DOI: 10.13009/EUCASS2019-743

PROMETHEUS: Precursor of new low-cost rocket engine family

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Abstract
PROMETHEUS is the Precursor of a new liquid rocket engine family designed for low-cost, flexibility and reusability.
This project, undertaken through cooperation between CNES and Ariane Group, entered in ESA Future Launchers Preparatory Programme (FLPP) after the Ministerial Conference in December 2016, with Germany, Italy, Belgium, Sweden and Switzerland joining France in this programme.
The aim of project is to design, produce, and test an advanced low-cost 100-tons class LOx/LCH4 reusable Engine. This engine, designed for 1M€ recurrent cost, targets also flexibility in operation through variable thrust, multiple ignitions, compatibility to main and upper stage operation, and minimized ground operations before and after flight.
To reach those ambitious objectives, an extreme design-to-cost approach is mandatory, as well as innovative technologies and advanced industrial capabilities; among the major levers, there are the extensive recourse to Additive Manufacturing for the production of engine components, the introduction of a full electric command system and the on-board rocket engine computer (REEC) for engine management and monitoring.
In addition, Prometheus programme promotes the application of agile and frugal methodologies to get maximum profit in product innovation and value creation in operation.
Prometheus is key in the effort to prepare competitive future European access to space.

1. Context

Since its beginning, the Ariane 5 launcher has been a remarkable success. Ariane 5, while guaranteeing independent access to space for European states, managed to capture 50% of the open market for launch services. As early as 2020, Ariane 6 will continue this success at the half the cost of Ariane 5.
While Ariane 6 and Vega C, thanks to their reduced cost and versatile capabilities, will ensure the competitiveness of the European launchers in the short term, additional efforts must be invested in a longer-term view to prepare the future of the European launchers.
Concerning the future of Ariane, and in front of the increasing competition pressure, the system architectures [7] and technology activities [8] in ESA Future Launchers Preparatory Programme (FLPP) shall prepare the options that will ensure sustainable competitiveness, for instance aiming a launch cost reduction by a factor of two compared to Ariane 6, starting with the achievement of a liquid propulsion system allowing to drastically reduce production costs.

As one of the most central elements of launchers, liquid rocket propulsion has been a field of strategic interest in Europe for more than 40 years, resulting in the development of world-class competences in designing, modelling, manufacturing, testing and operating rocket engines. In Europe, liquid propulsion

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activities have mainly concentrated on LOX/Hydrogen and storable propulsion systems, powering all European launchers since Ariane 1.
The future evolutions of the European launcher family request to achieve recurrent cost reductions by up to a factor of ten compared to current cryogenic engines, together with new propellants, the systematic application of design to cost approach and innovative manufacturing technologies.
The analyses performed in the recent years in Europe confirm the interest of the combination of liquid oxygen and methane for liquid propulsion for launchers - compared to other hydrocarbons - including cost reduction and reuse capacity.
To start this new ultra-low-cost engine generation, a demonstration shall be first performed in order to bring the technologies and the LOX-Methane propulsion at a level of maturity enabling a fast and informed decision to move further toward more concrete applications, if justified by future European launchers competitiveness in front of concurrence.
The "PROMETHEUS" (Precursor Reusable Oxygen METHane cost Effective propUlsion System) demonstrator shall meet this goal.
This LOX / methane reusable prototype engine is considered as an essential building block in order to pave the way towards very low cost European system launchers. In the range of 100 tons of thrust compatible with the launcher propulsion for lower stage, and upper stage, this engine which will be produced in large series aiming at covering also different potential targets.
Furthermore, the reusability option, for future liquid boosters and/or lower stage, is under evaluation through Ariane Group studies currently ongoing. Design-to-cost and time-to-market are critical issues to be treated, but those studies shall also put emphasis on a coherent approach w.r.t. the current Ariane 6 launcher design.
The Ariane Next fleet under study, as shown in Figure 1, has the PROMETHEUS engine as baseline. It paves the way for the evolutions of Ariane at 2025 horizon, and for possible subsequent evolutions of Ariane configuration by 2030. The notional ESA/FLPP roadmap towards reusability is shown in Figure 2. To know more about the way the reusability option for Ariane Evolution is treated in the FLPP system studies, refer to the reference [7] which also includes main results and the preparation of in-flight reusable vehicle demonstration (THEMIS).

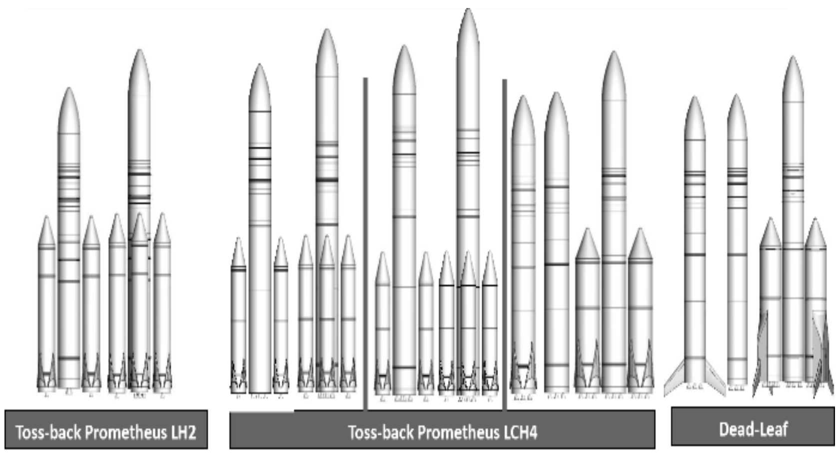

Figure 1: Ariane Next fleet with reusable stage as investigated in the frame of ESA FLPP

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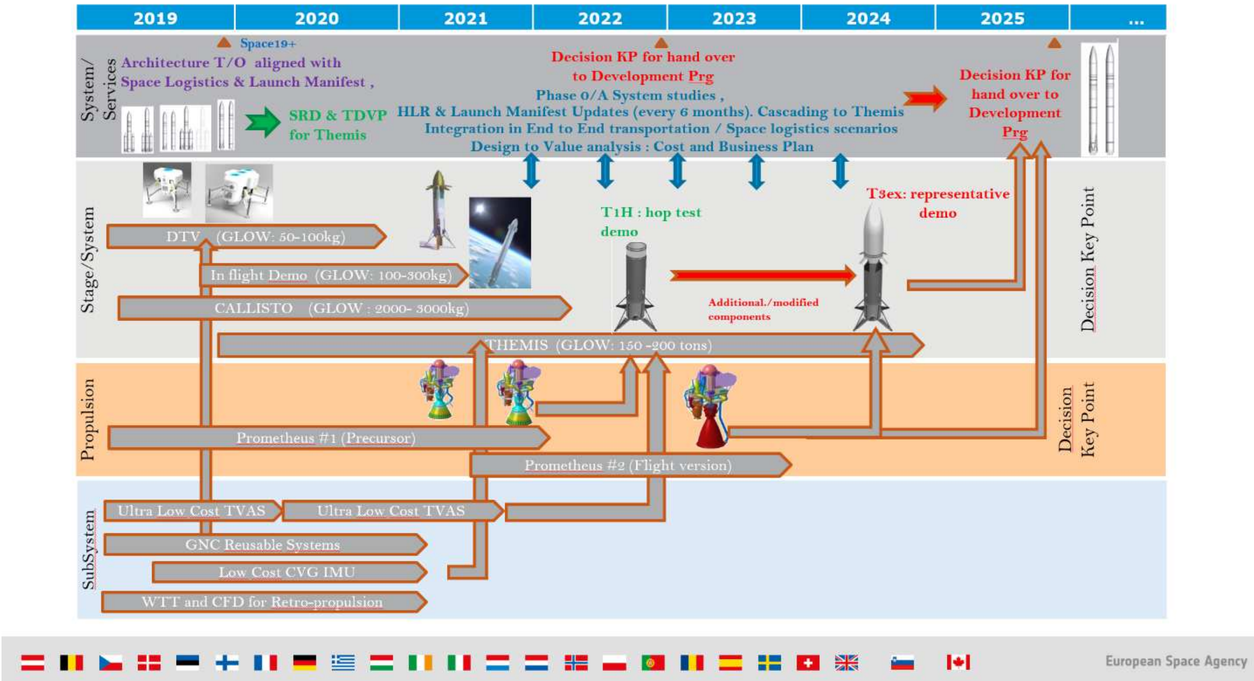

Figure 2: ESA/FLPP Reusability Roadmap

The high level requirements of the ultra-low-cost engine precursor aim at covering most of the needs (low cost, maturation of the LOX-Methane propulsion, light mass, thrust level, reusability features …) of an operational engine of a future launcher.

The main challenges assigned to this project are:

- Breakthrough in terms of cost (unit cost of derived operational engine lower than 1 M€ at a production rate of 50 units per year);
- Breakthrough in terms of manufacturing process and cycle (broad use of additive manufacturing, low cost subsystem technologies, participation of suppliers from non-space mass production industrial sectors, fast and robust assembly procedures);
- Challenging schedule to begin hot fire tests end 2020: combined agile and lean management scheme, including technological and organisational aspects, riskier development steps, short design cycle;
- Pragmatic design-to-reusability approach, engine’s health diagnosis in real-time to justify reuse without retrofit, large range throttlability, electric command, while maintaining the objective of a low recurring cost engine;
- Excellent thrust/weight ratio and full use of the performance potential of the LOX/methane propellants;
- Robust design engine, guaranteeing high reliability level including reuse;
- Versatile engine, in terms of application (single engine vs multi-engine propulsion bay, lower and upper stage), use in flight (re-ignition, thrust throttling …), ground maintenance (single use vs reusability).

A full scale demonstration in the thrust class of 1000kN is then proposed to address these objectives. This precursor shall be radically different in its design compared to current engines Vulcain and Vinci which were designed respectively in the 80s and 90s. This Oxygen/Methane reusable engine is also considered as a vector of transition towards the industry 4.0 in the field of large liquid propulsion.

DOI: 10.13009/EUCASS2019-743

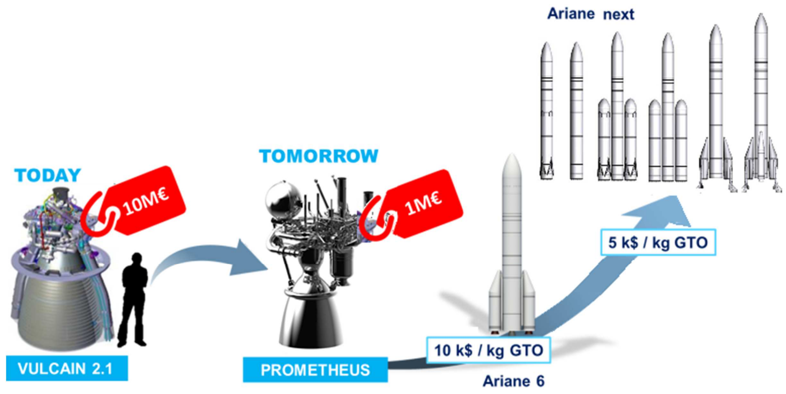

Figure 4: PROMETHEUS cost objectives

2. Programmatic status

The engine concept was initially mature in a national frame with a preliminary project of 2 years managed by the French Space Agency CNES , the Prometheus Project was transferred into the ESA/FLPP-NEO programme in 2017, following the decision taken during December 2016 Council at Ministerial level in Lucerne, where the Prometheus project received a total subscription of 88 M€.
European partners joined the Project as sub-contractors based on Ariane experience and industrial competitiveness perspectives:

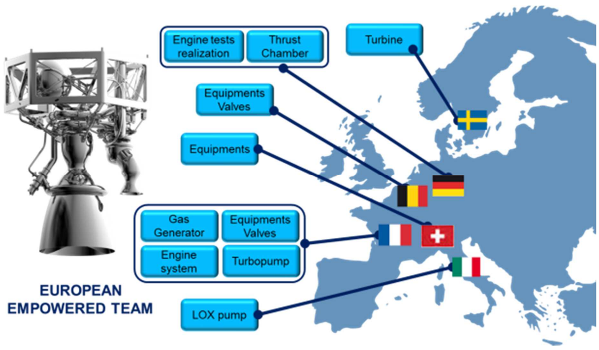

Figure 4: PROMETHEUS European team

The PROMETHEUS demonstrator development progresses quickly. In around one year, preliminary design phase focused on low cost approach has been performed and now the detailed design phase has been recently achieved allowing tostart the engine Hardware Manufacturing Review which is ongoing since last month. The ambition is to go as fast as possible into hot-fire testing of a full scale Prototype.
To achieve such an ambitious ultra-low-cost PROMETHEUS engine concept, the detailed definition and justification phase had been performed throughout an iterative spiral approach. A Design-to-Cost methodology has been deployed to ensure that the definition of the engine parts and components are being optimised accordingly to a process that includes the production strategy and the elementary cost objectives for each element of the engine.
In parallel, dedicated technological activities are carried out on specific components, such as valves, sensors or health monitoring based also on hardware fast prototyping (gas generator, turbopump, valves and thrust chamber components) and the necessary subsystems tests to validate definition/processes compatibility.
These activities will enable the achievement of the end goal of the project, namely the hot-fire tests at engine level end of 2020 at P5 test bench, DLR Lampoldshausen. P5 facility will be adapted to enable hot-fire tests of the PROMETHEUS engine in LOX-Methane. The Engine precursor will be hot-fire tested during two campaigns. This will allow validating and demonstrating the engine performances as well as some of the reusability aspects (ie: verification of the requirement associated to the cost of re-configuration).
The test campaigns shall bring the LOX-Methane propulsion technologies developed in the Prometheus project to the requested readiness in Europe.

DOI: 10.13009/EUCASS2019-743

3. PROMETHEUS description & mindset

3.1 Engine cycle architecture

The engine cycle is a gas generator cycle well mastered in Europe and in line with the low cost target objective of this project and the achievement of overall good performance. The reference engine cycle is presented below.

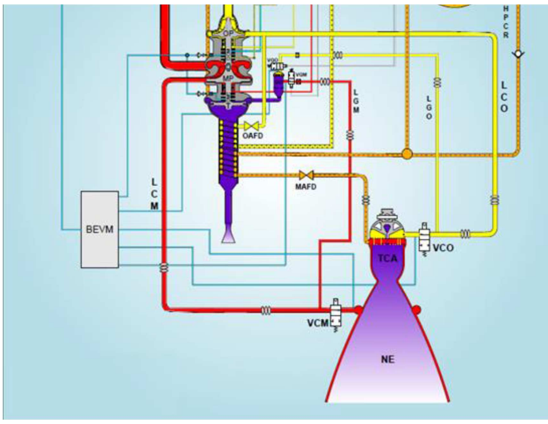

Figure 5: PROMETHEUS Engine cycle

This engine cycle consits of:

- A mono-shaft turbopump
- A gas generator
- Two chamber valves (VCO & VCM)
- Two gas generator valves (VGO & VGM)
- A regeneratively cooled combustion chamber

As depicted before, the engine is defined in order to deliver 1000 kN thrust in vacuum conditions. The engine shall be able to throttle down the thrust to approximately 300 kN at sea level. A challenging point is precisely the mastering of the low thrust operating point. The PROMETHEUS engine has the particularity to be versatile and ultimately reusable. The engine shall be able to operate on a large thrust range and electric control & command is necessary to do it. Control of the engine regarding thrust domain is based on a full electrical valves actuation. It is completely different compared to the Vulcain 2 engine full pneumatic actuation associated to a single operating point. PROMETHEUS engine will be equipped with a dedicated control unit, the REEC (Rocket Engine Electronic Controller), which will be able to perform engine control & command during flight, meaning throttlability from 1000kN down to 300kN of thrust. On top of this choice of full electrical command, Health and Usage Monitoring System (HUMS) is also part of the smart characteristics of PROMETHEUS in order to make possible immediate diagnosis, engine status and reusability potential.
Regarding the mechanical architecture, the choice has been made of a deported Power-pack incorporating turbomachinery and gas generator and the use of a simplified frame to ensure the stage/engine interface plug and play by simplifying the assembling, an easy maintenance and increase the engine agility during the spiral development (and after).
RAMS & MRO occupied also an important place as identification of the potential failure modes and the maintenance plan definition will directly impact the cost of the engine.

3.2 Extreme Design to Cost and Factory 4.0

Prometheus project is based on three main principles which are in rupture with past rocket engine design approaches. These are based on the following guidelines:

- Extreme design to cost such as in typical automotive industry
- Frugal development, keeping the innovation at the center

DOI: 10.13009/EUCASS2019-743

- A general agile approach in the program implementation aiming at reaching high product value with early results, as recourse to fast prototyping part production

Extreme design to cost is a major component of Prometheus approach in order to reach the ambitious economic recurrent cost targeted for this new engine family. The main low cost design choices are:

- Simplified cycle architecture
- Low cost mechanical set up
- Standard electrical command
- Simplified sub-systems
- Additive Manufacturing

Figure 6: Simplified engine setup

Development of this approach requests systematic detailed analysis of engine production cost in a representative factory, optimized for the production of this engine at high rate. The green-field approach makes possible anticipation of what will be the economic conditions for production in future model.
Identifying the optimal industrial organisation induced by the production rate and allowing to gain in flexibility, the refinement of industrial set-up needs, the optimization of all identified flows inside the manufacturing and the assembly are derived. Simplification principles are present at each level:

- Facilitate the supply chain: by using standard material, increasing manufacturing tolerance, simplify the parts definition
- Facilitate the production line: no pairing, no particular affectation, no waiting time during the assembly phase, improvement of anomaly recording process.

In the transition towards the advanced connectivity of the plant, the REEC is integrated in the control logic of the Engine, ensuring data exchange between the operator and the Engine. Automatic management of the maintenance activities of the engine after its flight will be also integrated in the REEC via the Health and Usage Monitoring System capabilities.
The high yearly production rate of the engine requires different industrial standards compared to Vulcain relying on digital factory.

As for HUMS, Additive Manufacturing (A.M.) process is one of the pillars of this industry 4.0 and as such gets an important place in the technologies promoted for PROMETHEUS.
Thus, as a result of the global optimization toward Extreme design to cost, Engine definition is the result of the definition of the industrial transformation process.

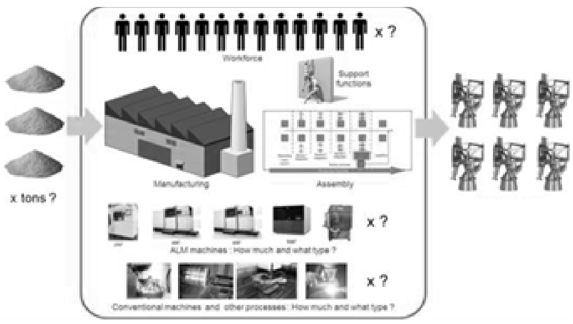

Figure 7: Greenfield Analysis

DOI: 10.13009/EUCASS2019-743

3.3 Additive Manufacturing Processes

So far, only few AM (Additive Manufacturing) parts have been employed as primary elements in rocket engines with a main functional and structural role due to the typical size limit of the LBM (Laser Beam Melting) machines.
As explained before, since one of the key technology approaches of PROMETHEUS engine is the extensive use of AM, fostering design flexibility and reduced production time, a large effort was paid in the development of AM processes for the production of low-cost engine components. Maximum capabilities of existing equipment for AM have been used for the production of large casing, pump impellers and turbines.
In the same way, new additive capabilities are developed for the production of engine components.
This effort is essential since the AM provides agility in the engine development: this process shortens the development cycle and feeds the spiral logic implemented in this project through rapid prototyping.

4. Technical status

End of 2018, in line with the initial roadmap, an important milestone for the program has been passed; the Engine Definition Review was conducted by ArianeGroup and ESA, supported by experts from the French and German space agencies, CNES and DLR.

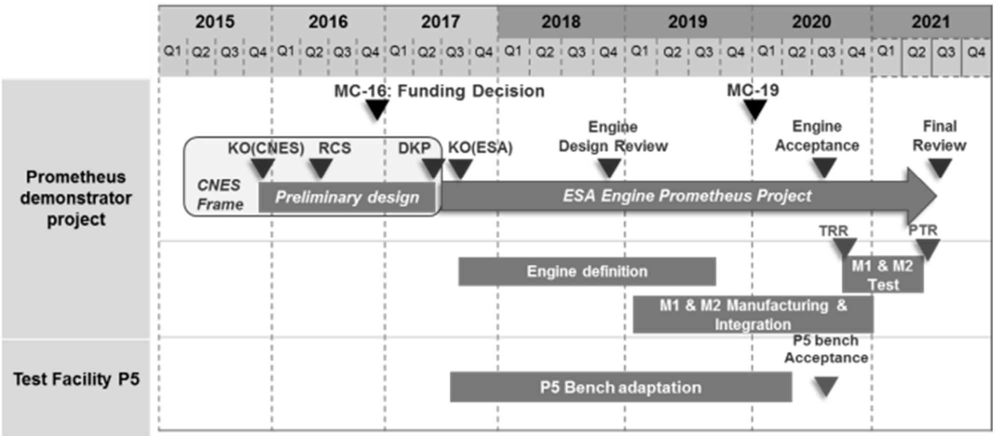

Figure 8: Main development steps of PROMETHEUS precursor

This review aimed at demonstrating the relevance of the design and the technological choices made, and at confirming the program’s ambitious recurrent cost objectives.
Presently, the program is facing the set of Manufacturing Readiness Reviews (MRR) which will open the way to the production of Precursor components.
Up to know, more than 2000 hours have been spent for prototypes manufacturing by 3D metal printing over dozens of parts (Turbopump housings, turbine disk, gas generator, valves, combustion chamber …) allowing to assess the feasibility of the concepts and increase the manufacturing maturity of the AM parts. Several parts have also undertaken dedicated tests campaign such as gas generator of valves which has been tested twice at P8 test bench at DLR Lampoldhausen.

4.1 Turbopump

The AM mono-shaft turbopump is a key technology. It leads to a drastic simplification of the engine layout and actively contributes to the cost reduction. The turbopump will take full advantage of the 3D printing process capabilities by production of highly integrated net shape components.

Major components have already been 3D printed by ArianeGroup and its partners.

DOI: 10.13009/EUCASS2019-743

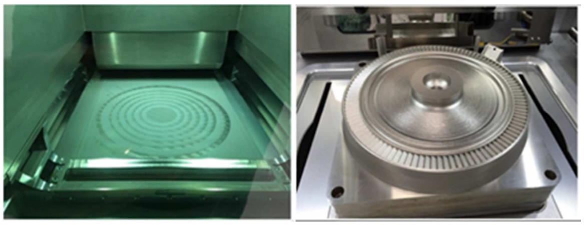

Figure 9: PROMETHEUS turbo-pump ALM process

In addition some components test campaigns have already been undertaken, such has cavitation test, to consolidate the design choices before entering in Precursor components production.

Figure 10: Turbo-pump cavitation test bench

4.2 Thrust Chamber

Concerning the thrust chamber, a trade-off regarding different concepts has been performed including igniter, injectors, liner part, ablative body, metallic nozzle extension.
ROMEO thrust chamber hot fire tested in 2016 by industry at DLR Lampoldshausen test centre is a significant asset and input for the engineering studies for topics like injection, transient, HF instability and throttling. Further tests on PROMETHEUS injectors have been performed in the frame of German national Research & Technology funding.
In parallel, notable achievements in thrust chamber new technologies maturation have been secured in 2018 in the frame of FLPP NEO Core. These results are an important milestone towards the production of a full additive manufacturing thrust chamber.

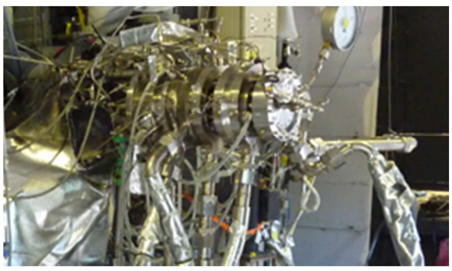

Figure 11: Injection element test bench

4.3 Gas generator

Concerning the full-AM gas generator, two test campaigns have been performed in 2017 and in 2018 at P8 test bench at DLR Lampoldshausen test center allowing to collect important information on the innovative design proposed. A large domain of operation has been explored with more than 1300s of steady-state operation performed. This information enabled to characterize extensively the performance of the gas generator in term of combustion efficiency, thermal stratification and stability margin (LF and HF) for the full operational domain. A last campaign is foreseen this summer to validate the final design and to test the valves control loop.

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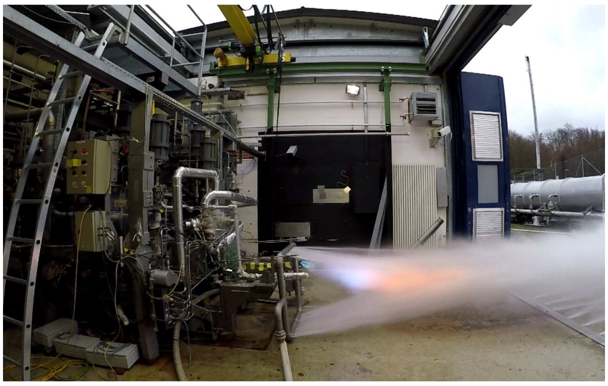

Figure 12: Prometheus gas generator test at DLR Lampoldshausen

4.4 Valves and equipment

The PROMETHEUS engine is constituted of 4 main valves of two families:

- The methane and oxygen chamber valves (VCM & VCO) which control the mass flow rate to the thrust chamber.
- The methane and oxygen gas generator valve, with integrated purge valves (VGO & VGM) which control the mass flow rate which feed the gas generator.

Valves benefit also of the ALM process and of the idea of simplifying or merging different functions. Additionally, COTS hardware is part of the design-to-cost strategy for the valves as well.
A first set of gas generator valves has been manufactured and integrated for testing in the last months. This allowed verifying the significant improvements obtained thanks to the extreme design-to-cost & design-to-manufacturing approaches with respect to Vulcain 2 hardware.

Figure 13: First VG body set manufactured

4.5. Engine Controller & HMS

The design of the PROMETHEUS engine controller (REEC), the definition of the regulation and HMS algorithms and the real-time model of the engine are under finalisation.
The validation of the electrical architecture and development of the engine control laws and regulation is set on the real-time test bench, known as ISFM Platform [6].
Software and Hardware-In-The-Loop test campaigns are foreseen in the coming months with the specific hardware (REEC and electrical actuators) developed for the demonstrator.
The PROMETHEUS REEC/HMS will be used for the engine firing test at DLR P5 bench at Lampoldshausen by the end of 2020. Therefore, a close partnership with DLR has characterised the past months activities in order to consolidate the electrical architecture and to converge on the interfaces between REEC and bench control system (SMCC).

DOI: 10.13009/EUCASS2019-743

5. Test bench preparation

P5 Test Bench modification for PROMETHEUS test campaign is under DLR responsibility with ESA contract. The challenge is not only to allow performing a test campaign with methane propellant, but also to do it as simple as possible (in respect of future ambitious cadence of engine tests per week), to ensure multi-boost capacity for each test (coming from foreseen reusable mission profile) and to perform the implementation in a short time with a test campaign starting end of 2020.
In addition, the modifications of P5 test bench shall not prevent comeback to a test bench configuration compatible with Vulcain2.1 engine test. In order to allow fast switchovers between propellants, it has been then decided very early in the project to have a separate methane tank.

The Preliminary Design Key Point has been held in November 2018 at DLR Lampoldshausen with the following outputs:

- New methane tank with baseline at 250m3
- Use of existing feedlines and hydrogen pressurization system
- Integration of the engine in the test cell in lowered position with a dedicated mechanical interface adapter.
- Increase of flare height in order to cope with the different LNG conditions, and use of a dedicated liquid/vapour separator

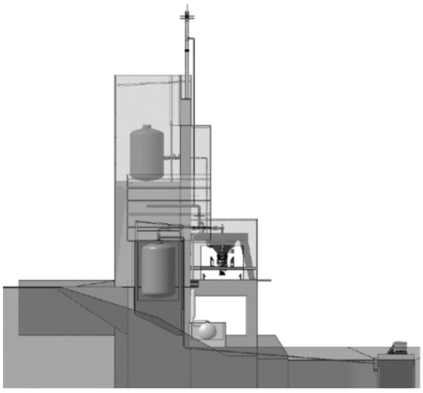

Figure 14: Preliminary general architecture concept (Courtesy of DLR)

During the Engine Definition Review held in December 2018, the bench adaptation has been considered in line with the ambitious demonstration plan.

The current design phase of the test bench preparation focuses on the detailed engineering of the new systems and of the modifications of the existent systems. This phase will conclude late 2019 with the Critical Design Key Point. Additionally, long lead items like the methane tank and its housing are currently procured with priority.

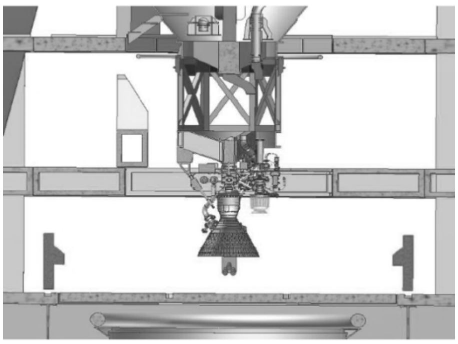

Figure 15: Sectional view of test cell (Courtesy of DLR)

DOI: 10.13009/EUCASS2019-743

Figure 16: Handling stand for PROMETHEUS engine installation at P5 (Courtesy of DLR)

The realization of bench modifications in the next phase will cover all the procurement, manufacturing, installation and tests/validations of modifications at P5. The aim is to guarantee the Test Qualification Review of P5 bench modifications by end of 2020 to be on time for the engine test campaign.

6. Conclusions

Preparing the future of space transportation ESA, CNES, DLR and ArianeGroup have started the development of a new low cost & reusable rocket engine demonstrator called PROMETHEUS to power the next generation of launchers.
Designed around a gas generator cycle, PROMETHEUS is an engine precursor using LOX/LCH4 of 100 tons vacuum thrust level aiming at ultra-low-cost engine target of 1 M€, with short manufacturing time, reusable, re-ignitable, and with a high throttling capability.
Throughout three major disruptive approaches, i) extreme design-to-cost approach, ii) generalized agility, iii) frugal innovation and development, the programme has already achieved important milestones to cope with the ambitious targets assigned to this engine.
These targets are considered today achievable for Prometheus project thanks to years of research and demonstration, enabling today new technologies such as the digital revolution or the additive manufacturing.
Redesign of industrialization schemes based on extensive use of ALM process is indeed one of the key to achieve the 1 M€ production cost.
The results already obtained tends to show that the 1 M€ production cost target objective is within reach. The Definition Review end 2018 confirmed the good trends.
Prometheus project, implemented within the ESA FLPP-NEO programme, will rely on an European industrial/institutional team fed by ambition and enthusiasm. The ambitious objectives for the coming years are very challenging for Europe. Prometheus project, success oriented, federates a new working methodology with the goal of preparing next ultra-low-cost engine generation but also future European industry.

7. Acknowledgements

The authors thank all the people from all entities directly or indirectly involved in this project for their remarkable work, their passion and their will to go further and push forward this project.

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