French Flight Test Program LEA Status

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ABSTRACT

The present lecture of the RTO-AVT-VKI course "HIGH SPEED PROPULSION: ENGINE DESIGN – INTEGRATION AND THERMAL MANAGEMENT" is focused on the French flight experiment program called "LEA".

French R&T effort for hypersonic airbreathing propulsion is focusing on needed technologies for the propulsion system and acquisition of aero-propulsive balance prediction capability. A large part of technology development effort can be led on ground and is currently dedicated to combustion chamber to ensure its performance and thermo-mechanical strength. On the contrary, it is mandatory to flight demonstrate capability to predict the aero-propulsive balance. In that view, MBDA and ONERA are leading the flight testing LEA program. Started in January 2003, the program will end in 2015 after 4 autonomous flight tests of an experimental vehicle in Mach number range 4 to 8. Guidelines for LEA vehicle and its propulsion system design have been validated in 2006 by a Preliminary Design Review. The running Phase 2 aims at getting a detailed design while validating the aero-propulsive configuration by a first free jet test series to be performed early in 2011. It led to a Critical Design Review performed in June/July 2009…

INTRODUCTION

Since early nineties, MBDA and ONERA are leading a large Research and Technology effort aiming at acquiring detailed knowledge on high-speed airbreathing propulsion and at developing corresponding technologies.

The development of operational, civilian or military, application of the high-speed airbreathing propulsion depends of two key points:

- Development of needed technologies for the propulsion system as a low weight, high robustness fuel-cooled structure for the combustor; and
- Capability to predict with a reasonable accuracy and to optimise the aero-propulsive balance (or generalized thrust-minus-drag).

Then, MBDA and ONERA are today focusing their effort on these key issues.

TECHNOLOGY DEVELOPMENT EFFORT

Even if technologies will finally need to be flight proven, a large part of the technology development effort can be led with limited adaptation of available ground test facilities [1] and classical numerical simulation (thermal stress, mechanics…).

In that field, the effort started during the PREPHA Program has being continued last decade through several initiatives taken by ONERA and MBDA [2]:

- JAPHAR program ([3] to [5]);
- WRR program ([6] to [8]);
- PROMETHEE program ([9]);
- A3CP ([10]);
- PTAH-SOCAR (MBDA-Astrium ST); and
- Cooperation with research laboratories (Ref[11] to Ref[13]).

Today, the technology development effort is pursued on different aspects which contribute to ensure the performance and thermal and mechanical strength of the combustion chamber:

- Variable geometry, needed to optimize the performance on the overall flight Mach number range;
- Endothermic fuel used as coolant for combustion chamber structure ([14] to [17]); and
- Fuel-cooled structure itself ([18] to [20]).

In the field of fuel-cooled structures, several PTAH-SOCAR C/SiC composite panels have been successfully tested by MBDA and Astrium ST in representative conditions and long accumulated test duration. This effort led to the development of a part of a combustion chamber duct, made of one single part, which has been successfully tested at ONERA ATD 5 test facility in early 2006 (Fig.1).

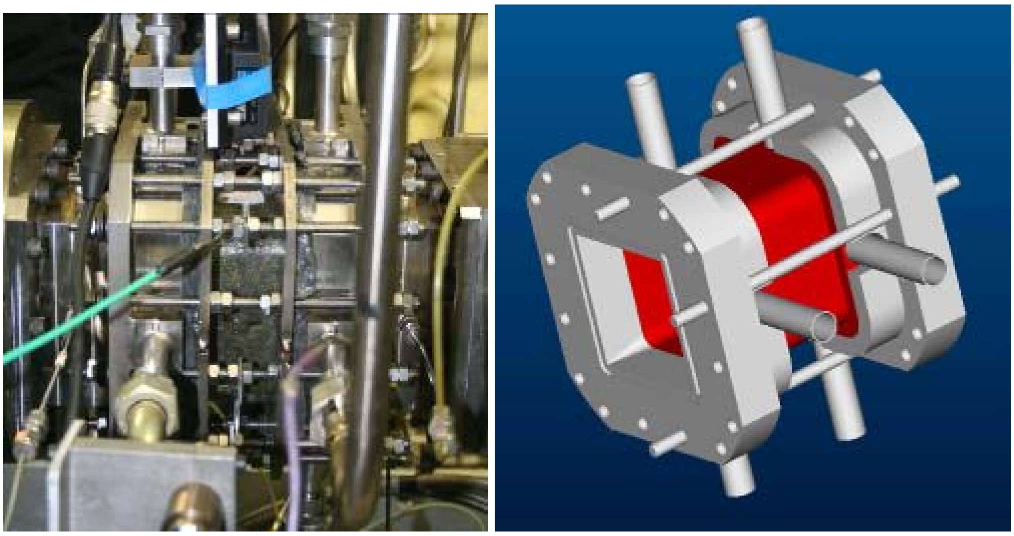
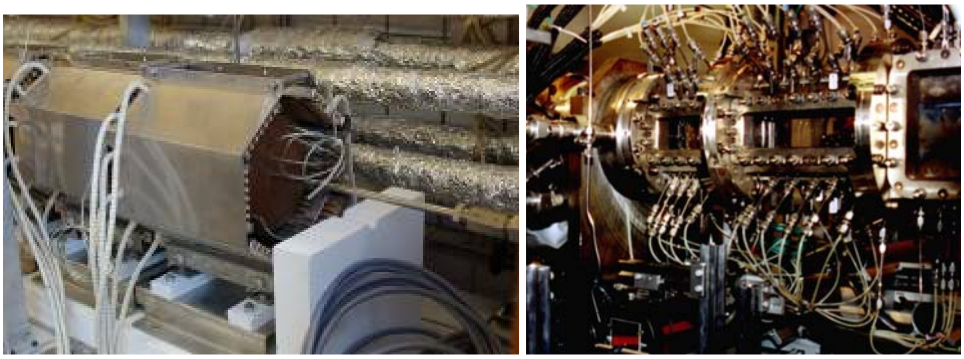


Figure 1: Cooled composite combustion chamber duct (in red) tested at ONERA ATD5.

Today, the development of the fuel-cooled C/SiC structure technology is pursued, not only for high-speed airbreathing application [21], and will lead to new demonstration steps by taking advantage of the new test facility METHYLE [22].

Regarding studies related to endothermic fuels, the effort is shared between reforming kinetic modelling (cooperation with DCPR research laboratory in Nancy) and basic experiment at ONERA (called MPP) to understand the reforming process and to validate the modelling (Fig.2). These works allowed to develop a numerical tool able to simulate the operation of a fuel-cooled structure taking into account the heat exchanges, the fuel hydrodynamics and its reforming kinetic [19].



MPP LAERTE

Figure 2: Basic experiment on endothermic fuel at ONERA.

More recently, the work has been focused on heterogeneous pyrolysis [23] or catalytic reforming [24] and combustion process of the reforming products. For this last point, on one hand, a specific effort has been undertaken to establish relevant chemistry kinetic model for combustion and, on the other hand, the MPP has been coupled with hypersonic test line of LAERTE laboratory at ONERA Palaiseau in order to perform preliminary combustion tests of reforming products and check the effect of chemical composition on ignition delay.

Other details can be found in the lecture "scramjet thermal management" [41].

Beyond works already in progress, the test facility, developed by MBDA and ROXEL in their Bourges Subdray test center in the framework of PREPHA program, has been upgraded. The new test facility, called METHYLE (Fig.3, [22]), allows performing long endurance test in representative conditions to pursue and reinforce technology development by using a modular water-cooled dual mode ramjet combustion chamber able to integrate different kind of testing parts as for:

- Element of variable geometry;
- Sealing system;
- Fuel-cooled structure;
- Measurement techniques; and
- Engine control system.

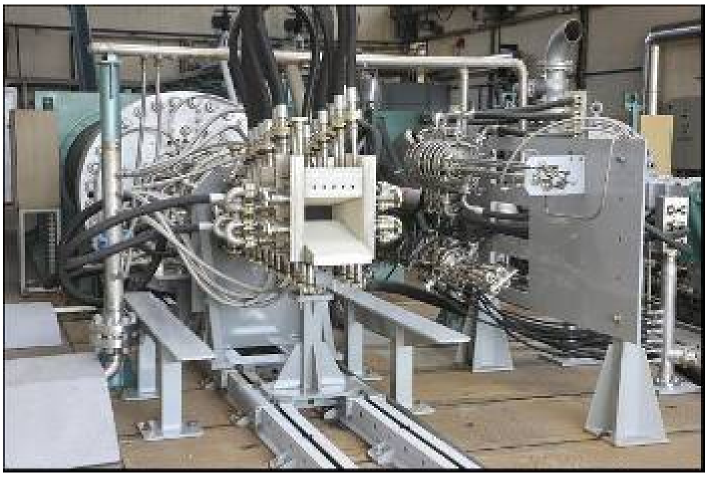


Figure 3: METHYLE test facility at MBDA/ROXEL test center.

Thanks to two endothermic fuel preheaters, it is possible to separately test the engine cooling by endothermic fuel while burning gaseous methane and hydrogen mixture in the combustion chamber or test the combustion of reformed endothermic fuel products while cooling the engine by water.

METHYLE entered into service early in 2009 and two operational test series using a modular water-cooled dual-mode ramjet combustion chamber, called SMR, have been performed in 2009 [22].

LEA FLIGHT TEST PROGRAM CONCEPT

The extreme sensitivity of the aero-propulsive balance on one hand, and the limited capability of ground test facilities to represent right flight conditions on the other hand, make mandatory the definition of a specific on-ground development methodology coupling very closely experimental and numerical approaches.

Obviously, such a methodology is very challenging. Before starting any operational development, it must be demonstrated that applying this approach will give an accurate value of the performance, allowing to guarantee design margins and to identify properly right directions for optimizing the system design. That is why, a flight experimental program, allowing applying the methodology and flight validating it, is a mandatory step towards future operational developments.

Beyond all current technology development works mentioned here above, and on the basis of previous acquired results, MBDA and ONERA started a flight test program, called LEA, in January 2003 with the support of French Administration.

In order to limit the cost, this flight test program will be carried-out with a minimum size experimental vehicle without any technology demonstration purpose (use of existing technologies as often as possible) (Fig.4). In the same view this vehicle will be non-recoverable, then non-reusable.

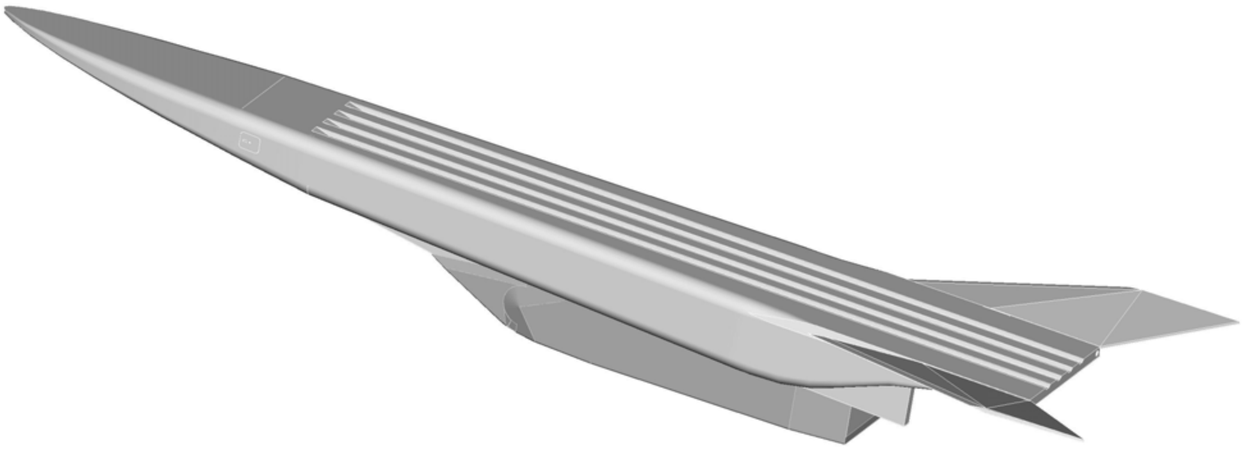


Figure 4: CAD view of LEA vehicle.

The test principle consists in accelerating the LEA experimental vehicle specimen thanks to an air-launched booster up to the given test Mach number, chosen in the range 4 to 8. Then, after booster separation and stabilization, the experimental vehicle will fly autonomously during 20-30 seconds (Fig.5).

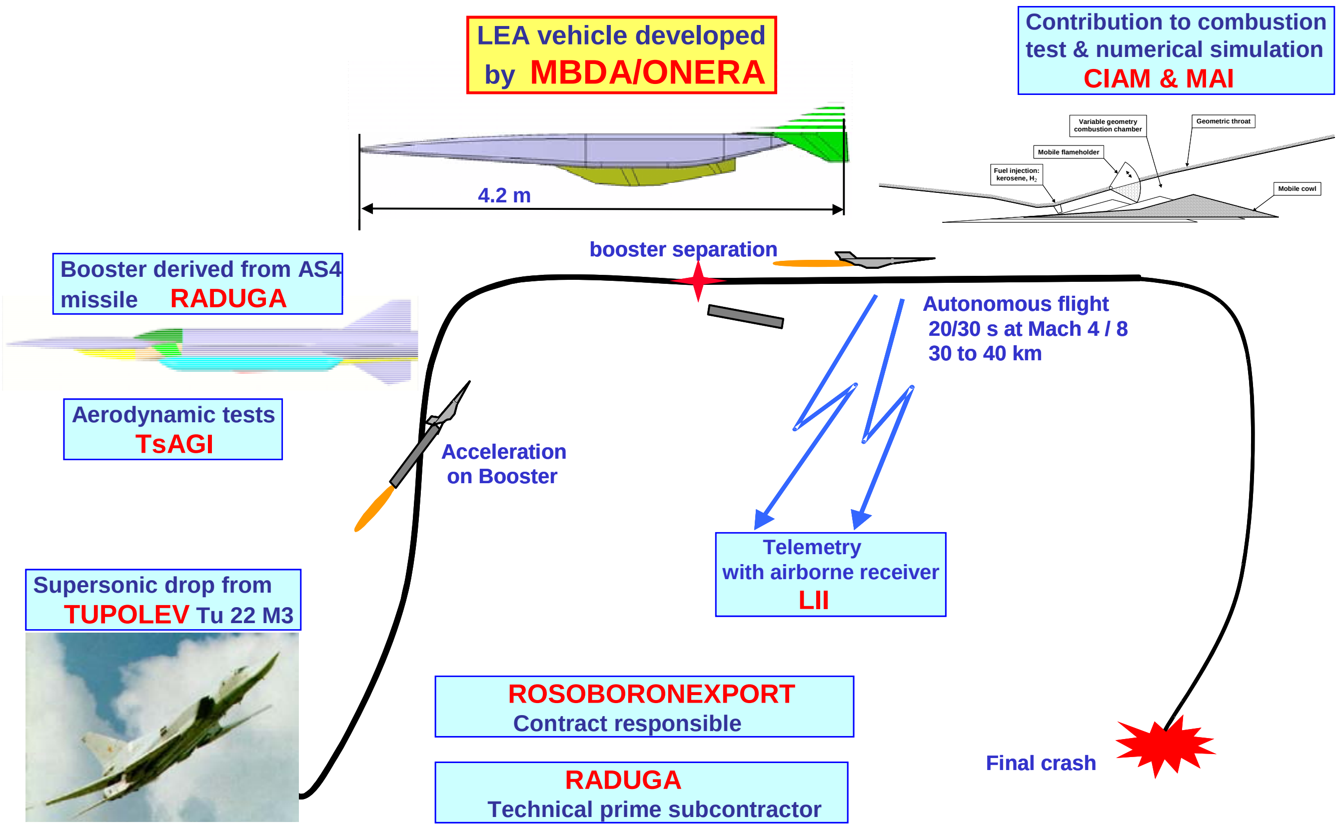


Figure 5: LEA flight testing sequence.

During this autonomous flight, the airbreathing propulsion system will be ignited during 5 to 10 seconds with a fuel-to-air equivalence ratio variation. This approach, already used by X43A in USA, allows ensuring flight data acquisition at the right Mach number without mandatory need to get largely positive aero-propulsive balance (generalized thrust minus drag balance). Then the vehicle design constraints can be slightly relaxed.

Taking advantage of this last point, the vehicle would be specifically instrumented to give a precise evaluation of the aero-propulsive balance with and without combustion and to determine the contribution of each propulsion system component to this balance. All measured parameters will be transmitted to ground by telemetry.

As shown by Fig.5, a cooperation has been set up with Russian partners in order to take advantage of existing acceleration means and available test range.

As explained previously, and beyond a detailed understanding of the components contribution to the aero-propulsive balance, such a flight test program will give the opportunity to define, implement and validate a development methodology applicable to any future operational development.

TECHNICAL STATUS

Engine Concept

The airbreathing propulsion system concept has been chosen by taking into account all results acquired during engines developments performed these last 15 years. The finally selected concept is a variable geometry one using a simple translation movement of the engine cowl and a thermal throttling (Fig.6).

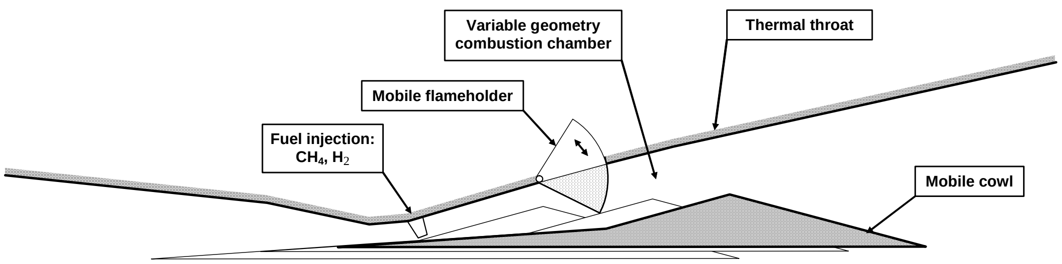


Figure 6: Concept of translating cowl variable geometry engine.

Nevertheless, as each flight test will be performed at a quite constant Mach number, a fixed geometry engine will be used on board of each LEA test vehicle, this engine configuration being representative of the selected variable geometry concept at the tested flight Mach number.

In order to limit the complexity and cost of the system, it has been decided to base the design on metallic heat sink structure with a high temperature low thermal conductivity coating.

The fuel has also been chosen. The most part of French experience in supersonic combustion is related to Hydrogen. But, considering the very low density of Hydrogen, it is preferable to avoid this fuel in order to limit the size of the tank, then the size of the vehicle and consecutive difficulties to find a possible acceleration system complying with the needs (integration constraints, needed total energy release…). On the other hand, liquid hydrocarbon fuel could be considered. But, our experience is limited with such a fuel and it would be difficult to ensure a robust ignition and a good combustion efficiency without previous reforming in a regenerative cooling system (simplest technology used on board of the experimental vehicle). Finally, a mixture of gaseous Methane and gaseous Hydrogen has been selected. By using this mixture, it is possible to increase the fuel density then limit the fuel tank size. It could be also possible to vary the H2/CH4 ratio during the flight to ensure a robust ignition and control the heat release along the combustor.

Aero-Propulsive Configuration

Some specific works have been performed to adapt numerical simulation codes to the particular CH4/H2 fuel ([25] to [28]). These codes have been validated thanks to basic experiments led in updated ONERA LAERTE test facility. Moreover, ONERA ATD 5 test facility has been updated to allow CH4/H2 tests for the LEA engine. By waiting, a first test series has been performed with already existing JAPHAR combustion chamber to acquire a first experience with such a fuel ([29]).

Combustion chamber design is still under progress while the optimization of the aeropropulsive configuration is pursued by combining numerical simulation and ground testing ([30]).

Two test facilities are available for the program to perform full scale direct connected pipe with two different technologies for the combustion chamber structure.

At MAI, after the development of a new preheater (vitiator), a full scale water-cooled model (with a 2/3 width) has already been tested in the flight Mach number range 2 to 7+, first with H2 and K as fuels, then with CH4/H2 mixture (Fig.7). A new full scale model with full width has then been developed and new test series is to be performed untill October 2010.

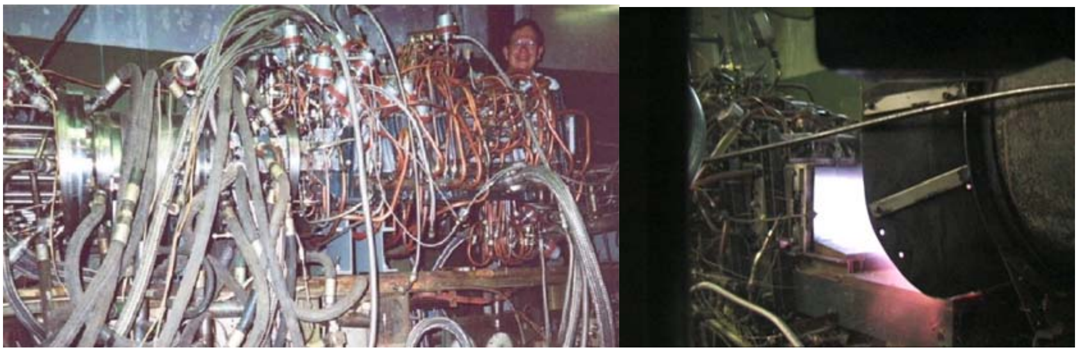


Figure 7: Engine test at MAI.

In parallel, at ONERA ATD 5 test bench, a new copper alloy heat-sink full scale model, called CLEA, is under testing in the flight Mach number range 4 to 7.5. This model is burning CH4/H2 mixture as fuel (Fig.8).

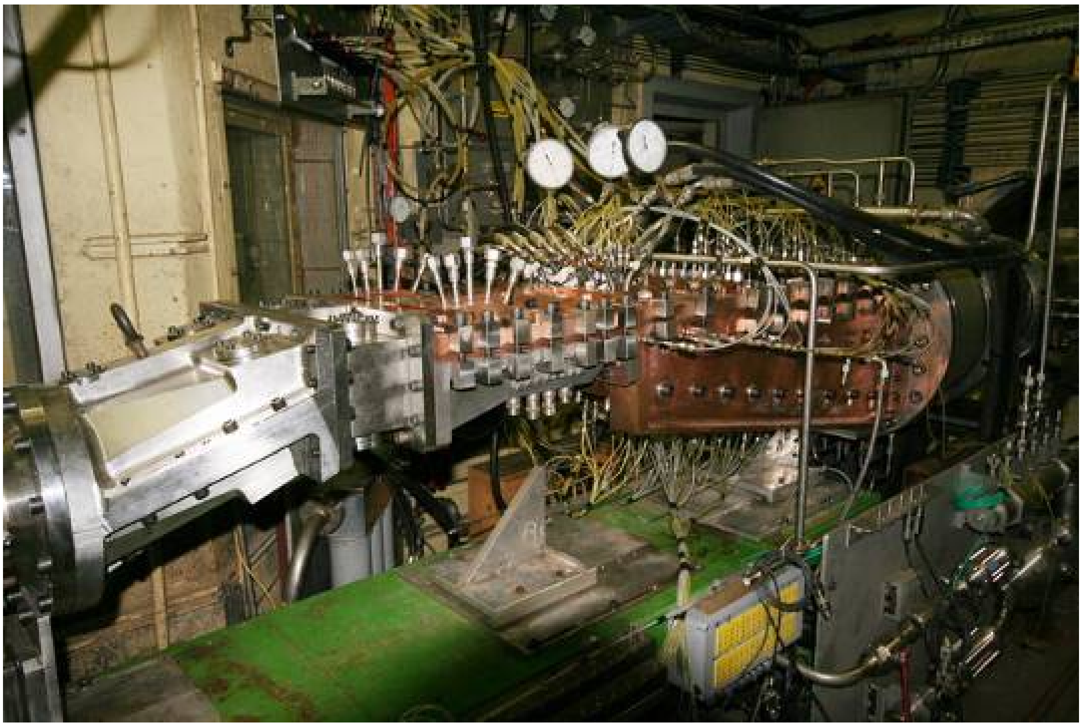


Figure 8: CLEA model under test at ONERA test facility.

Some parametric studies related to forebody have been carried out in order to determine a set of design parameters allowing a satisfactory pre-compression while complying with technology constraints.

Then, the air inlet design has been optimized and a first test series has been performed in the Mach number range 2 to 8 (Fig.9). A new model of the sub-system forebody/air inlet at scale 1/3 has been manufactured and tested to check the forebody boundary layer transition and its effects on inlet performance, to finalize the optimisation of the design and to acquire a detailed characterization of the finally selected inlet configuration.

Figure 9: Forebody/air inlet tested in the Mach number range 2 to 4.

Due to the particular configuration of the afterbody/nozzle, a specific effort was also led to optimize the propulsive performance and well understand the interaction between the propulsive jet and the external flow in order to accurately determine the effect of propulsive jet on external aerodynamic (Fig.10).

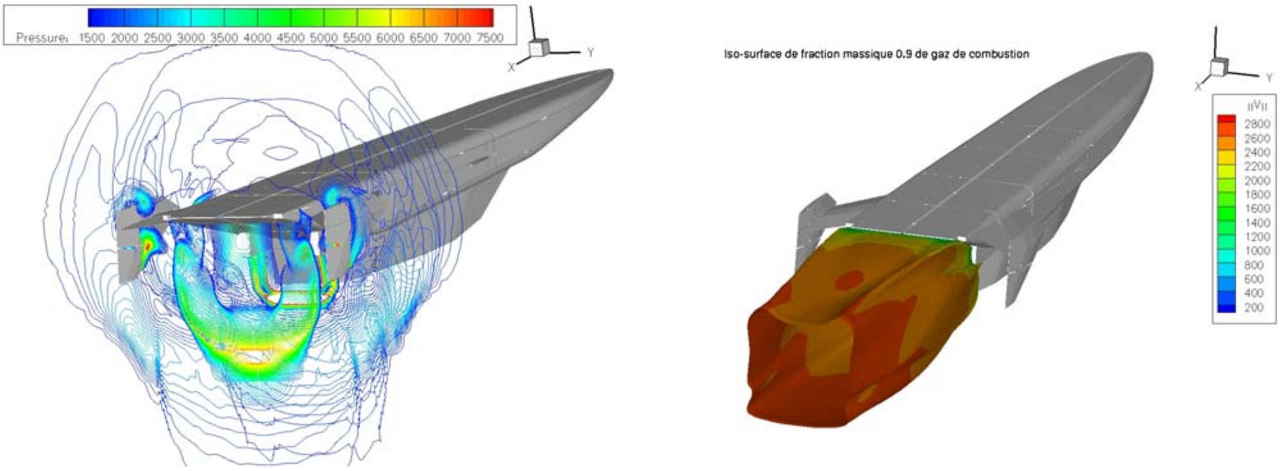


Figure 10: Study of the interaction between propulsive jet and fins.

Aerodynamic behaviour of the LEA vehicle and of the Flight Experimental Composite (FEC) constituted by LEA and its booster have been evaluated by computation. By waiting FEC experimental characterization to be done at TsAGI, a first test series of aerodynamic test has been carried out in May 2008 at ONERA Modane test center. This test series was performed with a ¼ scale permeable model (Fig.11).

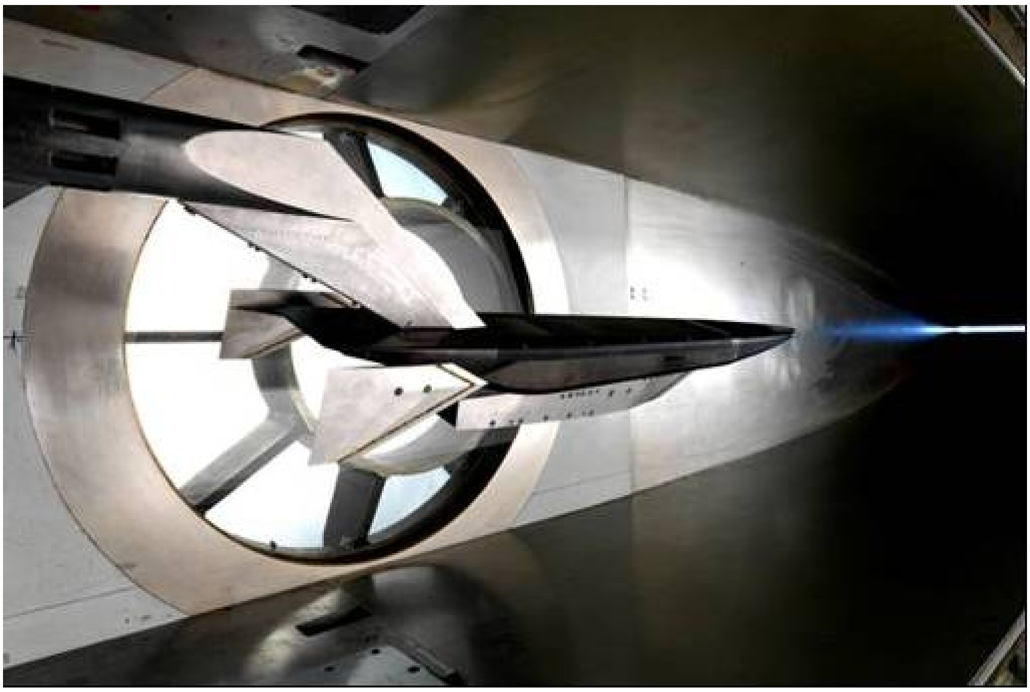


Figure 11: LEA vehicle aerodynamic model – scale ¼.

By another way, aerodynamic test series has been performed at TsAGI to determine aerodynamic interactions during FEC dropping from TU22-M3 aircraft.

The LEA vehicle/booster separation phase can obviously constitute a risk and must be carefully studied. In order to be able to specify in detail all elements of the separation chain, some preliminary computation have been performed to determine aerodynamic interaction. Such study takes into account both close and open air inlet door configurations in order to optimize the sequence and timing between separation and air inlet opening (Fig.12). The aerodynamic model shown in Fig.11 will be later used to perform some tests to check interaction provided by the booster to the LEA vehicle.

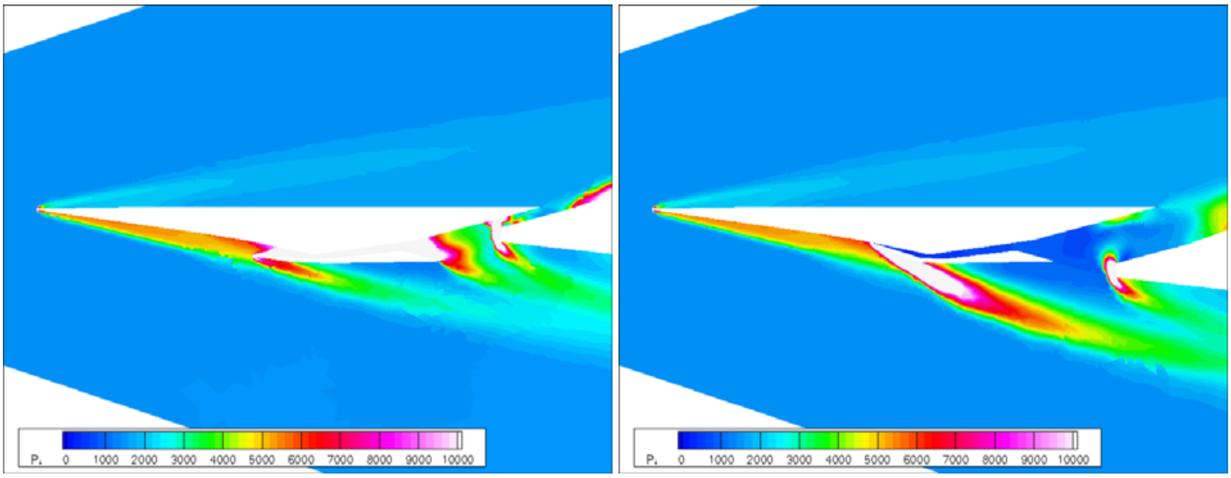


Figure 12: Examples of LEA/Booster interaction with close and open air.

Finally, a large effort has been dedicated to the development of Nose-to-Tail computation tools. Thanks to this, two approaches – NtT computation by blocks or integral NtT computation – are available and daily used to evaluate and optimize the aero-propulsive balance of the vehicle (Fig.13). These computations are also useful for refining the development methodology as well as for understanding all phenomena affecting the aero-propulsive balance like thermo-mechanical deformation or for assessing the relevant parameters to be taken into account within performance models.

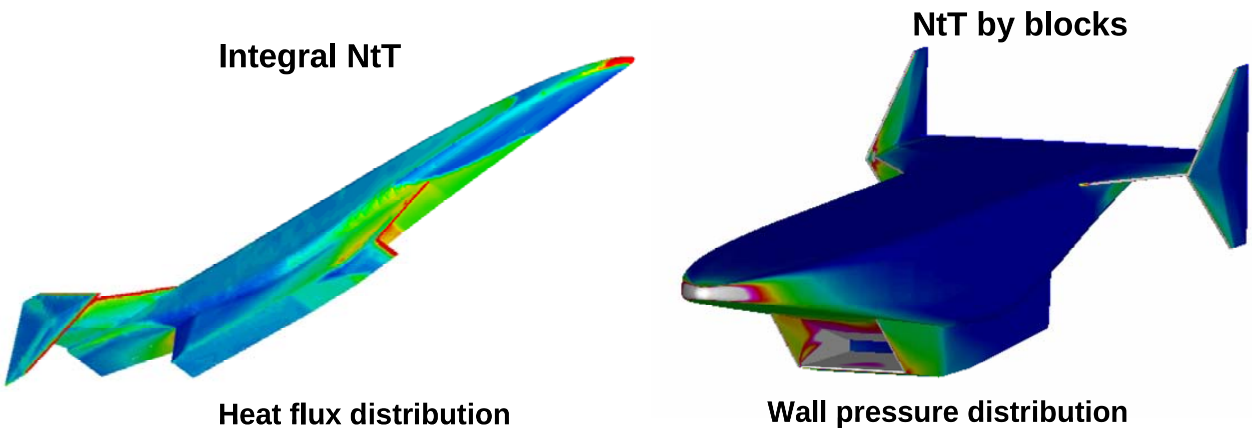


Figure 13: Examples of Nose-to-Tail computation.

All the previous elements have been used to establish a performance model of the vehicle used in a detailed flight simulation covering a complete flight test sequence – LEA/booster dropping from air carrier, acceleration on booster, separation, descent trajectory of booster, LEA autonomous flight up to final crash – and providing:

- Assessment of reachable maximum LEA/booster separation conditions;
- Detailed check of separation phase; and
- Dynamic stability of the LEA vehicle during its free flight.

Vehicle Design

Other activities have also been carried out to chose the basic technologies used for the LEA vehicle and its propulsion system and a preliminary design has been performed and validated by a Preliminary Design Review. This preliminary design has been refined before a Critical Design Review performed in June 2009. During this refinement phase, a particular focus has been made on integration process (both in France and in Russia) (Fig.14) as well as on mass optimization while internal layout and instrumentation and equipment are defined in detail.

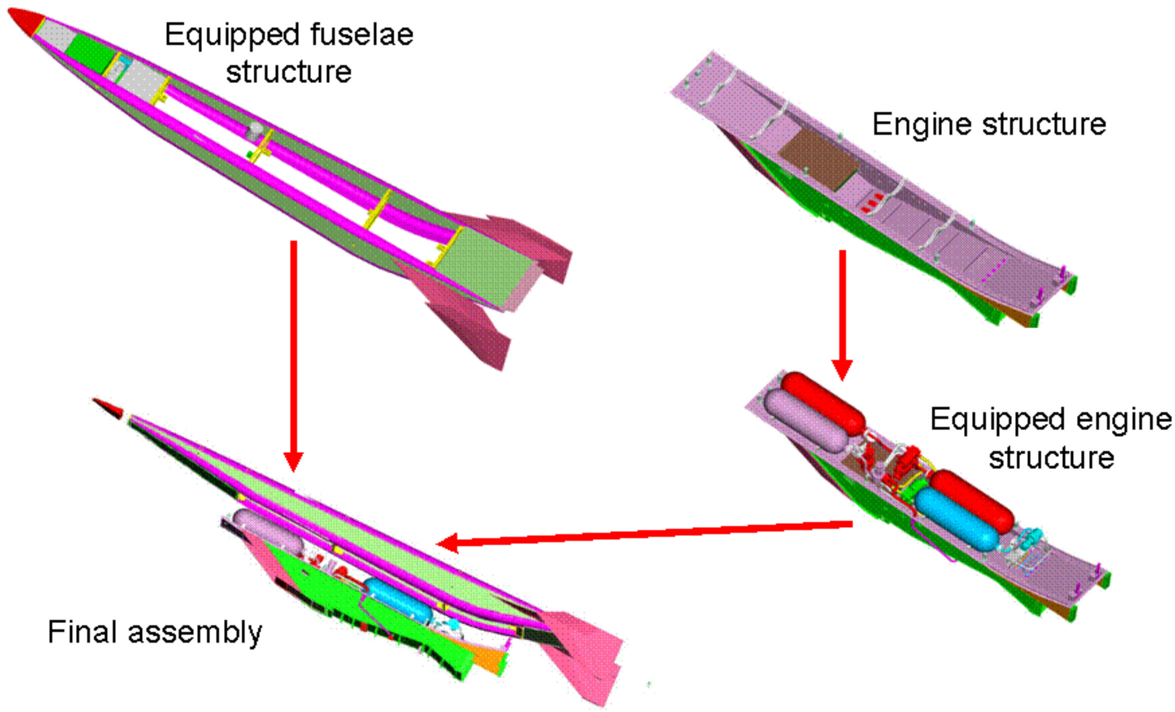
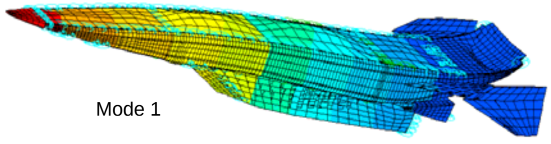
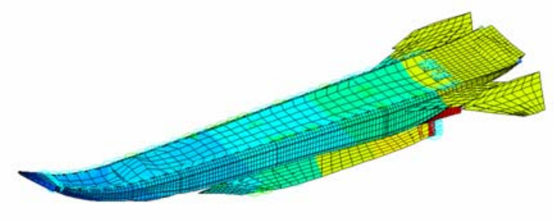


Figure 14: General integration process.

On the basis of the preliminary design, some mechanical and thermo-mechanical simulation have been performed to assess the mechanical behaviour of the vehicle when fixed to the booster through the inter-stage (heavy mechanical loading) as well as in free flight (thermo-mechanical deformation) (Fig.15). A first mechanical test has been carried-out confirming these computation (Fig.16).



Mach 7.5 Free flight thermo-mechanical deformation



Eigen values - 1st mode

Figure 15: Example of mechanical and thermo-mechanical analysis.

Figure 16: LEA vehicle mechanical mock-up under testing.

In the same way, detailed thermal simulation are led to justify the design against thermal loading for specific parts like forebody nose (in which a flush air data system will be embedded) (Fig.17) or for internal equipment and for all fuselage and engine structures.

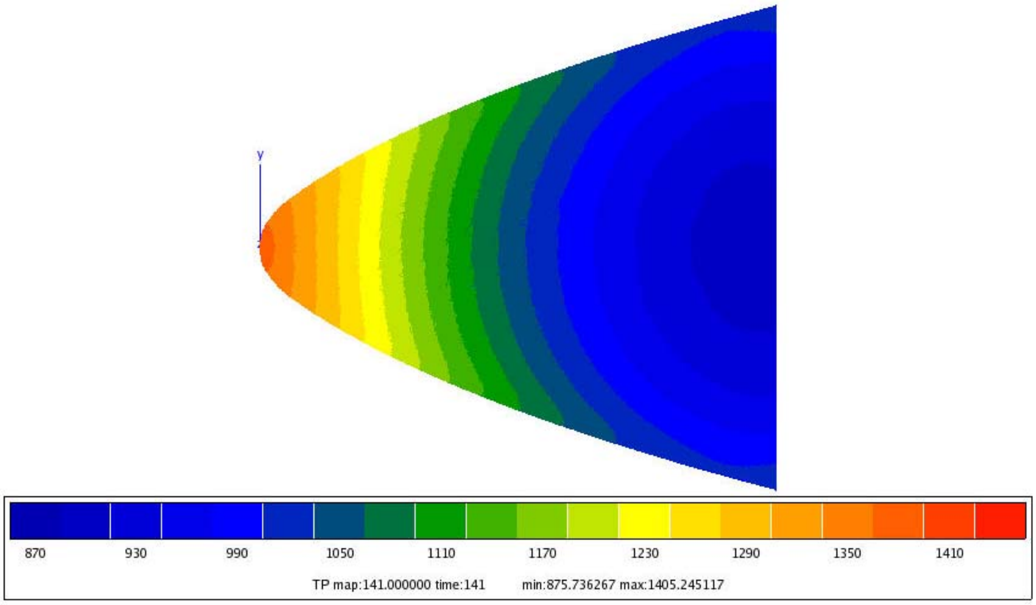


Figure 17: Temperature profile on forebody nose.

GROUND TESTING LOGIC

By another way, the general approach for on-ground testing has been refined accordingly to Fig.18.

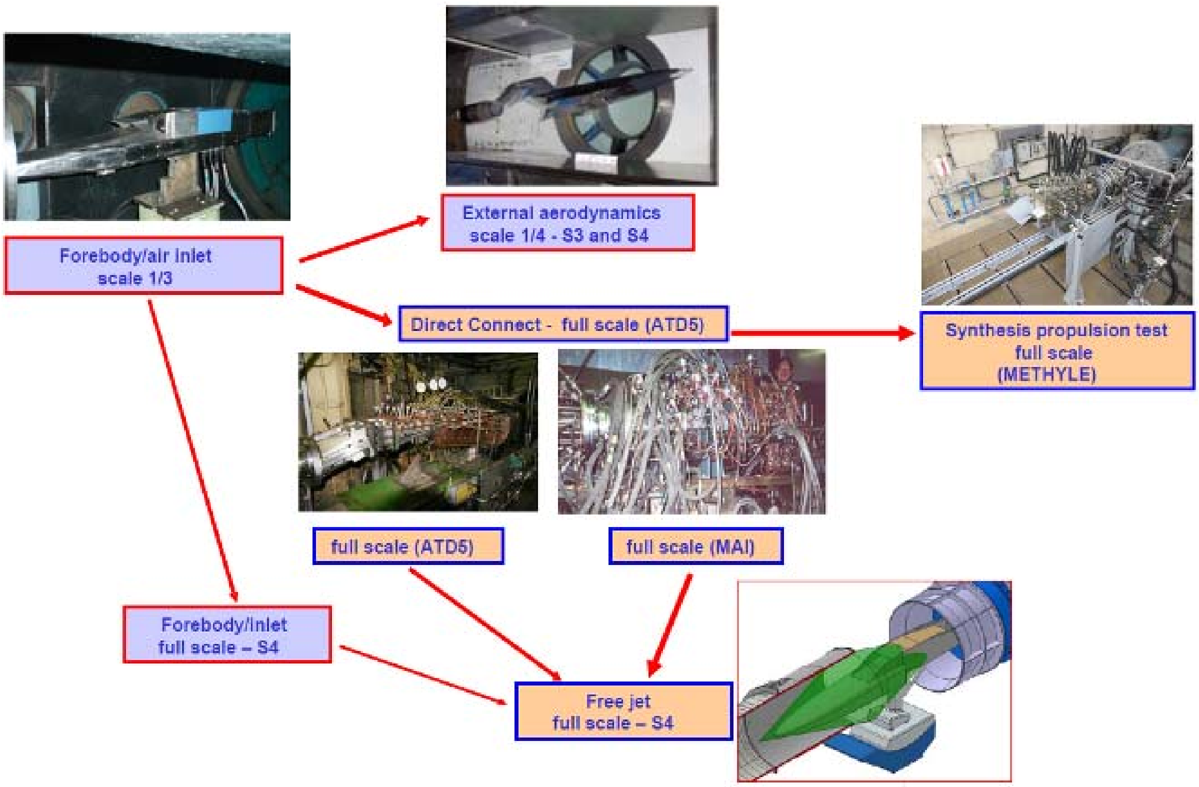


Figure 18: Ground testing logic.

Two options have been evaluated for the planned free jet tests. One consisted in upgrading the S4Ma wind tunnel, located in ONERA Modane test Center in the French Alps, in order to take advantage of the existing alumina pebble bed heater which allows to perform test with air non vitiated by water vapour up to Mach 6.5 conditions (1800 K). Thanks to a complementary pre-burner or to an updating of the pebble bed heater, tests corresponding to Mach 7.5 flight conditions will be also feasible.

The other one consisted in upgrading the METHYLE test facility to take advantage of the already existing fuel system and the large capabilities of mass flow and extraction ([22]).

Detailed design studies have been performed to verify the feasibility of S4MA upgrading (Fig.19) and evaluate precisely the corresponding cost as well as for METHYLE facility.

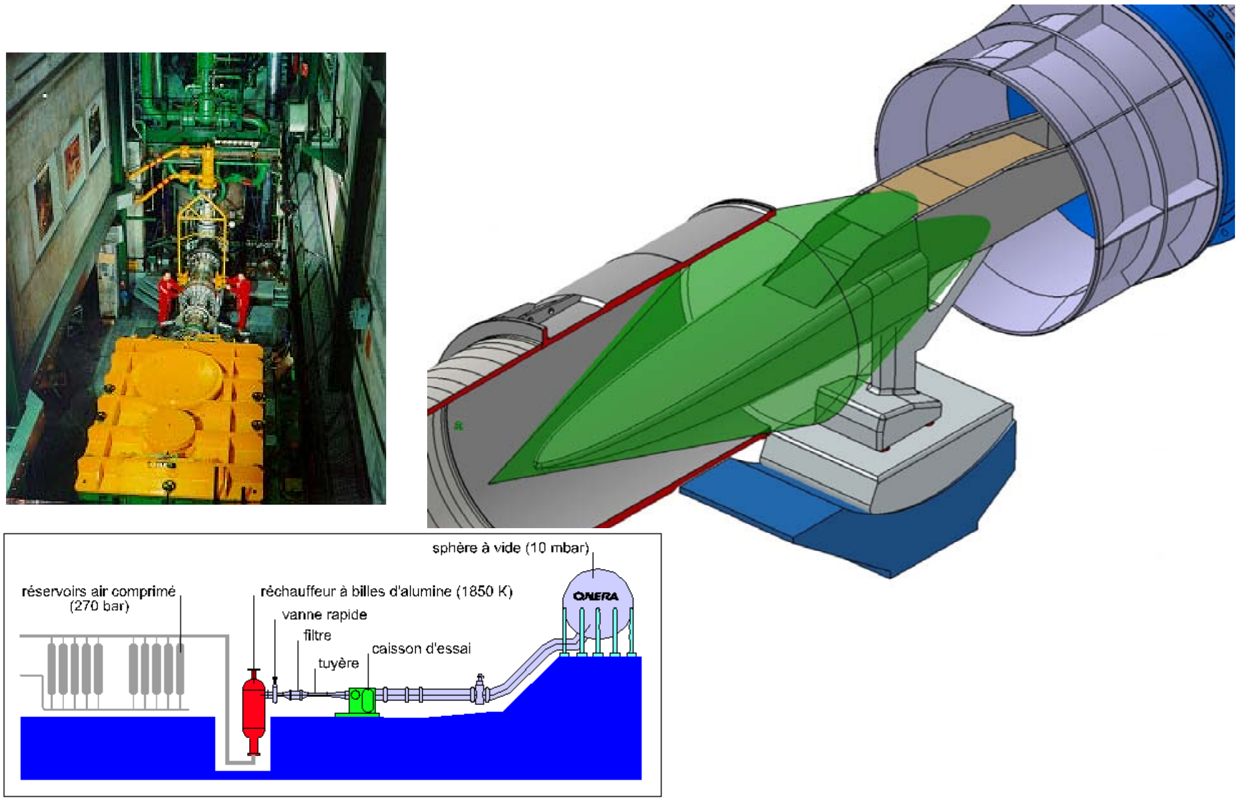


Figure 19: LEA free-jet test installation in S4Ma test facility.

Finally, S4Ma wind tunnel has been down selected and the upgrading is currently in progress ([30]). A first test series at Mach 6 flight conditions with un-vitiated air is planned early in 2011. Then, further test series should be performed.

It has to be noticed that the competitive evaluation of the two potential test facilities gave the opportunity to address in detail the key issue of air vitiation encountered in ground test facilities. Thanks to that, it has been possible to define a set of similarity rules which should allow to accurately represent the actual flight conditions at high Mach number in a vitiated free jet test facility as well as in direct connected pipe test facilities.

CONCLUSION AND PERSPECTIVES

The dual-mode ramjet concept constitutes the main air breathing propulsion system which can be used in a very large flight Mach number range up to Mach 8 (storable fuel) or 10/12 (hydrogen fuel) and then could allow developing future fully reusable space launcher and military systems.

As part of worldwide activities, a permanent Research and Technology effort is being pursued in France since more than fifteen years. Today, this effort aims at addressing the two key technology issues which are the accurate prediction of the aero-propulsive balance of an air breathing vehicle flying at high Mach number and the development of high-temperature structures for the combustion chamber able to withstand the very severe environment generated by the heat release process while ensuring reliability and limited mass and should allow to conclude on the feasibility and interest of possible applications by 2015.

The LEA flight test program constitutes a very important first step in the definition and the validation of a development methodology for hypersonic air breathing vehicles. Nevertheless, if we consider possible application of high-speed airbreathing propulsion to future reusable space launcher, it is clear that the airbreathing phase will have to be extended up to Mach 10/12 ([31 &[32]).

In that view, a minimum R&T program has been proposed ([33]). It includes an extension of the flight domain of the LEA vehicle (LEA +) thanks to the upgrading of the present acceleration system or by selecting an other one with higher capabilities. At least, taking into account corresponding background and associated working partnership, it should be possible to define the most efficient flight test program (in term of scientific and technological return to financial investment). But, considering the limited budget which could be potentially available in Europe within the next years for such a flight test program, a preliminary and less ambitious flight test program, called EAST for European Advanced Scramjet Test, has been proposed with, unfortunately, no success up to now ([34]). Such a program, dealing with an integrated propulsion system, would allow extending the already defined development methodology by taking into account new ground test possibilities as, for example, high enthalpy short time wind tunnels F4 at ONERA Fauga or HEG at DLR Göttingen and to acquire a first flight validation. By another way it would be possible to take advantage of the quite complete propulsion system configuration to flight test the needed improvements of LEA technology to sustain higher flight Mach number conditions.

Beyond these technology development efforts, the need was also clearly identified to restart system studies taking advantage of recent progress made regarding knowledge, tools and technology and focusing on more innovative airframe and propulsion system concepts enabling better trade-off between structural efficiency and propulsion system performance.

In that field, ONERA was leading some preliminary design studies related to airbreathing micro-space launchers derived from PREPHA program generic vehicle.

In the same time, MBDA is considering an axi-symmetric configuration for a fully re-usable micro-space launcher (10 kg payload + 30 kg avionics). The vehicle is based on a main stage powered by airbreathing propulsion, combined or not with liquid rocket mode, and a “kick stage”, powered by a solid rocket engine provides the final acceleration (NEO concept) (Figure 20–[35]).

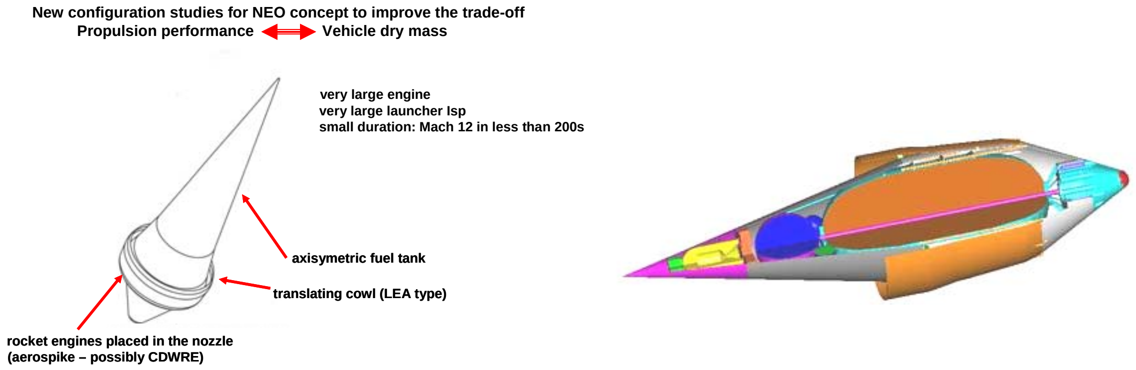


Figure 20: Space launcher NEO concept.

A preliminary design has been performed for different variant: one using a separated booster and a purely airbreathing main stage, a second one using a booster and a main stage combining airbreathing and rocket mode, a third one without separated booster, the main stage ensuring the initial acceleration in liquid rocket mode and a complementary acceleration phase in rocket mode beyond the airbreathing propulsion system operation. In addition, the liquid rocket engine of this third variant can be replaced by a continuous detonation wave rocket engine ([37]). Results obtained on trajectory simulation show the interest of airbreathing propulsion despite the fact that application to micro-launcher is not the more efficient one. In the same time, the development of such a micro-launcher could provide a very good and low risk opportunity to demonstrate the feasibility of a full scale fully re-usable airbreathing vehicle.

Finally, MBDA and ONERA are active partners in the frame of the LAPCAT2 program, funded by European Union and coordinated by ESA/ESTEC, focusing their effort on Mach 8 vehicle (Fig.21 - [38] to [40]).

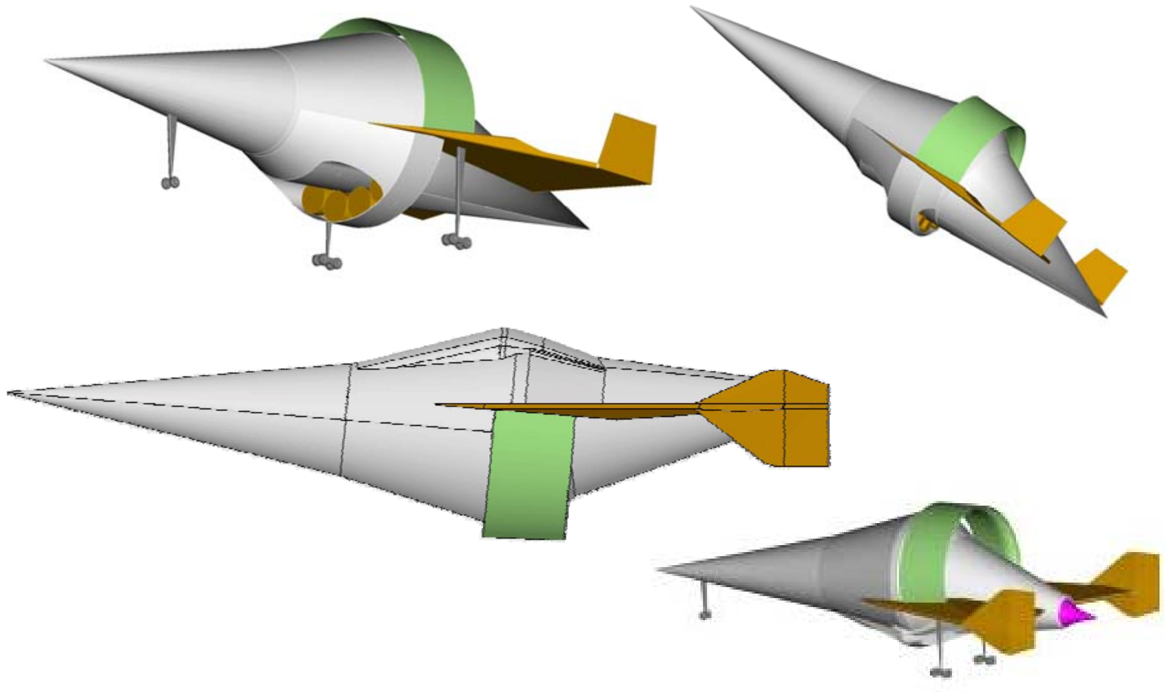


Figure 21: LAPCAT 2 – Mach 8 airplane studied by MBDA.

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