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Towards a new class of engine for future heavy lift launch vehicles

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Abstract

The speech of the President of the French Republic at the Space Summit Meeting in February 2022 recalled the European interest for exploration and manned spaceflight.
A double observation can be made on this basis:

- Ariane 6 is on its way to launch operations, the present studies of future heavy space transportation systems rely on the 120 tons class PROMETHEUS® reusable engine, and first stage recovery demonstrations (Callisto and Themis demonstration stages). These launchers (A6 and next step prospects) belong to the class of heavy launchers (max 20T LEO).
- The context is moreover evolving, with in the one hand the intensification of the participation in the exploration programs, as well in Earth orbit as in Lunar orbit (and beyond), and in the other hand the fierce competition for commercial access to space.

This might lead for Europe to the need of a significant increase in payload capacity, therefore in launch system class as well as propulsion class. Two questions then arise: What type of transportation system (architectures and launch strategies), and what technological steps to prepare this scenario, in particular in the field of Liquid Propulsion, which is a long-term matter? This forward-looking approach resulted in a set of internal studies as well as the performance of a workshop dedicated to European super-heavy launchers prospects and associated technologies, during which the evolutions of the Propulsion Systems were addressed in particular.
Several system and engine concept studies have already been started in this way, with the aim of reviewing knowledge and past achievements, then leading to the initiative toward a very-high-thrust engine, possibly with a staged combustion cycle.
The objective of this initiative is to prepare the dedicated skills in the French industrial ecosystem and the technologies associated to very high thrust / staged combustion engines, including the benefit of synergies with the existing PROMETHEUS® development: engine hardware that can serve as demonstration platform, available test benches for PROMETHEUS® and Themis, team competences at ArianeGroup in Vernon.
The first phases of the study are already running to identify engine configurations and technological challenges to overcome, and the demonstration elements of a staged combustion cycle engine will be the next objective of this approach to be implemented.

1. Introduction

The context of space launches is changing, under the effect on the one hand of increased commercial competition, which is likely to induce larger volumes, and on the other hand of the prospective missions linked to exploration (and in particular the Artemis projet), which could lead to much higher masses.
The demand for commercial launches is constantly increasing, and competition in this market is increasingly fierce, in particular due to new players. This launch service demand concerns conventional commercial or institutional payloads for GTO and LEO/SSO orbits as well as constellations for medium and low orbits. While the smallest payloads can now potentially rely on the abundant supply of micro and mini launchers, heavier payloads (as well as cluster solutions) continue to express a need for heavier and larger means.

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Additionally, Europe's participation in exploration programs (including the Artemis program) could lead to missions beyond Earth orbit, in auto/cargo flight, or even in manned flight in the future.
Depending on the cooperation options that will be adopted, and the individual initiatives of the various space powers interested in the prospects for lunar missions, several types of missions could then be envisaged.

These two changes in the context motivate the analysis of solutions for increasing launch capacity, either to allow a more competitive commercial offer, or to allow the sending of larger payloads to low orbit or even, for instance, to the Moon. One of the responses to increased demand and increased competition may result in an increase in the volume, and therefore in the total mass, available for the payload (at the level of the fairing or of the entire launch vehicle). Increasing the volume under fairing, on the series of current or planned launchers, could constitute a first solution to reduce the price per kilo. This effect could be amplified by an increase in total mass launch capability.
The injection of payloads intended for exploration could concern habitable station modules and recoverable, automatic or even manned spacecraft, representing both larger masses and volumes, towards low orbit and then, later, towards the cislunar environment.

2. Future heavy lift launch vehicles

Due to the level of performance of the current class of space launch vehicles, solutions for upgrading the launcher system must be considered: changes to the current system, or even a new, more ambitious architectural concept, possibly in combination with more elaborate injection strategies.
The current launcher series in development or in project are enabling to foresee architectural evolutions exploiting the potential of existing industrial and operational means, leading for example to heavy class launchers that can be part of a range or family logic.
Different architectural evolution options concerning the boosters or the central body could make it possible to aim for a doubling or even a tripling of the existing capacity, opening the way to other types of missions.
In parallel, it would also be possible to consider in the longer term the development of a more ambitious concept, of higher class, generalizing the notion of recovery. As an alternative to the evolution in continuity leading to a heavy-class launcher, and if the conditions justifying such a development were met, a new concept, of larger size and higher tonnage, therefore of super-heavy class, could then be considered.

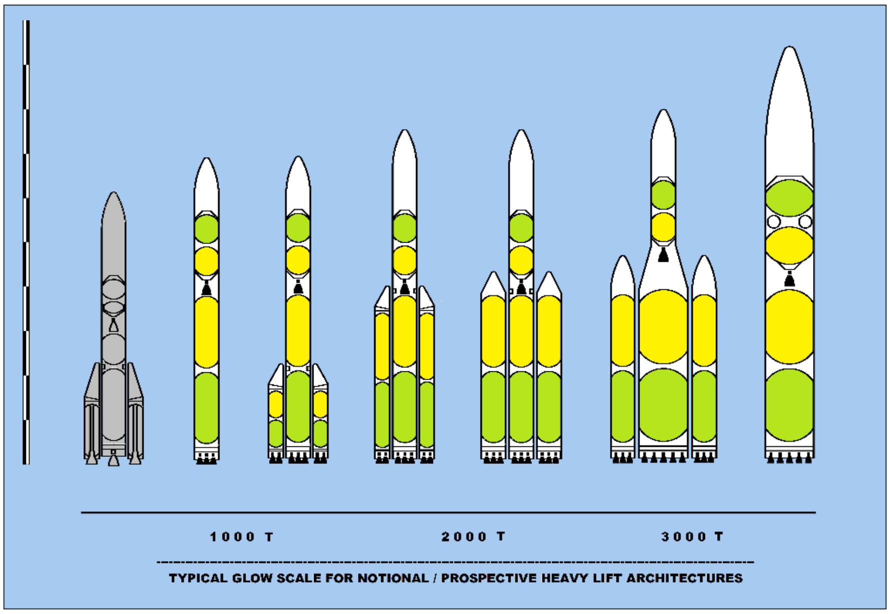

Figure 1: Prospective heavy lift architectures

The analysis of these different ways highlights the possibility of carrying out heavy missions in low orbit as well as lunar exploration missions, some of which must be associated with new choices of injection strategy.
The detailed analysis thus highlights a launch capacity in low orbit compatible with heavy circumterrestrial missions and lunar missions for concepts based on an extension of the potential of launch vehicles from current or planned series. The capacity of the series of current or projected launchers, which come under a class of around 1000T at take-off, is compatible with carrying loads of around 20T in LEO, i.e. the class of a station element, a supply module, or

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even an automatic or manned capsule. In addition, the evolution towards a heavy class 2000T architecture doubling or even tripling the capacity would make it possible to carry out most of the commercial, institutional or exploratory missions envisaged.
To enable them, or to maximize their performance, some of these cislunar exploration missions should however be associated with elaborate injection strategies based, for example, on the notions of "space train" and perhaps orbital refueling. The use of a 2000T class heavy architecture, ensuring a performance greater than 50T in LEO, would make it possible to envisage cis-lunar missions in association with an injection strategy based on a splitting of (2) launches in view to form a space train of the order of 100T at least (order of magnitude of target mass to enable for a TLI).
As mentioned above, more ambitious concepts based on architectures of another class of geometry and GLOW / Gross Lift-Off Weight (3000T+) would make it possible to achieve equal or better performance and to cover all the missions envisaged, at the cost of a greater development effort.

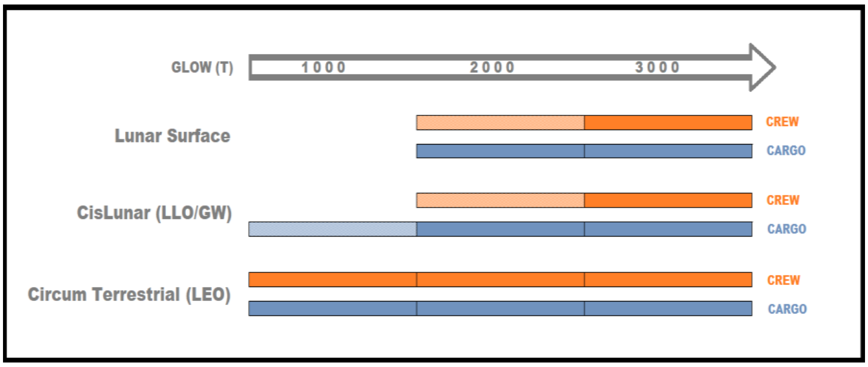

Figure 2: foreseeable type of mission as a function of the GLOW

Nevertheless, the results of the analysis highlight the potentially marginal nature of the capacity likely to be obtained from current or developing means of propulsion for the class of future launcher envisaged, and the interest in developing engines of a more suitable class is therefore appearing.
For launch vehicle concepts resulting, by continuity, from an extension of the potential of current or planned series and leading to increased or heavy versions of 2000T ("Heavy" type), the performance obtained by means of current or planned engines (from 100 to 150T of thrust) appears at the limits of the compatibility range of the objectives, with an additional growth potential being difficult to emerge. The calculation shows that a more powerful propulsion, providing about twice the thrust, and an increased specific impulse, could meet the need in a more "comfortable" way.
Considered as a component of a multi-engine bay, the target engine should have a thrust level designed to: ensure takeoff in conditions meeting performance and safety objectives, allow the landing of a first stage in its reusable version, and be compatible with the constraints and accommodation objectives of an aft bay for a booster and a conventional launcher from the current or in-development series (as well as that of a new concept of super-heavy launcher, for which it would also constitute the main propulsion). Based on these high-level preliminary criteria, the target thrust value is currently established in the range of 200-250T.

Hence, in order to generate some margin and an additional growth potential on the one hand, and a propulsion adapted to the future needs of a higher-class launch system on the other hand (associated to a growth in the currently envisaged series or to a new, more ambitious one), it seems therefore appropriate to consider and prepare for the development of a propulsion system with greater thrust, typically at twice the current levels.
This should enable to increase the capacity to respond to commercial competition, and to carry out elaborate and ambitious exploration missions beyond Earth orbit.

3. Towards a staged combustion cycle for increased engine performance

While in Europe, LOX-Methane propulsion maturation is progressing rapidly with different engine projects ongoing like MIRA-10 and PROMETHEUS® (Precursor Reusable Oxygen METHane cost Effective propUlsion System), the engine cycle considered are fully mastered and adequate to meet the requirements; respectively, an expander and gas generator cycles. PROMETHEUS® engine is under development to respond to the need of an ultra low-cost reusable engine of 1000kN thrust class. To increase the engine performance to the level required for heavy lift launcher vehicles, the maturation of a staged combustion cycle engine is now necessary.

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Several studies and projects have been carried out in Europe in the past on staged combustion engines as ESA FLPP SCORE-D project. In 2021, the French national space agency CNES and Ariane Group restart the advanced studies on staged combustion engines focused on LOX/Methane 2000kN thrust. The main objective was to identify, not the engine configuration to respond to an inexistent launcher requirement, but a clear list of technology locks to feed the CNES Research & Technologies maturation Programme. The starting point was to take profit of all the learnings, the frugality and the innovation already deployed on PROMETHEUS® engine demonstrator to propose a new approach. Two engine concepts were proposed: one linked to a low cost staged combustion engine using PROMETHEUS® design–to-cost approach, the other one targeting a fully optimised high performance version (high cadency, high reusability) with no cost constraint. A large trade-off was performed, driving to the selection of a configuration for each of them.

End 2022, the configurations were updated considering the output of the Heavy Lift Vehicle requirements, from 2000kN up to 2500KN. A mechanical study was carried on to propose engine architecture for each concept.

Figure 3 : Baseline concept (@Arianegroup Courtesy)

4. HIGH THRUST ENGINE

Beginning 2023, CNES decides to launch the High Thrust Engine project in a national frame. A first step towards this newclass engine generation is the development of a staged combustion LOX/methane reusable engine demonstrator, introducing the needed technologies. A demonstrator is proposed by Arianegroup. Nevertheless, it could be foreseen several demonstrators to be tested.

The workplan is structured in three different elements:

1- Technology maturation
2- Demonstration through engine test campaign of a staged combustion cycle with limited level of thrust
3- Bench adaptation

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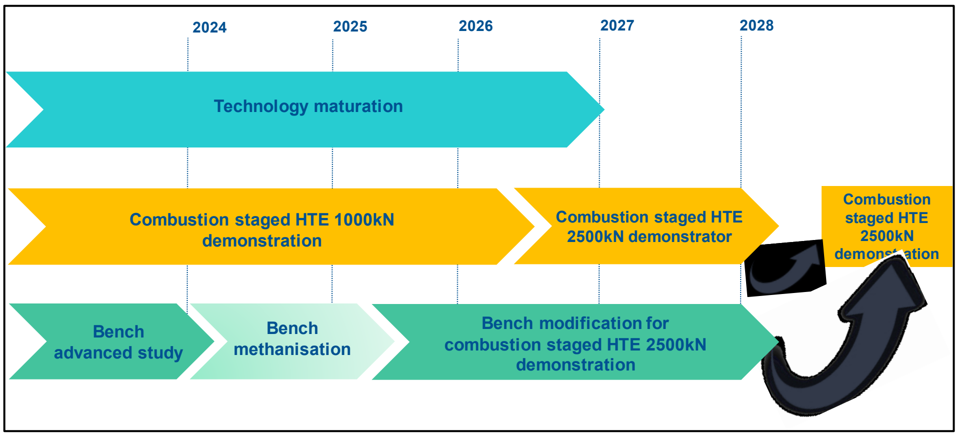

Figure 4: High Thrust Engine Workplan

4.1 Technology maturation

Several workshops were carried out between Arianegroup and CNES experts, to identify the challenges and the technology locks on the different engine components and subsystems for the staged combustion engine concept relying on the performance requirements in terms of high pressure, high mass flow, high temperature, strong thermal gradients in transitory phase and thermal flux. In addition, high reusability is also a challenge, as well as the mastering of the engine ignition. The topics addressed were the following:

- Combustion (combustion chamber, preburner, igniters)
- Fuel and oxygen turbo-pumps
- Engine regulation and valves
- Oxygen compatibility
- Engine architecture

Through the workshops the main challenges per topic were identified as well as the necessary maturation activities to increase the technology readiness. They were classified and a first assessment of potential demonstrations was established. In the coming two years, the efforts will be deployed on the preburner, the oxygen compatibility, the new materials and the combustion chamber.

The technology maturation component will be performed by several partners including research centers like Onera, laboratories, industry and start-ups. The objective is to integrate the maturation components onto the final demonstrator.

Finally, additive manufacturing will be largely used for the production of engine components as allows design optimisation and cost reduction. Another major advantage of the additive manufacturing is to reduce the time and cost of making the different parts of the rocket engine, so then, perfectly adapted for a one-shot demonstration considering that the design will be reoptimised after analysis of the test results. The manufacturing with new materials needed for a high performance engine will be part of the maturation roadmap. The size of the available 3D printing machines or, those under development targeting larger sizes, are of particular interest for the High Thrust Engine project. On the other hand, the welding processes will be addressed as a potential capacity to optimise the 3D printing machine occupancy in order to reduce future production cost.

Manufacturing the copper-based liner for the engine combustion chamber is the first step. Different copper-alloys (copper- Chrome-Zirconium, Copper- Chrome-Niobium), will be considered for 3D printing manufacturing maturation, mainly by Laser Beam Melting (LBM). Test samples, material characterization and testing will be performed along with hot-fire testing of subscale chambers in order to prepare the full scale demonstration. The second step is to mature the bimaterial process of the full combustion chamber based on the experience of BOREAS project [4]. The mechanical integrity was ensured by a CMO (Organic Matrix Composite) envelope welded between two Inconel flanges connected to the inlet and outlet regenerative circuit manifolds.

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Figure 5 : Combustion chamber samples on CuCrZr produced by Volum-E

Different Proof-of-Concepts (POC) will be tested to increase the technology readiness level. Two test campaigns are foreseen during second half of 2024 for the preburner and a subscale combustion chamber. For this, BAMOCRY test bench (BAnc MOdulaire CRYogénique) from ArianeGroup at Vernon [3] (shown in Figure. 6) is one of the selected benches to perform subscale tests. This modular test bench has been developed under France Relance Program with CNES for answering the different needs expressed by the NewSpace start-ups.

Figure 6 : BAMOCRY test bench at PF1 Vernon facilities (@Arianegroup)

4.2 Engine demonstrator test campaigns

Three hot firing test campaigns are foreseen starting beginning 2025, to achieve a demonstration of a staged combustion cycle engine demonstrator before end 2026. The subscaled engine thrust will be a 1000kN class mainly coming from LOX/Methane benches limitation. The selected test bench is the new stage test stand THEMIS-1G at PF20 in Vernon funded by the CNES under France Relance Programme. It was built taking benefit and synergy of THEMIS-1G vehicle and PROMETHEUS® engine demonstrators (under ESA FLPP Programmes) to perform the first PROMETHEUS® test campaign [2]. This test facility allows high flexibility, test cadence and quick short test (up to 20-40s) particularly useful and adapted for demonstration test.

Figure 7: Themis-1G test bench – View of the flame trench (@Arianegroup Courtesy)

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4.3 Way forward 2500kN Staged Combustion engine demonstration

Today there is a limitation on the maximum engine thrust bench capability to perform the demonstration test campaign at full scale (2500 kN). An advanced study is ongoing to identify the potential modification to be implemented on the PF50 bench and the comparison with a dedicated new bench. The modifications of the bench will start in 2025 to be ready for the full scale staged combustion HTE demonstrator test campaign foreseen in 2028.

5. Conclusions & Acknowledgements

The objective of this initiative is to prepare the dedicated skills in the French industrial ecosystem and the technologies associated to very high thrust / staged combustion engines. The first phases of the study are already running to identify engine configurations and technological challenges to overcome, and the demonstration elements of a staged combustion cycle engine will be the next objective of this approach to be implemented

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