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PROMETHEUS® tests on T1Bench in Vernon - 10th EUCASS – 9th CEAS

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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 the ESA Future Launcher Preparatory Programme after the ESA Ministerial Conference in December 2016, with Germany, Italy, Belgium, Sweden and Switzerland joining France in the support of this Programme.
The aim of Prometheus® project is to design, produce, and test an advanced low-cost 100-tons class reusable Engine. This cost competitive Engine, designed for reusability, for flexibility in operation through variable thrust, multiple ignitions, compatibility to main and upper stage operation, and minimized ground operations before and after flight.

In early January 2021, following the visit of the French President Emmanuel Macron, an agreement preparatory to the testing of the new Prometheus® rocket engine at the Vernon site in Normandy was signed. This agreement, funded through the space component of the France Relance recovery plan in support to French industry, allowed to accelerate and de-risk the PROMETHEUS® test schedule whilst settling an agile stage test stand in ArianeGroup Vernon test area, the PF20-B, in an optimised synergy with the Future Launchers Preparatory Programme of ESA.

This paper presents the genesis of PROMETHEUS® tests on PF20-B / THEMIS-1Bench in Vernon, the status of PROMETHEUS® France Relance test campaign and gives insight to the stage test stand which was defined on frugal basis, taking maximum benefit of the elements made available by THEMIS stage first demonstrations.

1. Introduction

The leading objective of a European autonomy of access to Space as well competitive answer to the market is carried out by a new generation of European launchers Ariane6 and Vega-C for the next decade. However, it is crucial to

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invest additional efforts so as to prepare the future of European launchers and thus increase the competitiveness of the industry.

ESA through the Future Launchers Preparatory Programme (FLPP), CNES and certain other national space agencies in Europe implement both launchers systems' architecture studies and technology activities. These pave the way for options that target a substantial decrease of the launch cost (by a factor of 2 compared to Ariane 6). As a result, a full new liquid propulsion system was investigated, resulting in the launch of the development of a new engine family based on a demonstrator called PROMETHEUS®.

To accelerate the development of this engine, direct testing of the first engine at stage level has been identified as very challenging but making possible important breakthrough in terms of technical and methodologic approach.

This perspective was made possible thank to the development of THEMIS, a demonstrator of reusable stage as key element of European strategy toward new launch system developed in the frame of ESA FLPP, and the development of a specific stage test bench on ArianeGroup test area at Vernon thanks to France Relance support.

2. PROMETHEUS® : A new family of cost competitive reusable engine

To secure a step towards this new low-cost generation of engines, a demonstration approach was decided to bring High Thrust LOX-Methane propulsion at the right level of maturity in order to move towards applications.
This is why the PROMETHEUS® (Precursor Reusable Oxygen METHane cost Effective propUlsion System) demonstrator programme was launched under the momentum created by ArianeGroup and the French Space Agency CNES (Centrale National d'Etudes Spatiales) [3] and, thanks to the decision taken in December 2016 Council of ESA at Ministerial Level in Lucerne, ramped-up within the ESA/FLPP-Neo programme in 2017. This allowed European Partners, Safran Aero Boosters, GKN, DLR, AVIO, APCO to join the project as sub-contractors while ArianeGroup is prime contractor and design/demonstration authority. PROMETHEUS® footprint in Europe is given in figure 1.

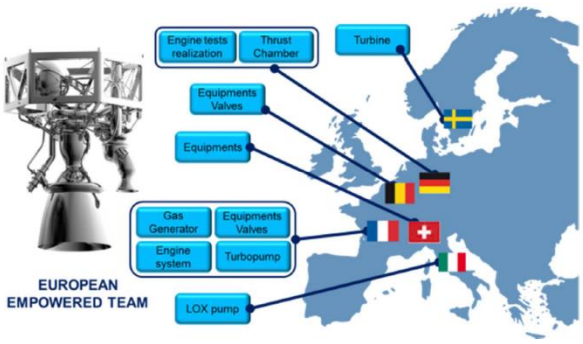

Fig. 1. European Contribution to Prometheus

The high level requirements of the low cost engine precursor aim at covering most of the needs (low cost, light mass, high thrust level, reusability features …) of an operational engine of a next generation launcher. The main challenges assigned to this project are:

- Breakthrough in terms of production cost resulting in breakthrough in terms of manufacturing processes and cycle with systematic recourse to additive manufacturing;
- Excellent thrust/weight ratio, and full use of the performance potential of the LOx/methane propellants;
- Robust engine design, guaranteeing high reliability level including large 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.

In addition to the high technical objectives, Prometheus development encompasses new methodologies such as:

- Iterative spiral approach for design/justification/prototyping/test of key components;

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- Agile development to realign continuously project management with production of short terms valuable results for the programme
- Design to cost/manufacturing to optimize the engine as a whole through the introduction of the production strategy as a key parameter, driving in a parallel approach engine design and green field factory design.

Thanks to the good results achieved during the design and justification phase, the last Council of ESA at Ministerial level in Sevilla end 2019 decided the undertaking of a new validation phase, aiming at settling the first step of industrialisation and making available of a first batch of engines for the reusability demonstrator Themis, developed in parallel by ArianeGroup under ESA FLPP contract.

The end-goal of the project is the hot-fire of the engine. Thanks to the opportunity presented by the THEMIS demonstration, in early January 2021, following the visit to the ArianeGroup site in Vernon by President of the French Republic Emmanuel Macron, an agreement preparatory to the testing of the new Prometheus rocket engine at the Vernon site in Normandy was signed. This agreement goal was to accelerate and de-risk the Prometheus schedule by beginning the first tests on the Vernon site at the end of 2021. It is funded through the space component of the France Relance recovery plan.
Following this de-risking test phase, the PROMETHEUS® tests will be performed at the P5 test bench in Lampoldhausen, DLR, Germany. This P5 facility will be ready end of 2023, after an important effort of adaptation to enable hot-fire tests in LOx-Methane.

3. PROMETHEUS® Programme

3.1 Engine Architecture

PROMETHEUS® engine is a gas-generator engine as for Vulcain or HM7B. This fully mastered cycle depicted in Fig. 1 is adequate to meet the requirements in terms of cost, performance and reusability.

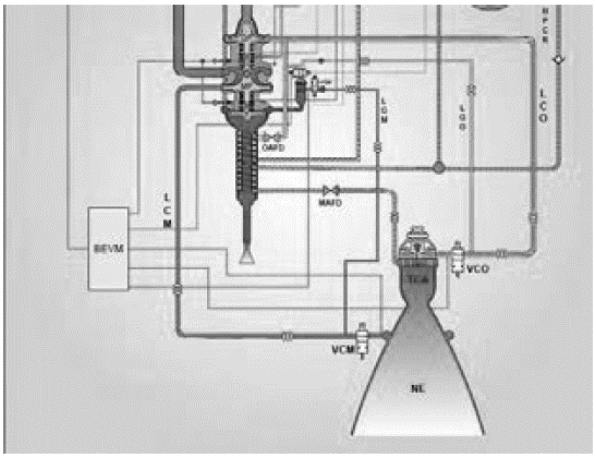

Fig. 2. PROMETHEUS® engine cycle

This engine cycle is composed of:
- A regeneratively cooled thrust combustion chamber;
- A gas generator;
- 2 chamber valves (VCO and VCM);
- 2 gas generator valves (VGO & VGM);
- A mono-shaft turbopump.

The demonstrator reference point is 1000kN in vacuum conditions with interval of operating thrust from 300kN at sea level up to 1100kN at sea level. This range of thrust is required for the reusability and versatility while reaching the low-thrust point is a technical challenge. To do so, a control of the engine is mandatory with electrical valves (chamber valves as well as gas-generator valves) that is an improvement with respect to Ariane 5 Vulcain 2 in-flight operating

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point control strategy. The control and thus throttability is performed with the REEC (Rocket Engine Electric Controller). Finally, contrary to Vulcain 2.1 engine, the engine architecture is based on a deported power-pack which incorporates the gas generator and the turbo-pump.
Furthermore, in order to ease the assembly and maintenance, a specific and simplified frame was created to ensure the Plug & Play stage/engine interface. Finally, as design to cost is a key factor for this engine, MRO (Maintenance and Repair Operations) & RAMS (Reliability, Availability, Maintainability and Safety) are taken into account through the identification of failure mode & maintenance plan definition.

3.2 Progress status

Due to CoViD crisis, delay in engine production was experienced; the first engine demonstrator was assembled in 2021 and made available in December of the same year as shown in Figure 3, in the historical Viking production building in Vernon where more than 1000 Viking engines were assembled for ensuring Ariane 1 to Ariane 4 flights.

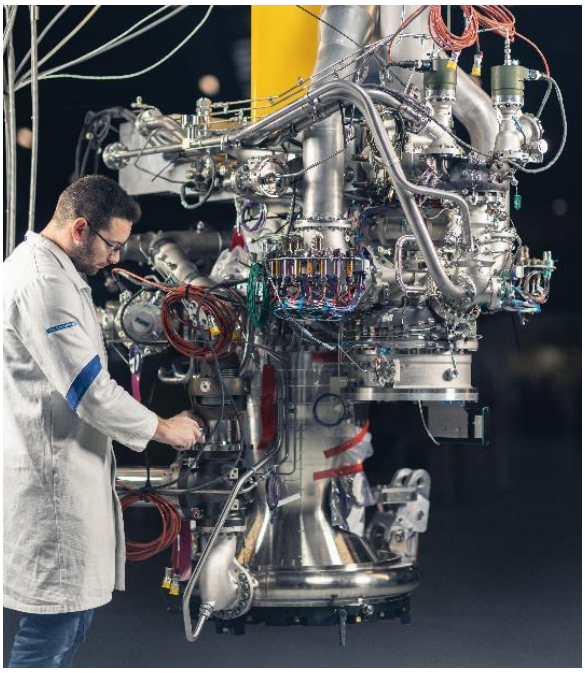

Fig. 3. First PROMETHEUS® engine delivered

Some insights of the development of the engine and its subsystems are given in reference [1] to [4].
It was shown that on the subsystems major achievements were fulfilled:

- The gas generator and its valves were successfully tested in P8 together with a control loop;
- For the Thrust chamber, maturation and development activities were on-going within the ESA FLPP NEO Core technological maturation Programme frame. For example, Cold Gas Spraying (CGS), for which a successful demonstration has been already achieved last year on ETID scale, has been selected because making possible production of large components under short production cycle.

3.3 DLR P5 Test bench preparation

P5 test bench (shown in Figures 4) in Lampoldshausen need to be adapted in order to accommodate the engine Prometheus but also to be able to supply methane through a dedicated feeding system composed of specific lines, tank, flowmeters and pressurization system.

These adaptations are accompanied with:

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- Measurement Control and Command System (MCC) extensions, to ensure compatibility with engine REEC, and
- development of mechanical elements such as the Thrust measurement system (TMS) and feedline adapters supplied by Magna Steyr, in order to cope with new engine interfaces.

During the second half of 2021, the methane tank has been installed and civil works were completed in 2022. Fluid supplies (both cryogenic and gaseous ones), flare-stack, cabling, and MCC extensions manufacturing are currently ongoing and foreseen to be installed in the coming months. R1/R2 acceptance should start then from later this year and end in 2023.

Fig. 4. aerial view of P5 during and after civil works (DLR Courtesy)

However, the planning is strongly impacted by Ariane development activities at the P5.2 since some means are either common to the two test benches (MCC) either cannot be installed before the end of the test campaign of the ULPM of Ariane 6 in P5.2 that is still ongoing.

4. Opportunity made possible by Themis Programme

However, due to bench occupation by Ariane 6 ULPM campaign as detailed in 3.3 and thanks to the opportunity presented by THEMIS demonstration and following the visit to the ArianeGroup site in Vernon by President of the French Republic Emmanuel Macron, development of a test solution based on THEMIS-1G was proposed to accelerate the Prometheus schedule by beginning the first tests on the Vernon site by end of 2021.

4.1 Themis: Demonstrator of Reusable Stage

Themis is a Demonstrator and a prototype of low-cost Reusable stage [5], which is part of ESA strategy toward preparation of future Space Transportation Systems.
This programme, initiated by ArianeGroup and CNES, has been introduced as component of ESA FLPP programme following the Council of ESA at Ministerial level in Sevilla end 2019. ArianeGroup is the main contractor and the design authority for THEMIS development

THEMIS initial phase integrates 3 different demonstrators:

- THEMIS-0, whose objective is to validate and optimize LOx/LCH_4 fluidic ground/board process up to Prometheus Interface;
- THEMIS-1G whose objective is to validate Prometheus operation in stage environment (hot firing test with 5s steady state at 700kN);
- THEMIS-1G Strike whose objective is to validate the integration of Strike tanks in view of T1H.

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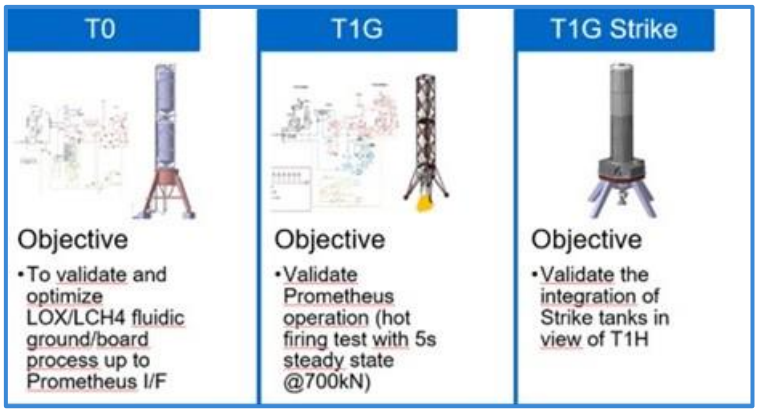

Fig. 5. THEMIS initial Phase specimens

Thanks to Themis programme and the support of France Relance, it was then decided to develop specific capabilities on Vernon ArianeGroup PF20 tests stand, to test PROMETHEUS® engine together with THEMIS, with extended capabilities in terms of thrust domain and test duration, leading to the use of THEMIS as a test bench called T1-B.

4.2 PF20: an historical test bench for Ariane

ArianeGroup test area on Vernon site has a long history of development of rocket engine, starting with LRBA (Laboratoire de Recherche en Balistique et Aérodynamique) activities at the end of the 1940's.
Many engines were tested on this area for Veronique, Vesta, Diamant, Europa then Ariane launcher.

PF20 test bench was developed in the second half of the 70's for the development of Ariane first stage propulsive system and the qualification of this L140 stage boosted by 4 Viking engines.
In the 80's, this bench received the qualification test of the improved first stage L220 for Ariane 4.

Fig. 6. Ariane 4 main stage test at Vernon PF20 bench

PF20 test bench was then decommissioned after L220 qualification and remains as unused area for more than 35 years.

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4.3 PF20-B: A new test bench for Stage test

If the first step of THEMIS initial phase testing activities were performed on the platform of PF20 area, known as PF20-A and it was initially foreseen to continue on this area, it become rapidly evident that the boosted tests of THEMIS-T1G/ PROMETHEUS® require specific capabilities to secure adequate conditions.
A new test stand, PF20-B was then developed thank to the support of CNES under France Relance frame to take profit of both demonstrators allowing to perform test campaigns for Prometheus engine increasing the firing test duration on the limit of the tanks capacity. A frugal and fast approach was proposed for the development of this stand. It was built in only 18 months.
The main components of this test stand are:

- Fluidic system with dedicated metallic support infrastructure
- Large scale diffusor with simplified water cooling system
- Metallic structure for stage support
- Control room compatible with Stage/engine control and measurement acquisition
- Flame duct ;

Fig. 7. Vernon PF20-B during building

PF20-B stage test acceptance test were performed in June 2022 making possible the first combined THEMIS-T1G/ PROMETHEUS® test.

4.4 Themis-1G/ PROMETHEUS® system

One of the main innovative approach for engine development, has been to use THEMIS-T1G as a test bench for the testing of PROMETHEUS® engine.
Considering the peculiarity of the engine, and especially PROMETHEUS® capability to manage functions which are generally managed by the test bench, it was therefore possible to run PROMETHEUS® engine in a safe condition on THEMIS-1G.

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Fig. 8. THEMIS-T1G/ PROMETHEUS®system

5. Status of PROMETHEUS® test campaign at PF20-B

First filling of the tanks as well as the first chill-down of the engine in liquid nitrogen were performed in June 2022. Test analysis show a good behaviour of the full system PF20-B/ THEMIS-1G/PROMETHEUS® in terms of process preparation and execution at all the level of the test system.
Liquid Nitrogen chill-down was identified as very beneficial for cost reduction, environmental impact and safety compared with propellant chill-down. A chill-down procedure in two steps, first with liquid nitrogen, then with propellant was then developed for the following test.

First Prometheus ignition took place in September 2022 which represents an important step in PF20/ THEMIS-1G/ PROMETHEUS® system operation. A first test campaign, devoted to the tuning of the transient sequences, was then performed, giving an important material for the validation of stage and engine design and the optimisation of the operations. During this campaign performed under CNES contract as part as France Relance framework, various operating conditions, transient including configuration were tested.

Figure 8: PROMETHEUS® Engine demonstrator during hot-firing tests

This campaign with several engine tests, made possible the acceleration of engine maturation planning while de-risking PROMETHEUS® with regard to upcoming P5 engine tests.

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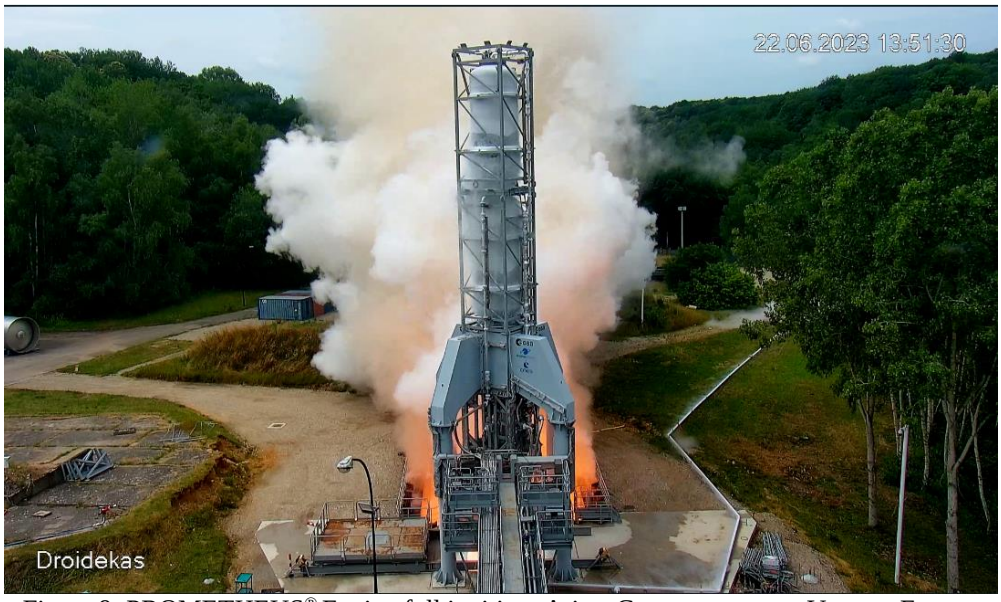

Figure 9: PROMETHEUS® Engine full ignition, ArianeGroup test center Vernon, France

Following this first test campaign focused on Prometheus engine, test devoted to THEMIS is foreseen in the frame of ESA FLPP.

6. Conclusions & Acknowledgements

The PROMETHEUS® programme paves the way for the preparation of the future of space transportation. The engine concept based on a gas generator cycle with LOX and Methane has ambitious targets, for costs, manufacturing time & performance (reusability, throttling & re-ignitions). To achieve these goals, disruptive approaches were carried out.

As part of disruptive approach, the use of THEMIS ground Demonstrator on PF20-B is a key component of this strategy.

By frugal and agile approach and maximum synergy between ESA FLPP programme and France Relance opportunity under CNES contract, this test facility including the revival of PF20 stand was developed at ArianeGroup Vernon in a very short time, making possible at the same time engine development and reusable stage development.

Thank to this test campaign at stage level, PROMETHEUS® has experienced a key acceleration in its validation, clearing the first engine test campaign foreseen at DLR Lampoldshausen P5 test bench. After the test of M1 engine on THEMIS 1B/PF20-B, a second engine will be made available this year for DLR for this campaign and a third engine will be made available for THEMIS -1H hop-test demonstration in Kiruna (Sweden) also this year.

Resulting from this initiative and the support of ESA FLPP relevant Elements and their Participating States, CNES and France Relance, a stage bench is now available of ArianeGroup Vernon test area, compatible with the testing of 100tons class stage, representing a key infrastructure unique in Europe.

The authors wish to thank the entire teams that are involved inside the PROMETHEUS® and the THEMIS projects as well as ArianeGroup teams in charge of PF20-B development and exploitation.
The authors want also to thank particularly ESA, CNES and DLR agencies, and France Relance programme for their support.

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