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PROMETHEUS, A LOX/LCH4 REUSABLE ROCKET ENGINE

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Abstract
Since 2015, ArianeGroup and CNES have initiated in strong partnership the development of a new low cost and reusable rocket engine to power the next generation of launchers after Ariane 6. Cryogenic rocket engine of 100tons class, it will run liquid oxygen and liquid methane. The Prometheus engine will have to meet ambitious design to cost approaches and still be capable of reusability. Equipped with a dedicated computer it will be able to perform thrust modulation and self asses its health condition for real time adjustment and maintenance purposes.
The Prometheus engine is not only a new engine but also the prototype of a new industrial approach to rocket engine design. Under the lead of a design team integrating industrial and institutional partners, the Prometheus engine design integrates the most promising solutions from R&T and other programs in the field of ALM, design to cost strategies, throttable thrust, on board computing, HMS and digital technologies.
The Prometheus engine is one of the main brick to build the next generation of launchers and to help optimize the industrial framework around it. Following ministerial conference at end of 2016 the project is being pursued in ESA FLPP NEO program up to firing tests in 2020 at DLR P5 test bench. This paper outlines the main design choices and the innovative approaches brought by Prometheus and its development.

1. Introduction

Prometheus rocket engine is the latest ambition of the European rocket industry. The goal is to provide a reliable engine of 100 tons class in a costly effective manner. The main idea is to merge manufacturing and design to support the development of parts that respond to the technical specification and allow a more efficient fabrication and lower production costs.
Manufacturing constraints are included in the design process within an Agile inspired environment and innovative approaches to industrialization are deployed.
The engine cycle is a traditional gas generator type, using LOX and LCH4 as propellants. The choice of methane as a fuel enables a good compromise between performances, reduced thermal gradients in the systems and cost reductions
The engine controller performs autonomous tuning from 30% up to 110% of the nominal thrust and innovative HMS algorithms are used to optimize engine health assessment for in flight HMS or post flight maintenance purposes.
This paper proposes an overview of the main technical elements of the engine as well as the core philosophy of the project.

2. Mission

Prometheus engine will constitute the main propulsive solution for the future European launchers such as Ariane Next (see Figure **3**)[1,2].

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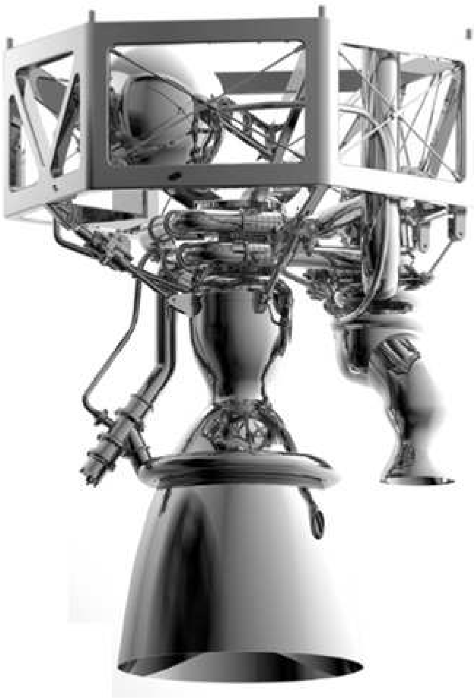

Figure 1Prometheus engine preliminary 3D model

It will be a unique propulsion system for main and upper stage (a cluster of engines for first stage application). The Prometheus engine will be designed to be reusable and to demonstrate cost effective reutilization: the cost objective is to achieve a reduction down to one tenth of today engine such as Vulcain 2 Figure **2**.

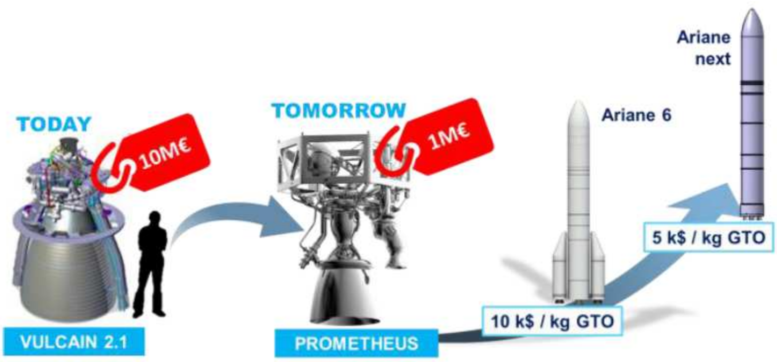

Figure 2 Prometheus cost objectives

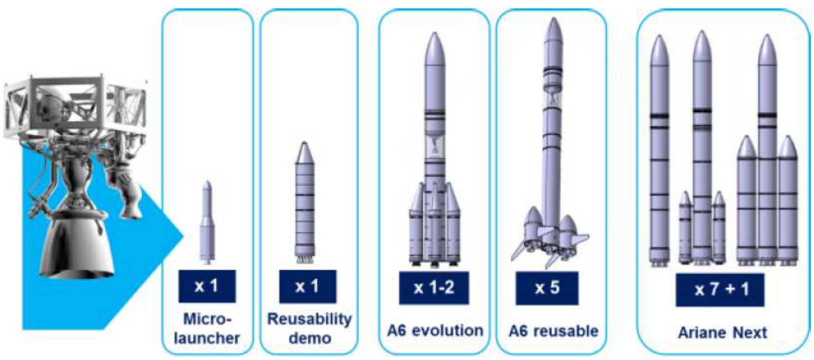

Figure 3 Prometheus launcher target, and number of engines per type of application

3. Engine description

3.1 Engine cycle architecture

After a preliminary phase started end of 2015 multiple trade-off were performed leading to the final choice of a gas generator engine type, Figure **4**. This allows the integration of low cost design solutions in a system with satisfying overall performance level.

The engine delivers 100tons of thrust. A single shaft turbo-pump is used to feed the combustion chamber, cooled via a methane regenerative circuit. Four main valves feed the chamber and the gas generator. Three of them are fully regulated valves and allow a throttling level from 30% up to 110%.

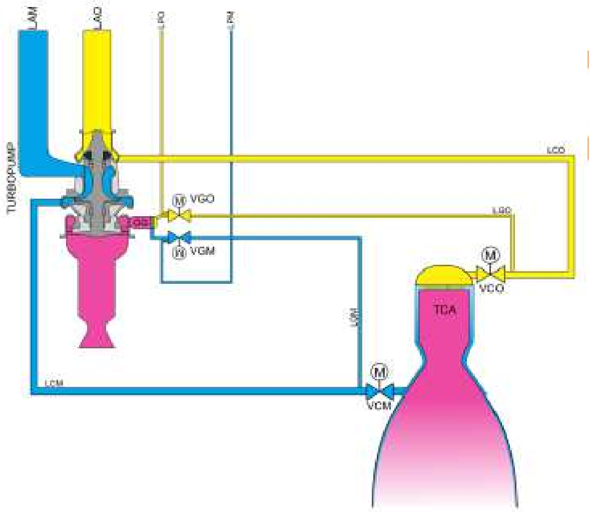

Figure 4 Preliminary engine architecture

The nominal combustion chamber pressure is set to 100 bar, on the basis of engine mass correlation, engine feedback and performance target. The combustion chamber mixture ratio is set to 3.5 which is near the optimum for the combustion chamber, as it is illustrated in Figure 5 .

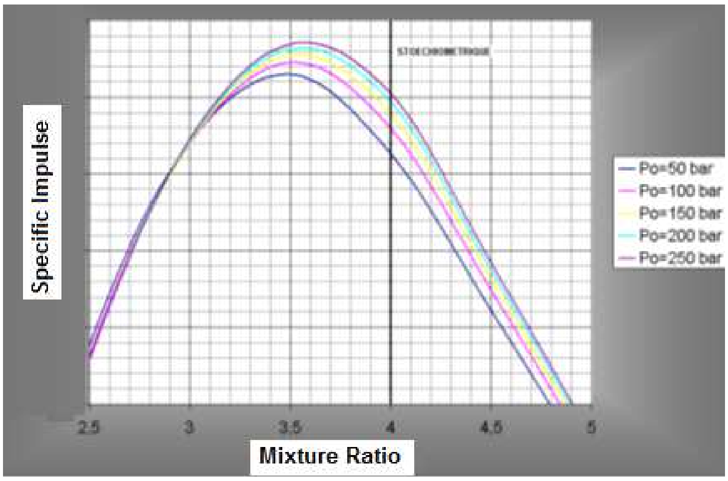

Figure 5 Combustion chamber pressure and mixture ratio selection over specific impulse

The ejection pressure was selected to 400 mbar. This value was chosen because the Prometheus engine is a 1^{st} stage engine and needs a good sea level thrust.

During the preliminary design phase, CNES performed some supporting studies thanks to the Penelope facility, involving mission optimization and calculation together with engine design loops (“Plateforme d’évaluation numérique de l’environnement lanceur et optimisation des paramètres d’étagement”) Figure **6.** This approach led to an update and optimization of the nozzle expansion ratio and thus the selection of the appropriate ejection pressure at sea level.

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Figure 6 CNES concurrent design facility « Penelope »

3.2 Low thrust behaviour and throttling

The key difficulty in throttling a liquid rocket engine is maintaining an adequate pressure drop across the injectors, which is necessary to provide propellant atomization and mixing. For the combustion chamber, cooling can be an issue too due to fluid properties variations as approaching the critical point (45 bar for methane). For turbomachinery, the primary considerations are to avoid cavitation, stall, surge, and to consider bearing leakage flows, critical speed, and structural dynamics. For valves, it is necessary to design valves and actuators that can achieve accurate flow control at all thrust levels. It is also important to assess the amount of nozzle flow separation that can be tolerated at low thrust levels for ground testing.
At this stage of the project extensive analysis is performed at system and subsystem levels to analyse the critical behaviour of the engine during low thrust throttling. Extensive domain analysis has been performed to confirm the main system design choices revealing the engine performances.

3.3 Combustion devices

Several families of thrust chamber have been proposed with the objective of achieving innovative low cost manufacturing as the thrust chamber cost target is a few part of the global engine cost. This trade-off is fed by BOREAS programme [7], ROMEO programme [8], past experience, etc.
The PROMETHEE GG design is a fully made with ALM.

3.4 Turbopumps

Taking large benefit of ALM process for manufacturing, the turbopump design is the result of a design to cost process. The Prometheus single shaft turbo pump develops an overall power of around 10 MW.

3.5 Valves

The reference engine has 4 main valves :

- 2 Chamber Valves (VC) which control the combustion chamber feeding. The VCO is used to control the chamber mixture ratio. Thus it is a shut-off and a regulation valve
- 2 Gas generator valves which control the gas generator feeding. The VGO and VGM are used to tune the engine power and to control the GG mixture ratio. Thus these valves are shut-off and regulation valves.

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4. Innovative manufacturing approach: ALM and innovative processes

One of the key technology approaches of Prometheus engine is the extensive use of Additive Layer Manufacturing (ALM), fostering design flexibility and reduced production time.
Up to now, ALM has been extensively used for the production of secondary tools or parts, on board of satellites or airplanes, providing interesting alternative for elements such as cabine elements or equipments struts. Few ALM parts have been employed so far as principal elements in engines with a main functional and structural role.
One limiting factor for the evolution of ALM manufacturing is the typical size limit of the ALM (Laser Beam Manufacturing) machines [4]. For the first time, the Prometheus pump main casing, constitutes the biggest part produced (in partnership with Volum-e) today with an ALM machine at once, that is without recharging, and using Inconel powder with a M400 machine [4]. The size limit has been pushed to 40cm. Manufacturing of all the parts of the engine will be tested with certified ALM manufacturing solutions and machines. The objective of Prometheus program is to achieve the best compromise in manufacturing ease and final performances.

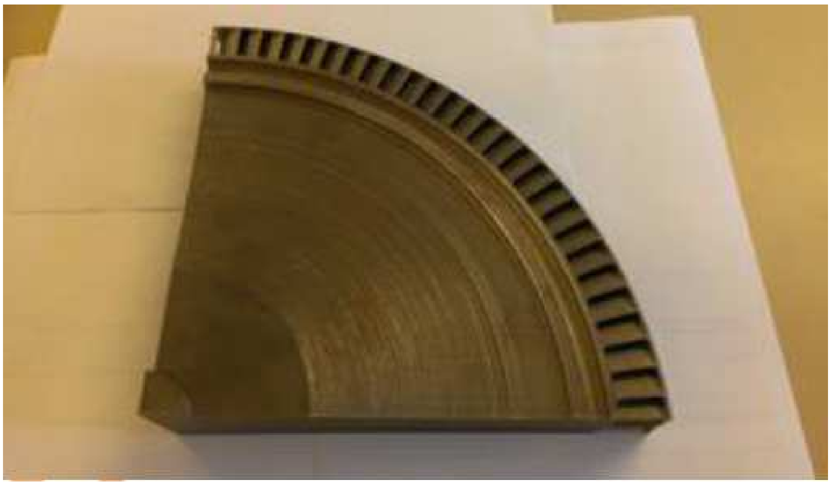

Figure 7 Turbine prototype

Figure 8 ALM Casing prototype

5. Industrial set up

Industrialization has been taken into account from the beginning of the project. The ArianeGroup industrial team is part of the project and thus integrating possible design constraint in the industrialization logic.
Some of the ideas leading up to the design of the engine manufacturing site are:

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- 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.

The mounting cycle of the sub-system and engine final assembly will be improved thanks to minimization of the waiting time between two operations, anomaly process or optimization of the setting of specific elements mounting.
The high production cadency associated to Prometheus (between 50 and 100 engines per year) requires an assembly plant very different from the classical engine production, innovative methods will be applied such as pulse line manufacturing sites [6].
Prometheus is an innovation vector, leading to an innovative industrial set-up making intensive use of ALM and digital technologies.

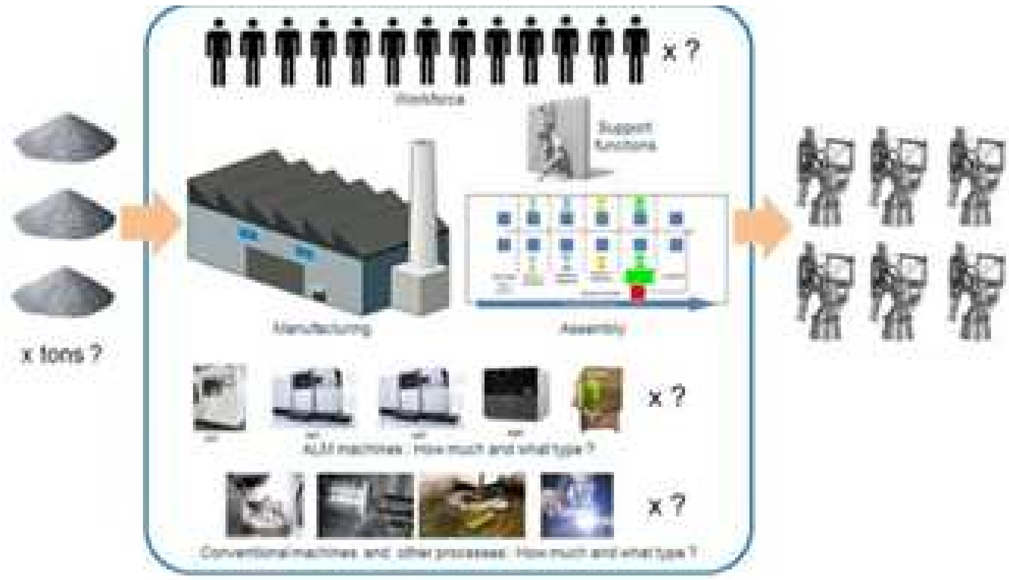

Figure 9 Greenfield analysis

6. Agile, frugal and design to cost

Prometheus project is based on three main principles which are completely breaking with past rocket engine design approaches.
These are based on the following modern guidelines:
- Extreme design to cost_ such as in typical automotive industry
- Frugal development, keeping the innovation at the center
- A general Agile approach in the program implementation

Aggressive design to cost is achieved thanks to several years of experience and also by bridging the gap among design choses and manufacturing constraints.
The main low cost design choices are:
- Simplified cycle architecture
- Low cost mechanical set up
- Standard electrical command
- Simplified sub-systems
- 3D ALM fabrication

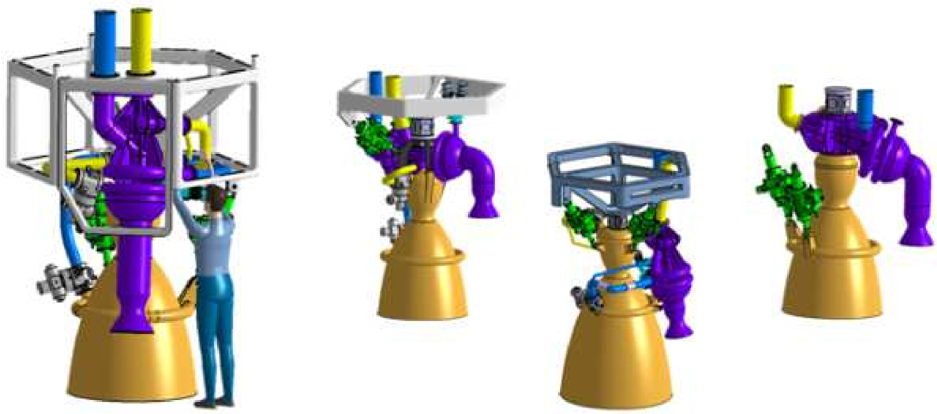

Figure 10 Simplified engine setup

The basic principles of the Agile method is that we go from the V cycle to a spiral approach. The final product is achieved via iterative building of the product : this reduces the tunnel effect, provides tangible value as early as possible , splits a complex endeavor into simpler elements, delivers frequently and improves based on direct feedbacks from users, clients and teams and finally it mitigates risks by addressing early the product parts that involve a degree of uncertainty.

The Prometheus design team integrates at maximum the Agile approach thanks to the innovative manufacturing methods provided by ALM and by the creation of an innovative team where design engineers work together with manufacturers in the same facility. This leads to the possibility to quickly produce prototype of the parts and to boost system engineering thanks to the proximity to the subsystems.

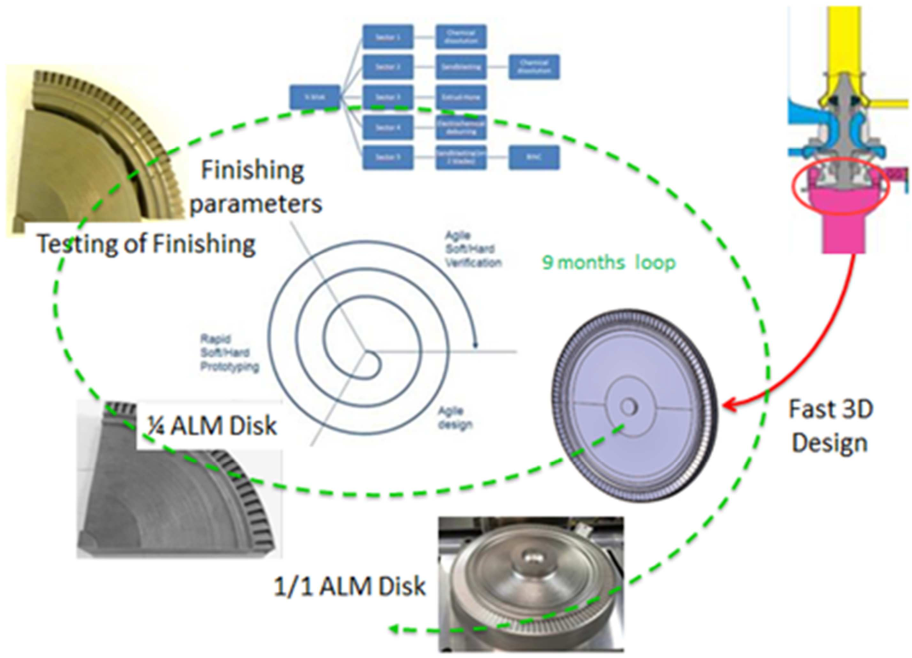

Figure 11 Overview of Prometheus innovative concepts such as Agile, Frugale and ALM

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7. Reec (engine control and HMS)

Prometheus engine will be equipped with a dedicated control unit, the REEC, which will be able to perform engine control during flight, meaning throttability from 1000kN down to 300kN of thrust, and most of all it will manage autonomous in flight health check and contribute to launch pad operations and maintenance purposes.
It is thus a central element of the engine success and it is based on many years of experience in regulation and HMS demonstration. Prometheus REEC computer will be developed following agile philosophy making extensive use of ISFM bench [3, 5].

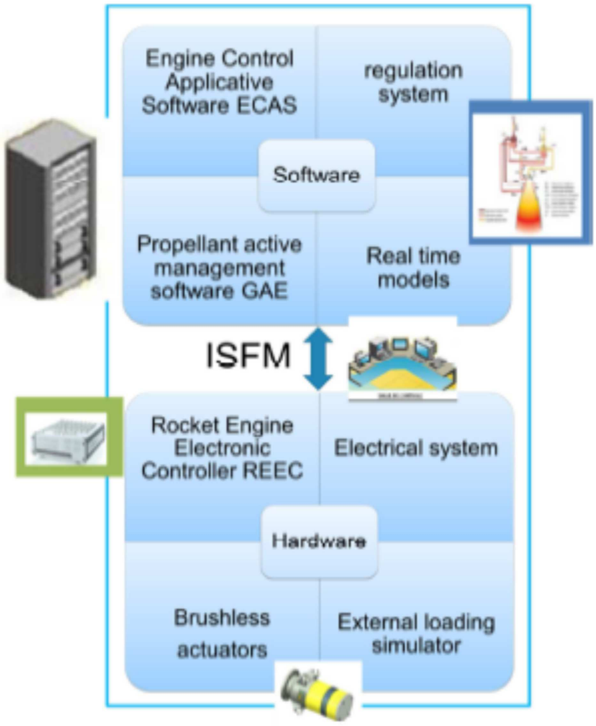

Figure 12 Global view of the different ISFM components

8. Prometheus team

The Prometheus project proposes an innovative approach to rocket engine design by integrating the principle of aggressive design to cost and agile development approach in an already setup industrial environment. As a consequence this philosophy has practically dictated a new way to live the workplace: engineers, designers and manufacturers have to work together and share ideas as soon as possible, they also have to be as close as possible to the hardware and learn from experience in a proactive way. To boost the possibilities of integration of innovative ideas coming from a broadened panorama of research & innovation activities, CNES since the initial phase of the project (2015-2017) have been strongly involved in the team, providing support and expertise on critical items and on different topics linked to innovative and alternative solutions.

9. Conclusions

Prometheus engine is an ambitious project that aims at developing an innovative propulsion system capable of throttling and reusability for European future launchers. The challenge is to ensure optimum performances and still to drastically reduce costs by implementing aggressive design to cost strategies and advanced industrialization methods.
An innovative approach to rocket design is at stake and the Prometheus team and project will lead to important and disruptive achievements.
The project has been initiated and matured from 2015 to 2017 in the frame of a strong cooperation between CNES and ArianeGroup. Thanks to the successful outcomes obtained so far the project has been accepted at ministerial level and is now part of ESA FLPP NEO project.

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