours of On Time (in both steady state and pulse mode), 50 kg or 34 litres of 98% HTP and accumulated 8,261 pulses. The thruster performed very well and many of the key requirements that were tested were achieved or exceeded. At the nominal design point of 22 barA inlet pressure the thruster is producing a thrust of 13.07N and an Isp of 182.7 seconds. The gas temperature is 908°C.

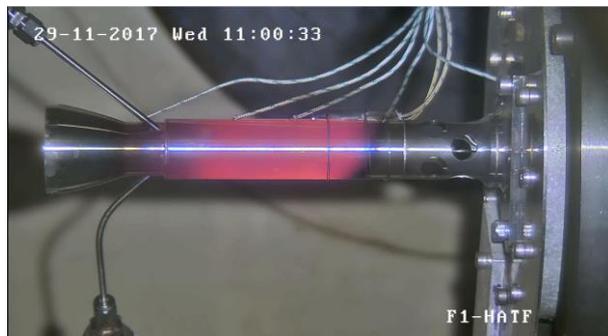


Figure 37: Hotfire test under vacuum of the 10N ACT thruster © Nammo

8.5 WP5: Near-anhydrous hydrogen peroxide

The major activity of this work package was the 98% HTP production and delivery, with the production of 260kg of PROPULSE 980 (98% HTP) at a production rate of 8kg/day:

- Delivery of 60kg of PROPULSE 980 HTP to Nammo Westcott ACT test campaign
- Delivery of 200kg of PROPULSE 980 HTP to Onera for the hybrid demonstrator test campaign



Figure 38: 12.5l Aluminium can for PROPULSE transportation. © Evonik

8.6 WP6: Dissemination & communication

Scientific communication in conference papers, with papers presented at EUCASS'17 conference in Milan and 5 papers to be presented at the Space Propulsion'18 conference in Sevilla.

Videos & interviews of each experimental test campaigns, with a last public edit of the project video for the Final Review, shared on youtube: <https://www.youtube.com/watch?v=5ZNLghWbads>



Figure 39: HYPROGEO Final project video

9 SYNTHESIS OF R&D ACTIVITIES & IMPACT AT SYSTEM LEVEL

9.1 Benefits and potential drawbacks of hybrid propulsion for system

As other hybrid propulsion system, the one tested provides both:

1. A good compactness, higher than between liquid propulsion but lower than solid propulsion,
2. A good safety with regards to pyrotechnic issue and thanks to segregation of fuel and oxidizer,
3. Pulse capability thanks to liquid valve on H2O2 side,
4. Throttling capability through use of specific oxidizer valve to control liquid mass flow,
5. Potential low cost propulsion thanks to:
 - a. low cost of basic material for propellant(s)
 - b. low cost operations (no pyrotechnic constraints and no toxic component)
6. Correct reliability, higher than between liquid propulsion, thanks to a reduced number of components, but lower than solid propulsion,

NB1: Even if there is a good compactness with hybrid, combination of thruster and fuel storage in a single part leads to a large monolithic volume. Layout could suffer of such a volume depending on the spacecraft architecture.

NB2: actual chosen propellants allows reaching high level of theoretical specific impulse level, This level is located on high side of solid propellants Isp range and is close to level provide by storable liquid propellant(s).

Low cost is potentially mitigated in 98%H2O2 use case due to:

1. Final industrial process needed to get high concentrated and pure hydrogen peroxide, which could have an impact on oxidizer cost, However, PROPULSE980 is already commercially available with the pilot plant at a price comparable to traditional propellants (Hydrazine).
2. Harsh selection required about materials used on propellant storage and distribution (for compatibility issue) and those used on catalytic bed and combustion chamber (for thermal and integrity issues),
3. Detailed and complex operations to clean potential contamination leading to H2O2 decomposition.

In addition to these classical hybrid propulsion characteristics, there are some specific potential

technical positive and negative impacts identified at system level and linked to this suggested new hybrid propulsion principle:

1. To keep a maximal and constant specific impulse thanks to a mixture ratio always in the optimal range,
2. To get a low and constant reactivity along all thruster life. Indeed, linked to low constant combustion chamber volume, thrust rise delay and thrust decay duration are minimized.
3. Long duration capability. Especially with regards to solid propulsion, which offers high thrust but on limited duration mainly linked to thermal problem, new principle reduces high thermal exchange areas around combustion chamber. In addition heat flux is partially blocked thanks to cooling brought by oxidizer mass flow thanks to the swirled injection which pushes the flame to the center axis of the combustion chamber.
4. Constant thrust over long durations firings. This capability is already offered by some classical hybrid systems, but only for short firing duration. For example, using a cavitating nozzle on liquid H₂O₂ feeding system, Nammo provides hybrid propulsion system with a quasi-constant thrust level, but not scalable to longer firings (fuel grain consumed thickness and exposed area increasing overtime in a radial combustion configuration)
5. Potential cost increasing linked to additional fluidic components. Indeed a pressurization system is needed in applications with long firings and multiple restarts, to guarantee solid fuel block motion during combustion. That system shall then be able to be depressurized at the end of the firing sequence to avoid fuel extrusion during soak-back to ensure a safe restart with constant combustion front parameters.

9.2 Technical issues of present principle

To meet all these paper advantages, some technical points have to be solved:

- Removal of pre-firing phases: in order to meet good level of temperature a pre-heating phase is implemented before nominal firing process. During this delay thrust level is reduced and thruster is running in monopropellant mode.
- Removal of post-firing phases: in order to get a correct fuel burning extinguishment and/or

feedline line draining a post-firing phase is implemented. During this delay fuel motion is stopped and thrust level decreasing needs few seconds which will be solved on a flight design by a positioning of the valve closer to the HTP decomposition chamber inlet.

- To remove central hole digging on fuel block during firing. This hole size is increasing with firing time duration. It means an un-mastering of combustion area and fuel mass flow.
- Re-ignition demonstration

An overall technology evaluation has been performed with the following compliance matrix with respect to the system-level needs, confirming the interest of the technology and the need to continue development effort & demonstration of the thruster capabilities, perturbed by the planning issues faced near the project deadline.

Table 5: System-level technology evaluation

Parameter	Notation	Remarks
Environment	●●●○○	No vacuum test
Propellants	●●●●●	OK
Mixture ratio* (-)	●●●●○	Difficulty to keep MR in a reduced range for long firing
Thrust (N)	●●●●◐	Same order of magnitude than goal
Isp* (s)	●●●●○	Linked to comb. efficiency and complete nozzle in vacuum
$\eta_{\text{Combustion}}$ (-)	●●●○○	87 to 92% < 95%
η_{Nozzle} (-)	●●○○○	Complete nozzle not tested. Problem of material leak tightness
Chamber pressure (bar)	●●●●●	A reference pressure level was defined and tested
Thruster size (w long nozzle)	●●●●◐	Capability to meet required size is demonstrated
- Number of firing - T _{Off} (between 2 T _{ON})	●●◐○○	Capability to perform hot restart demonstrated, Capability, for structural part, to withstand heat soak-back shall be solved with relevant structural material, Difficulty to perform cold restart with same fuel bloc.
Cumulated firing	●●●○○	Linked to previous points, ~1000s cumulative firing already achieved
Reactivity and Mass	N/A	No requirement
Synthesis	3,6 / 5	Soon to be improved with a suitable nozzle Some points to be solved but no blocking point identified

9.3 Present, expected and required performances level

Table 6: Hybrid demonstrator test results evaluation and extrapolation to the flight system needs

Engine Parameters		Tests Results					Extrapolation***	Requirement	Discrepancy	Remark
Throat Diameter	[mm]	11,5					13,7	N/A	N/A	Test: design value, not actually measured
Internal chamber diameter	[mm]	250					298	< 800 mm	37%	Test: location of pressure sensor: 190mm
Ext. Ch. Φ (w/o inj)	[mm]							< 800 mm		
Ext. Ch. Φ (with inj.)	[mm]							< 800 mm		
Chamber Pressure*	[bar]	8.43	8	7.27	8.35	8.41	8.4	5 < Pch < 20 bar	OK	
Ox mass flow*	[g/s]	51.4	53.5	46.4	51	50.1	73.7		+ 3.6%	
Fuel Mass Flow*	[g/s]	10.07	5.75	11.31	7.08	8.35	10.2		+ 3.6%	Test: calculated from fuel weight measurement before and after firing
Mixture Ratio O/F**	[-]	5.1	9.3	4.1	7.2	6	7.2	7.2 < O/F < 7.5	OK	calculated via Ox and fuel consumption
Total Mass Flow**	[g/s]	61.5	59.3	57.7	58.1	58.5	84.0	79.7	+5.0%	
Eff. Throat Area**	[mm ²]	102.8	102.8	102.8	102.8	102.8	147.7		N/A	
Combust. eff. η_c **	[-]	86.2%	89.8%	80.4%	92.2%	90.8%	92.2%	95%	-2.8 %	
Cum. firing duration	[s]						180s	5000 s		
Number of firing	[-]							3		
Extrapolation (Area ratio = 400:1)										
Nozzle efficiency		92%	92%	92%	92%	92%	92%	97%	-5.0 %	
Vacuum.ISP	[s]	289.62	285.17	266.05	303.64	303.91	303.6	320	-5.0 %	
Vacuum Thrust	[N]	174.67	165.76	150.64	173.01	174.26	250	250	OK	Tested # -30%
Exit Nozzle ϕ	[mm]	230					272	< 800	OK	
Thruster length	[mm]						0.91m	< 1m		5000 s x 0.182 mm/s = 0.91 m

* : Measured Values from the test

** : Calculated Values from test measurements

Extrapolation on Isp is based on targeted mixture ratio and max tested efficiency and for targeted nozzle area ratio (vacuum and 400:1). Value of geometry is based on targeted thrust level.

There is no requirement about reactivity and about mass. Associated values are several second for time rise and time decay. No data about mass.

10 HYPROGEO PROJECT CONCLUSIONS

10.1 Project conclusions and impact

Both main objectives of HYPROGEO have been successfully demonstrated:

Study a new cost-effective subsystem for access to space using hybrid chemical propulsion technology and confirm the benefits as a complementary and cost-effective alternative to classical bi-liquid chemical engines and all-electric propulsion

Provide significant scientific progress and increase the European excellence and know-how in critical technologies and components of an operational hybrid propulsion system, in all four technical challenges:

1. Achieve high specific impulse:

- a. Fuel selection compatible with space applications and providing the highest theoretical ISP over 320s,
- b. Combustion efficiency with low regression rate, already close to the objective of 95% with 92.2% and improvement opportunities identified,
- c. Optimization of catalyzer and increase of HTP concentration at 98%.

2. Sustain long duration burn with medium thrust:

- a. Duration of burns (long firings / medium thrust), demonstrated up to 5min.
- b. Thrust stability.
- c. Geometrical arrangement of the fuel for long duration burns and constant performance with time.
- d. Compatibility and performance with the oxidizer hot decomposed gases.

3. Demonstrate the feasibility of using High concentration HTP:

- a. High concentration specificities (production, storage, decomposition, safety of operations) have been solved with the development of PROPULSE980 stabilizers by Evonik.
- b. Compatibility with material and subsystems, including the catalyzer material.

4. Integrate the hybrid propulsion within operational spacecraft and confirm the economic and Technical effectiveness

- a. Confirmation of cost impact and reduction of design complexity.
- b. Accommodation of the hybrid propulsion modules within the spacecraft.
- c. Geometrical arrangement of tanks.
- d. Reaction control thrusters
- e. Trade-off between upper stage and apogee engine scenarios.

The experimental demonstrations performed during the HYPROGEO project validated significant advancement in the respective Technologies Readiness Levels:

- **TRL4** for the hybrid thruster with the integrated demonstrator test campaign
- **TRL5** for the catalytic decomposition of 98% HTP
- **TRL5** for the 10N ACT engine using 98% HTP hotfire tested under vacuum
- **TRL6** for the production of 98% HTP

The remaining open points, mainly linked to the lack of the long endurance nozzle for the final tests, should be solved in the next months as soon as a leak-tight nozzle would be finalized by Nammo. With the same long endurance material, a nozzle adapted to vacuum conditions shall be also delivered to demonstrate a TRL5 of the complete hybrid engine, as very long firing (>10min) would then be achievable with a dedicated thermal management of the combustion chamber walls.

Thrust stability, through fuel regression uniformity, should be improved with work already on-going on the simulation capability of the combustion flow and optimization of the oxidizer injection flow.

10.2 Way forward & development roadmap

The development roadmap resumed as follows focuses then on 3 main parallel activities, to improve the efficiency and capability of this technology; demonstrate its relevance and effective performance; and qualify the building blocks by working on:

- Research activities:
 - improvement of the non-classical hybrid combustion chamber simulation capabilities
 - Optimization of the injection flow, circular distribution and form factor of the catalytic injector + combustion chamber related improvement
 - Combustion chamber material and/or thermal management
 - Target Regression rate uniformity for very long firings
- Development activities:
 - Material compatibility with HTP
 - Finalize development + Qualification of auxiliary thrusters with 98% monopropellant HTP (1N, 5N, 10N, 22N , ...)
 - Developments of hydraulic components in Europe compatible with HTP (Flow control valves, latch valves, filters...)
 - HTP tank development with a focus on long-term stability and venting management
 - Qualify a first HTP propulsion system for a LEO spacecraft
- Demonstration activities:
 - Long term in-orbit storage and decomposition (ISP decrease + outgassing)
 - In-orbit demonstration of a « quick-win » for hybrid: deorbitation module
 - Market analysis update to anticipate the newest trends in the need of kick-stages and hybrid propulsion for spacecrafts:
 - large LEO constellations & small GEO stacked platforms,
 - concurrence/synergies with future launchers direct-to-GEO capabilities
 - Compliance to French LOS regulation & ESA CleanSpace initiatives for space debris mitigation and controlled reentry deorbitation requirements

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