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BOREAS DEMONSTRATOR FOR FUTURE LIQUID PROPULSION ENGINES

DENEUVE A, DREYER S*, HUMBERT E*, LESAUNIER L*, GUICHARD D*, DU TERTRE A*,*
*LEUDIERE V**, HERPE J***
** Airbus Safran Launchers*
Forêt de Vernon BP806, 27207 Vernon, France
*** CNES Launcher Directorate*
52 rue Jacques Hillairet 75612 Paris, France

Abstract

CNES, the French Space Agency, and Airbus Safran Launchers (ASL), are preparing the future for new liquid propulsion rocket engines. The most promising technologies, with regards to cost and mass reduction, have been identified through Research and Technology activities, and are now evaluated on a set of demonstrators. This maturation process will enable to decrease the development duration of the next generation liquid engines. These demonstrators are engine components (turbopumps, combustion chamber, valves, nozzle extension, igniter …), at a scale harmonized around requirements for a low thrust LOx/LH2 engine (thrust: 10 kN, Isp: 450 s).

Among these specifications technologies are the bleed cycle, the low pressure igniter, and the engine operation in throttling or idle mode.

A focus will be made on the combustion chamber: manufacturing aspects as well as firing tests results at P8 DLR will be presented.

1. Introduction and project overview

1.1 Introduction

A demonstration program BOREAS (Bench Optimised for Research and tEchnology mAturation at Subscale) has been initiated in 2011 by CNES and ASL to develop a technological maturation platform for future liquid propulsion rocket engines. The most promising technologies, in regard to cost and mass reduction, have been identified in the frame of Research and Technology activities. Their Technology Readiness Level (TRL) will increase up to 4, thanks to the demonstration on the following engine sub-systems:

- fuel and oxygen turbopumps
- low pressure igniter.

These sub-system demonstrators will be assembled for a system demonstration, which would increase their TRL up to 6.

The reduced scale of the demonstrator BOREAS, a 10kN-thrust class bleed cycle engine, has been chosen to optimise the cost of the demonstration while keeping the most representative conditions. The expander bleed cycle has been chosen for its simplicity and robustness.

1.2 Project overview

The detailed design has been frozen by end-2016. The manufacturing of all the components are on-going.

The achievement of the subsystems demonstration tests is planned to 2018 (see Fig 18), followed by the system tests in the new P8.3 test cell.

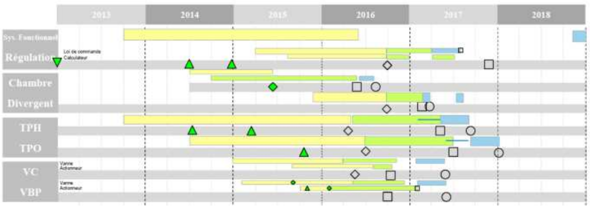

Fig 1: Demonstration planning

2. System design

2.1 Functional System

BOREAS engine is based on the bleed open cycle, which was initially designed with the CNES CARMEN platform [1] and maturated with ASL tools.

The main specifications of this engine are:
- Thrust 10kN
- Specific Impulse (vacuum)=450s
- Large operation domain (50-120% thrust)
- Low cost electronic engine control.
- Idle mode (at start up and/or during operation)
- Chill down consumption reduction
- Sub-systems interfaces simplification

Reference conditions match the 10 kN functional point (called N, see Fig 2), B and H are the 7 and 12 kN operating points that delimit the domain in which the engine should operate without limitation. M is a mid-thrust operating range, today fixed at 5kN.

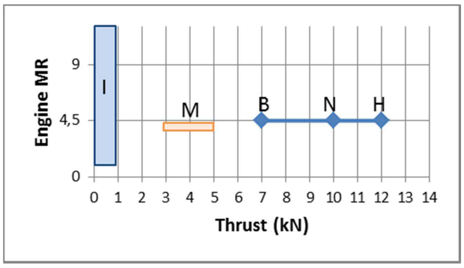

Fig2: Functional Points

The idle mode steady-state point (called I, see Fig 2) will be run at the run-up transient in order to reduce the chill down consumption. Two modes will be investigated: a pump idle mode (with turbopump in operation) and a tank idle mode (without rotation of turbopump).

Reference thermodynamic cycle (see Fig 3) is based on a serial scheme without gas generator or pre-burner, known as the expander bleed cycle.

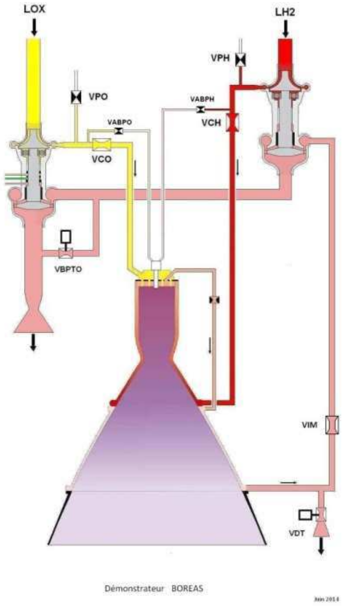

Fig 3: thermodynamic cycle

DOI: 10.13009/EUCASS2017-503

In this serial cycle, the full hydrogen flow discharged by the fuel pump is used for cooling the combustion chamber through regenerative cooling channels. Then, the major part of this hydrogen flow feeds the combustion chamber where the combustion with the oxygen flow produces thrust. The minor part left of the hydrogen flow goes into the "co-flow" regenerative nozzle and then feeds the turbines, before being evacuated into vacuum. The two turbines are fed in series: the hydrogen flow heated by the regenerative circuit of the nozzle first enters the hydrogen turbine, and then the oxygen one.

The main valves are located upstream of the thrust chamber and in parallel of each turbine to allow by-passing flows:

- The VCH feeds the thrust chamber regenerative circuit with the hydrogen flow. It is located at the hydrogen pump outlet just upstream of the regenerative circuit.
- The VCO drives the oxygen flow towards the main combustion chamber. It is located just upstream of the combustion chamber.
- The VDT, VBPTO and VIM are located on the turbines hydrogen circuit. The VDT is used to control the engine thrust and by-passes both the hydrogen and the oxygen turbine. The VBPTO is the oxygen turbine by-pass valve which is mainly used to set the mixture ratio. These two valves are used to regulate the system on the operating domain. The VIM is used during tank idle-mode to prevent H2-flow in the turbines.

Two engine functional models are used to establish the system technical specifications and the sub-system requirement specifications:

- the engine functional steady-state model, which builds the demonstration operating envelop (Fig 4) and issues the sub-systems performance requirements. The generated domains include manufacturing discrepancies and conception unknowns in order to specify the most dimensioning points at sub-systems level.
- the engine functional transient model (Fig.5) which establishes valves and control devices requirements, and sub-systems entry parameters. It helps to identify the critical sub-system performances during start-up, shut-down and transient between operating point.

The quality of the simulations, i.e. physical representativeness and degree of accuracy, is essential to provide:

- a good understanding of the engine behaviour, also in regard to the tests campaign
- accurate specifications of the subsystem

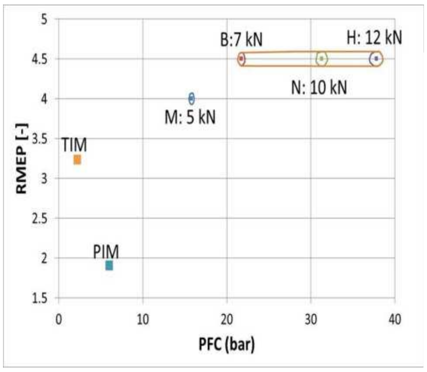

Fig 4: operating domain

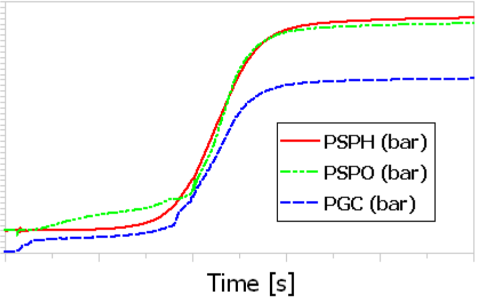

Fig 5: Amesim Engine start-up simulation

As the domain includes idle mode points with diphasic phenomena, new generation software is employed, which allows simulating multiphysic aspects thanks to conservative coupling between different solvers, a premiere at definition level.

DOI: 10.13009/EUCASS2017-503

2.2 Regulation and HMS

A key aspect of the demonstrator is to prepare an electrical, versatile engine functioning under a wide range of operating conditions.

Performances of the engine in terms of Combustion pressure and Mixture ratio will be though achieved by a control system, including electrical actuators, calculator and software control laws.

Several challenges are being taken up:
- Demonstrate low-cost calculator capabilities for low-cost engine embedded control system (hardware and software).
- Provide a control law on a large thrust range.

To prepare Health Monitoring System-Control System Interactions (HCI), several monitoring functions are designed and will be tested on the coming demonstrator, aiming at improvement of engine availability and reduction of test development operating costs.

2.3 Mechanical Integration

As BOREAS is a technical platform, the mechanical integration system demonstration focuses on the integration of technologies such as composite rods including damping devices or C ring seals to be tested under spatial environment.

New generation software is also employed to establish rapidly the system technical specifications and the sub-system requirement specifications.

3. Subsystem Design

3.1 Hydrogen Turbopump (TPH)

The hydrogen turbopump performance requirements at the extreme operating point H are the following:

	Specification	**Units**
Rotational Speed	90 000	rpm
Inlet Mass Flow	0.5	Kg/s
ΔP	47	bar

Design choices to comply with these requirements, together with the objectives of cost reduction and engine simplification, are given below:

- Single stage centrifugal pump with open impeller.
- Single stage supersonic turbine with partial admission nozzles.
- Foil bearings with gaseous hydrogen lubrication.
- Passive balancing system.

On this demonstrator, the technological breakthroughs are:
- The use of Titanium Additive Layer Manufacturing for the housing, for mass and cost reductions (Fig. 6)
- The open impeller for cost reduction.
- The foil bearings with gaseous hydrogen lubrication, for cost reduction, chill-down improvement and TP architecture simplification.

Fig 6: TPH Casing

Foil bearings tests have been performed on a specialised test case: with different features of the top and bump foils and on a wide rotational speed range (up to 90000 rpm). The fabrication process is matured and the choice of the design is finalised.

Moreover, specific innovative instrumentation have been developed and tested, such as optical rotational speed measurement or miniature sensors for cryogenic temperature or/and pressure.

3.2 Oxygen Turbopump (TPO)

The performance requirements at the extreme operating point H are the following:

	Specification	**Units**
Rotational Speed	30 000	rpm
Inlet Mass Flow	2.3	Kg/s
ΔP	48	bar

One major requirement of the oxygen turbopump demonstrator is to use as much as possible the same components as the hydrogen turbopump, in order to reduce the development costs and duration. The design choices are:

- Single stage centrifugal pump with open impeller
- Single stage supersonic turbine with gaseous hydrogen cooled bearings
- Passive balancing system.

The most promising technologies of this demonstrator are:

- The use of Inconel Additive Layer Manufacturing for the casing and the impeller, once again for mass and cost reduction
- The gaseous hydrogen cooled ball bearings for TP architecture simplification

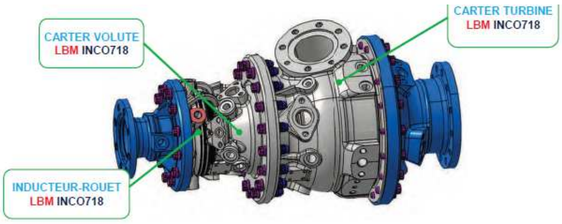

Figure 7: oxygen turbopump

DOI: 10.13009/EUCASS2017-503

3.3 Low Pressure Igniter Demonstrator

A challenging aspect in this demonstration program is the development of a low-pressure igniter. In this configuration the igniter is not fed by high pressure vessels but by direct tap-off from the main feed lines to the thrust chamber. This is considered as an economical and robust solution for future European liquid propulsion engines.

However, this low-pressure technology (3 bars) implies a strong coupling with the engine system since the propellants are directly taken on the engine lines. Therefore, additional system analyses are mandatory in order to ensure good igniter behaviour despite the various feeding conditions, to verify that the impact of the tap-off of propellants on the main lines is negligible and to define the valves sequences and engine transients.

A first trade-off has been performed to choose the H2 tap-off location. Tap-off just upstream the chamber valves (VCO and VCH) is chosen as reference solution within different possibilities: before/after chamber valves, before/after pumps, and for hydrogen side, in the injection head or at the end of the regenerative nozzle.

The second trade-off was on the functional design of the igniter itself. The solution adopted is a low temperature core combustion with fuel-rich mixture ratio (MR<1), supplemented with oxygen post-flow to increase the mixture ratio to 6.

The igniter body has been manufactured in Hastelloy X using Additive Layer Manufacturing.

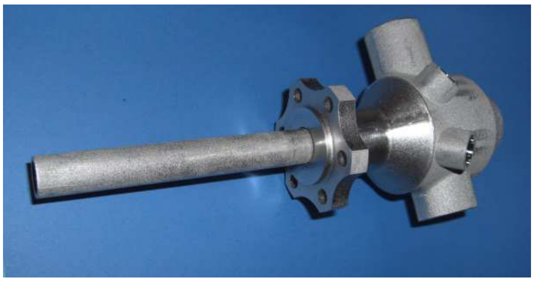

Fig 8: Igniter

Since 2014, several combustion test campaigns have been performed with the BOREAS igniter, mounted first on the injection head only, and then on the combustion chamber. A wide range of operating conditions has been tested, including pressure variations, H2/O2 or CH4/O2 configurations.
The high reliability of the igniter and chamber ignition has been demonstrated, together with the robustness and life duration of the igniter body. In addition, thanks to the large range of ignitions conditions tested and, in coherence with 3D Large Eddy Simulations of a 60 degrees domain with the AVBP code [2], the start-up sequence has been optimised and margins estimated.

Moreover these tests demonstrate the versatility of the BOREAS Platform.

DOI: 10.13009/EUCASS2017-503

3.4 Oxygen and Hydrogen Feeding Valve (VCO, VCH)

For this BOREAS program, cost, size and mass minimisation have also been strong criteria for the oxygen feeding valve design. In agreement with these objectives, a number of constraints related to the use of electrical systems on-board launchers, such as multiple command and control channels, have been relaxed.

This demonstrator uses the following technologies:

- Additive Layer Manufacturing of Inconel for the main valve casing, that allows significant cost reductions and releases some machining-oriented design constraints;
- Immersed rotor brushless electric actuator to supress ring and to increase the fiability.
- Rotor position control of the rotor through Hall effect probes
- 3 positions (open/closed/idle mode) poppet valve, that does not require precise positioning or closed-loop control of the poppet position

Fig 9: oxygen and hydrogen feeding valve

3.5 Regulation valve (VDT, VBPTO)

To allow its large functioning range BOREAS engine needs to control throttling and so a regulation valve was implemented.

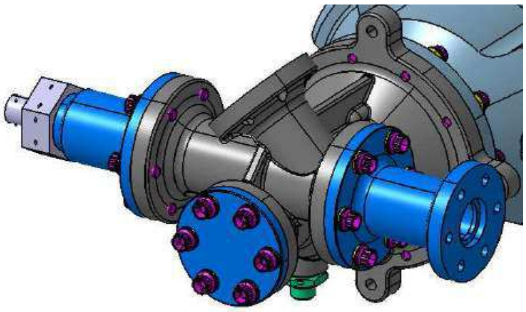

Figure 10: regulation valve

The technologies foreseen on this demonstrator are the following:

- Brushless actuator
- Tube valve with evolving opening to cope with the large operating domain targeted.

Design choices are driven by cost reduction, manufacturing and assembly simplification.

DOI: 10.13009/EUCASS2017-503

3.6 Combustion Chamber (CC)

The combustion chamber features a counter-flow H2 regenerative cooling circuit and a bleed tap-off in the injection head to feed the nozzle extension cooling channels. As for other subsystems, the selection of the technologies was based on cost and mass reduction objectives.

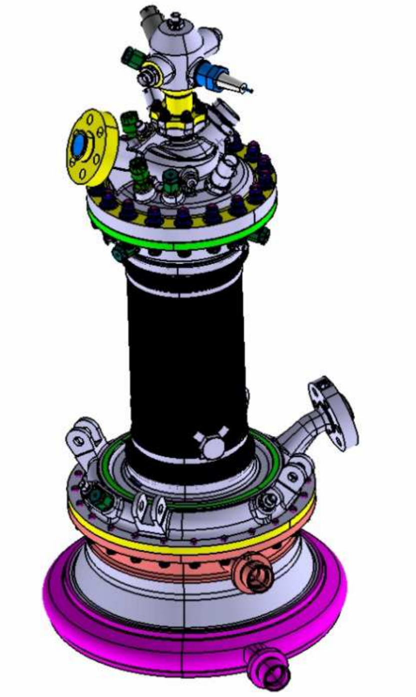

Fig 11: Combustion chamber CAD

The following technological breakthroughs have been selected in the trade-off phase:

- Injection head and inlet torus in Inco 718 were obtained by Direct Metal Laser Sintering (DMLS). The objective of using this process is to reduce the manufacturing costs and to increase the performance through geometrical improvements impossible with usual manufacturing methods. For example, the bleed tap-off is situated in the central part of the injection head (to reduce non-uniformity of the flow in the injection elements), design that is possible thanks to DMLS capabilities.
- CuAgZr plasma-sprayed liner: this technology aims at reducing both cost and lead time of the liner.
- Increased heat transfer enhancement thanks to longitudinal ribs: the technology aims at increasing the performance of the engine by increasing the H2 temperature at the end of the regenerative circuit.
- Structural part of the CC manufactured in PMC (Polymer Matrix Composite). This technology offers the opportunity to drastically reduce the mass of the combustion chamber as well as increasing liner life duration by reducing compression stresses, especially in throat area.

Concerning the CuAgZr Vacuum Plasma Sprayed (VPS) liner, the development of the manufacturing process that was realized by Snecma end of the 90's [2] in cooperation with LERMPS/UTBM, has been updated and adapted to the Boreas configuration.

Two kinds of CC have been manufactured thanks to this process:

- A "classical" smooth Hot Gas Wall (HGW) chamber
- A "ribbed" HGW chamber equipped with linear trapezoidal section heat transfer enhancers.

Thanks to several samples manufactured in the frame of the project, the material properties of the sprayed CuAgZr have been completed and used as input for mechanical justification of the liners The ribs design has been optimized to simplify the manufacturing process.

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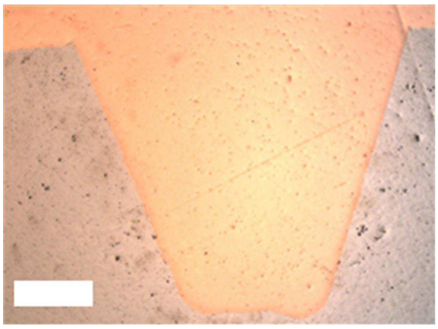

Fig 12: Heat transfer enhancer

The dimensions and position of the ribs has been studied and optimized from both mechanical strength and functional efficiency point of view. During hot fire test they allow a significant increase of the heat exchange between hot gas and coolant inside the liner channels without being damaged nor cracked.

Among the technologies developed for the CC, PMC jacket in particular led to a complete development program since no anteriority was available on similar component. Thanks to a constructive cooperation with Safran Composites (Safran Group) and DJP (Nimrod Group) in charge of the manufacturing, ASL proposed an innovative, low weight, low cost PMC jacket concept.
The main challenges were to select the right material/process couple to withstand both thermal and mechanical loads applied on the jacket and also to design the proper PMC/metal connections.
These technical choices have first been tested, optimized and then validated on technological specimen representative of the final PMC structural jacket. One of these specimens (instrumented with strain gauges and acoustic emissions sensors) is shown on Figure 13, ready for LCF and tension tests under cryogenic conditions. The specimen was also submitted to proof pressure test at RT. In both cases, the specimens performed well and allow anchoring the orthotropic material behaviour in the corresponding FEM computations.

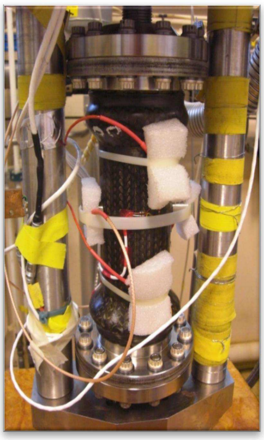

Fig 13: PMC technological specimen representative of final CC jacket ready for cryo tension test.

Thanks to these tests, the mechanical behaviour of the jacket and its bonding interfaces with metallic parts located at each extremity have been understood and this allowed to implement optimizations in the manufacturing process, in the connections design and in the identification of the material parameters in all directions.

On this experimentally and simulations consolidated basis, the chosen concepts were used “as is” on the full scale jackets for the real chambers which then performed hot fire test campaign with behaviours fully in line with predictions.

As previously mentioned, based on these components tests/manufacturing tests, two specimens of combustion chambers have been manufactured between 2014 and 2016: one ribs chamber (with heat transfer enhancers) and one smooth chamber (without).
Both chambers have been successfully tested in 2016 at the P8 test stand in DLR Lampoldshausen.

DOI: 10.13009/EUCASS2017-503

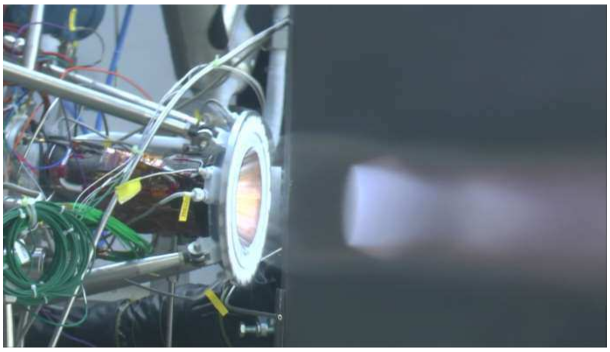

Fig 14: Combustion chamber at P8 in 2016

The main objectives of these tests were:

- To validated the thermomechanical robustness of the hardware on the full operating domain
- To characterise the performance of the manufactured design, and in particular of the heat transfer enhancers
- To gather relevant data for functional and mechanical tools anchoring

To this end the chambers have been equipped with extended instrumentation, including hot gas wall measurements implemented before liner and PMC jacket assembly at various locations on the CC.

During this campaign the full range of the operational domain, apart from idle mode, was covered in representative conditions. The CCs have experienced respectively:

- Ribs CC: 470 s of hot run and 9 cycles
- Smooth CC: 630 s of hot run and 6 cycles

The chambers proved their mechanical resistance over the campaign, both for the liner life duration, and the PMC jacket robustness. The stresses observed during test on the jacket were very similar to the foreseen evolution, validating the expected behaviour of the PMC.
The functional performance of both CCs could also be measured and compared. The observed behaviour is fairly close to the forecast with 3D CFD simulations with a significant heat transfer increase due to the ribs.

Further tests with these chambers are foreseen in the following years in order to follow-up the ageing process of the liner, and to use this hardware as a platform to improve the knowledge on heat transfer. It is planned in particular to perform tests with the same hardware in LOX/LCH4 and to study the impact of two-phase flow on heat transfer.

3.7 Regenerative nozzle extension (NE)

Initially foreseen to be manufactured in Vacuum Plasma Sprayed like the chamber, the regenerative nozzle extension (NE) underwent a second design loop in 2015/2016 in order to improve the lead time and cost of manufacturing. This improvement was made possible thanks to the availability of new larger machines for Additive layer manufacturing (ALM). This choice allowed to produce the NE as a single part hardware and drastically reduce the lead and thus be ready for tests as early as mid-2017.

Fig 15: Photo of ALM blank of NE

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It allowed also various geometrical optimizations to improve the performance of the NE, among which:

- Highly optimized cooling channels design
- Addition of heat transfer enhancers (see Figure 16)
- Integration of instrumentation in inner locations usually not reachable with machining

Fig 16: CAD view of the heat enhancers

The newly manufactured NE will be tested at P8 test stand in June 2017 on the BOREAS engine mount and under vacuum conditions. The vacuum is obtained thanks to the Advanced Altitude Simulation (AAS), an innovative passive altitude simulation with diffusor developed by DLR. This test campaign, in addition to the characterisation of the NE behaviour, will be a significant step forward towards the testing of the full BOREAS engine in conditions representative of an upper stage engine.

4. Conclusion and perspectives

This demonstration program will enable to test future technologies in representative conditions with LOX/LH2 and LOX/CH4 by 2017, achieving a TRL up to 6 at that time.

The small scale of the demonstrators is quite challenging, but decreases the cost of the demonstration significantly. Moreover, it is expected that using such a low-cost approach will allow to multiply tests days and to reach more numerous objectives, than on a full-scale hardware.

This demonstration program is included in a long term roadmap, built by CNES and ASL, to prepare new cryogenic engines for future launchers, by 2025.

References

[1] CARMEN, the liquid propulsion systems simulation platform, Space propulsion 2014, T.Juès
[2] AVBP. website: www.cerfacs.fr/cfd/avbp_code.php and www.cerfacs.fr/cfd/cfdpublications.html