Dual-Mode Ramjet Technology Status of R&T effort led in France

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Abstract

During the 20 last years, a large Research and Technology effort has been led by MBDA and ONERA to develop knowledge on high-speed air breathing propulsion and master associated technologies.

The development of operational, civilian or military, application of the hypersonic air breathing propulsion depends of two key points :

- development of needed technologies for the propulsion system as a low weight, highly robust fuel-cooled structure for the combustor,
- capability to predict with a reasonable accuracy, and to optimise, the aero-propulsive balance (or generalized thrust-minus-drag).

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

After past efforts led within the framework of several R&T programs, the technology development effort is now focused on combustion chamber technology to ensure its performance and its thermal and mechanical strength :

- variable geometry needed to optimize the performance,
- fuel used as coolant for combustion chamber structure,
- fuel-cooled structure itself.
- On the contrary, before any operational application, it is mandatory to demonstrate our ability to predict the aero-propulsive balance (generalized thrust-minus-drag balance) of a hypersonic vehicle, providing sufficient margins to start a costly technological program. Considering this mandatory step, MBDA France and ONERA are leading a specific scientific program, called LEA, organized as follows:
- Define a methodology for the development of a hypersonic vehicle using ground tests and numerical simulation
- Develop the required tools (experimental or numerical) for this purpose.
- Apply this methodology to the development of a simplified, scientific experimental vehicle
- Validate this methodology through a series of flight tests.

Started in January 2003, this program is planned to end in 2012 after 6 autonomous flight tests of the experimental vehicle in the Mach number range from 4 to 8. On the basis of all results acquired during engine developments performed these last years, a variable geometry concept has been selected for the air breathing propulsion system concept. 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 vehicle, this engine configuration being representative of the selected variable geometry concept at the tested flight Mach number. A mixture of gaseous CH_4 and H_2 has been selected as fuel. A parametric study has been performed regarding the size of the vehicle and its propulsion system in order to limit the corresponding development and production costs while ensuring the compliance with the technical requirement of the flight test program.

Step by step, the main design guidelines of the LEA experimental vehicle have been defined and finally confirmed by a Preliminary Design Review held early in 2006.

Today, the Phase 2 of the program is running and aims at getting a detailed design of the vehicle while validating the aero-propulsive configuration by a first free jet test series to be performed in 2009.

Introduction

During the two past decades, a lot of system studies, generally based on large technology development efforts, have been performed in France to assess the interest of high-speed airbreathing propulsion for both military and civilian application ([1] to [10]).

The development of such operational, civilian or military, application 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,
- capability to predict with a reasonable accuracy and to optimise the aero-propulsive balance (or generalized thrust-minus-drag).

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 available ground test facilities ([11]) 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 France to maintain and develop knowledge and preserve human and material investments in spite of the lack of new National or European R&T program [12]:

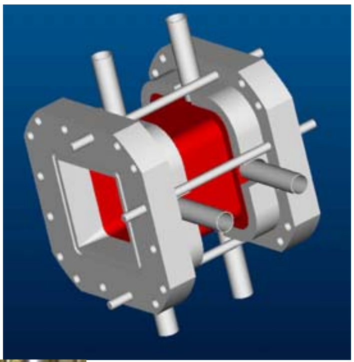
- JAPHAR program (ONERA and DLR) ([13] to[18]),
- WRR program (MBDA France and MAI) ([19] to[23]),
- PROMETHEE program (ONERA and MBDA France) ([24] to [27]),
- A3CP (ONERA/SNECMA/Pratt & Whitney)
- PTAH-SOCAR (MBDA France and EADS Space Transportation),
- Other cooperation with research laboratories ([28] to [36]).

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,
- fuel used as coolant for combustion chamber structure (endothermic fuel - [37] to [42]),
- fuel-cooled structure itself ([43] to [55]).

In the field of fuel-cooled structures, several C/SiC composite panels have been successfully tested (Fig.1) 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.2).

Fig.1 – Example of fuel-cooled panel tested in 2004



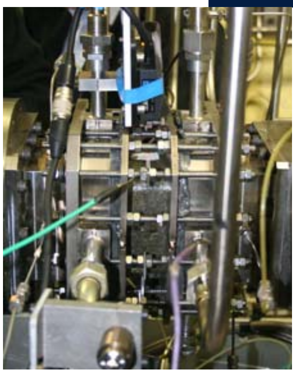


Fig.2 – Cooled composite combustion chamber duct (in red) tested at ONERA ATD5

Regarding studies related to endothermic fuels, the effort is shared between reforming kinetic modelling (cooperation with DCPR in Nancy) and basic experiment at ONERA to understand the reforming process and to validate the modelling (Fig.3). 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 (Fig.4).

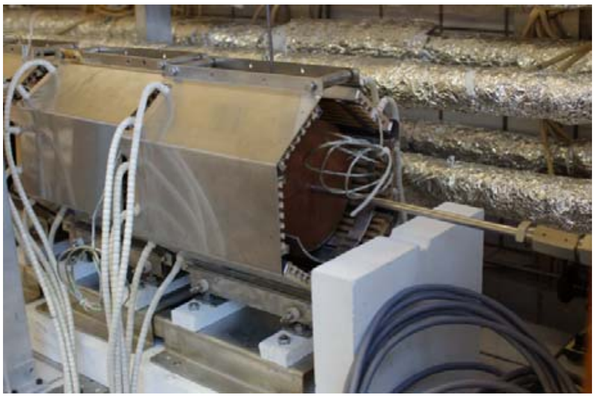


Fig. 3 – Basic experiment on endothermic fuel reforming at ONERA

Beyond the works already in progress, the test facility, developed by MBDA France and ROXEL in their Bourges Subdray test center in the framework of PREPHA program (Fig.5, [56]), is under upgrading. The new test facility, called METHYLE, will allow 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,
- engine control system…

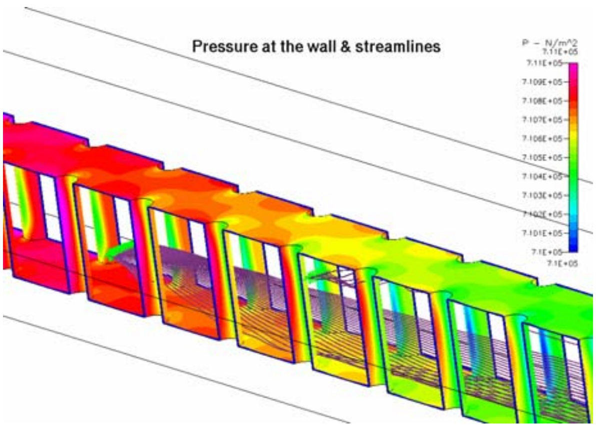


Fig. 4 – Example of coupled simulation of a PTAH-SOCAR fuel-cooled structure

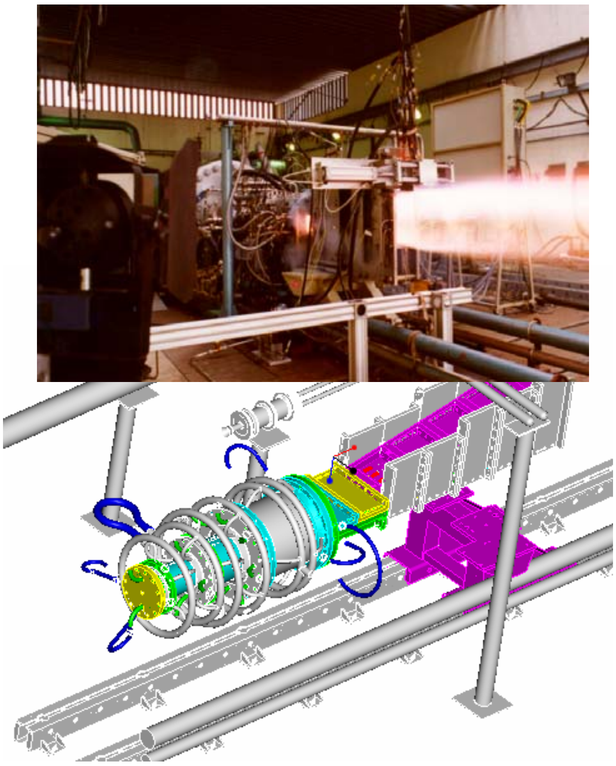


Fig. 5 – Hypersonic test facility at MBDA/ROXEL test center to be upgraded to METHYLE configuration

LEA flight test program

Aero-propulsive balance sensitivity

For an airbreathing propulsion system, the higher the flight Mach number, the more sensitive the net thrust. At Mach 8, for example, an error of 5 % on nozzle performance leads to a reduction of 35 % in net thrust.

Then, it is more and more mandatory to optimize the integration of the propulsion system into the vehicle airframe and propulsion system components are operating in a very coupled way which would require to test the overall system to determine the global performance.

But, when the considered flight Mach number increases, it becomes more and more difficult to simulate right flight conditions with on-ground test facilities. Generally, in such test facilities, air is heated up to total temperature before being accelerated through a nozzle to enter the test section at the right Mach number. What ever the heating process may be, that generally leads to the creation of radicals, and very often some pollution, into the feeding air which can change combustion process.

By another way, some scaling effect are difficult (or impossible) to solve with similarity rules. Then, the overall system should be tested at full scale that implies very large, and extremely expensive, if feasible, test facilities.

Development methodology

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. In such a methodology, the in-flight performance can be predicted only by a nose-to-tail numerical simulation. Then on-ground test facilities will be used to performed partial test of vehicle and propulsion system components separated or coupled two by two.

These tests have two goals :

- to allow components design tuning and verify a minimum performance,
- to verify, step by step, the ability of numerical simulation to predict accurately performance in conditions as close as possible to the actual flight.

Obviously, such a methodology is very challenging. So, 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 system design. That is why, a flight experimental program is a mandatory step towards future operational developments.

Beyond all current technology development works mentioned here above, and on the base of previous acquired results, MBDA France 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 realized with a minimum experimental vehicle without any technology demonstration purpose (use of existing technologies as often as possible) (Fig.6). In the same view this vehicle will be non-recoverable, then non-reusable.

The test principle consists in accelerating the flight 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.7). During this flight, the airbreathing propulsion system will be ignited during approximately 5 seconds with a fuel-to-air equivalence ratio variation.

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.

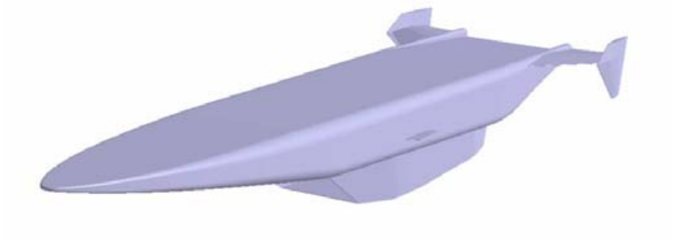


Fig. 6 – CAD view of LEA vehicle

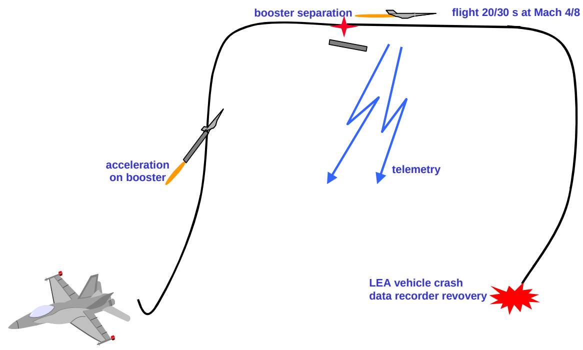


Fig. 7 – LEA flight testing sequence

The program aims at performing 6 flight tests, planned between 2011 and 2013 for exploring Mach number range 4 to 8.

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

Since the beginning of 2003, a preliminary design phase has been performed [57], [58].

For the experimental vehicle, the airbreathing propulsion system concept has been chosen by taking into account all results acquired during engines developments performed these last years. The finally selected concept is a variable geometry one using a simple translation movement of the engine cowl and a thermal throttling (Fig.8). 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.

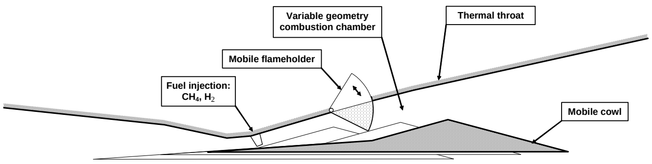


Fig. 8 – variable geometry PIAF engine

A parametric study has been performed on the possible technology for the combustion chamber. The finally selected solution is based on metallic heat sink solution 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 very 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 will 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.

Some specific works have been performed to adapt our computation codes to this particular fuel ([59] to [62]). 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 future 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 [63].

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

On the base of an air inlet design and corresponding performances, a first design of the combustion chamber has been realized thanks to 1D, then 2 and 3D computation. On this basis, a full scale mock-up is under manufacturing for future test in ATD 5 ONERA test facility.

Due to the particular configuration of the afterbody/nozzle, a specific effort is still under progress to well understand the interaction between the propulsive jet and the external flow to accurately determine the effect of propulsion on external aerodynamic.

Aerodynamic behaviours of the LEA vehicle and of the Flight Experimental Composite constituted by LEA and its booster have been evaluated by computation for preparing future aerodynamic tests.

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.9).

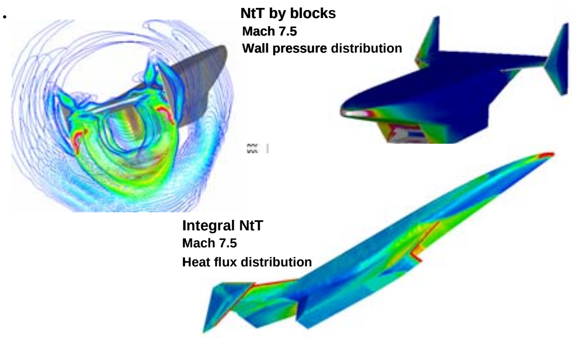


Fig.9 – Some Nose-to-Tail computation results

All the previous elements have been used in a detailed flight simulation in order to obtain a first evaluation of reachable maximum LEA/booster separation conditions. This flight simulation allows simulating a complete flight test sequence including LEA/booster dropping from air carrier, acceleration on booster, separation, descent trajectory of booster, LEA autonomous flight up to final crash.

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 (Fig.10).

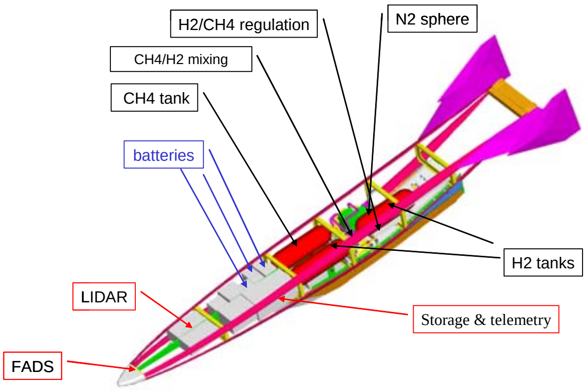


Fig.10 – LEA internal layout

By another way, a general approach for on-ground testing has been defined but still remain to be refined and confirmed.

Indeed, as Fig.11 shows and on the base of previous studies [64], a large part of the on-ground testing program should be realized in the S4Ma wind tunnel located in ONERA Modane test Center in the French Alps.

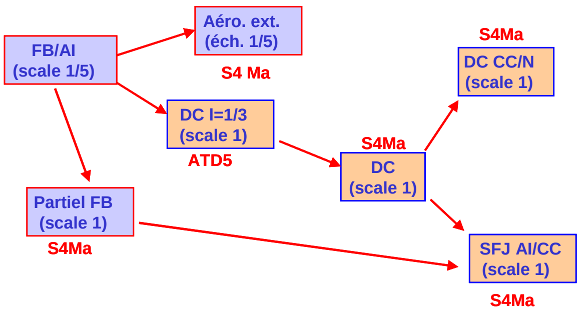


Fig. 11 – general approach for on-ground testing

It is intended to upgrade this test facility 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 7.5/8 flight conditions should be also easily feasible ([56] and [63]).

Detailed design studies, as for example free jet test configuration (Fig.12), have been performed to verify the feasibility of such an upgrading and evaluate precisely the corresponding cost.

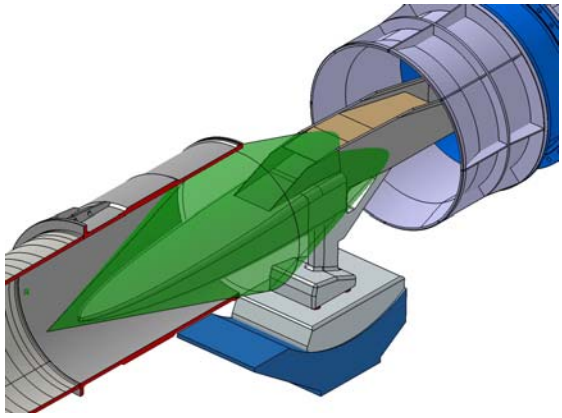


Fig. 10 – Study of LEA free-jet test installation in S4Ma ONERA test facility

Further possible development

The LEA flight test program constitutes a very important first step in the definition and the validation of a development methodology for hypersonic airbreathing vehicles. Nevertheless, if we consider the 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 ([4], [7]).

In that view, a minimum R&T program has been proposed [66]. 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 the 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, the budget which could be potentially available in Europe within the next years for such a flight test program will be limited. By another way, the on-going LEA flight test program between Mach 4 and Mach 8 has to be first performed. That is why, considering these two points, a proposal has been submitted to ESA regarding a preliminary and less ambitious flight test program, called EAST for European Advanced Scramjet Test, which could be performed by 2012.

The EAST program would consider a subscale (~1/4) twin engines configuration derived from LEA vehicle (Fig.13). EAST would not be a simple supersonic combustion experiment within an academic combustor but would consist in testing the system forebody / air inlet / combustion chamber / partial nozzle during a captive flight on top of a booster derived from a sounding rocket system (Fig.14). The EAST experiment would be fixed on the booster thanks to a strut equipped with a thrust measuring system.

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.

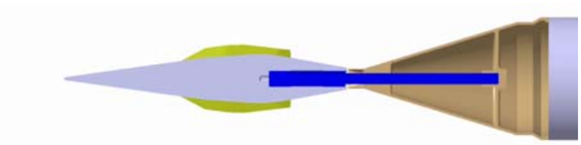


Fig. 13 – EAST configuration

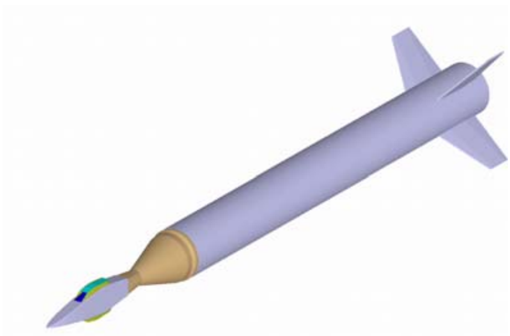


Fig. 14 – EAST on top of the sounding rocket

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/propulsion system concepts enabling better trade-off between structural efficiency and propulsion system performance.

In that field, ONERA is 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) (Figure 15 – [67]).

The vehicle is based on a main stage powered by airbreathing propulsion, combined or not with liquid rocket mode. A "kick stage", powered by a solid rocket engine provides the final acceleration (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 ([68]).

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.

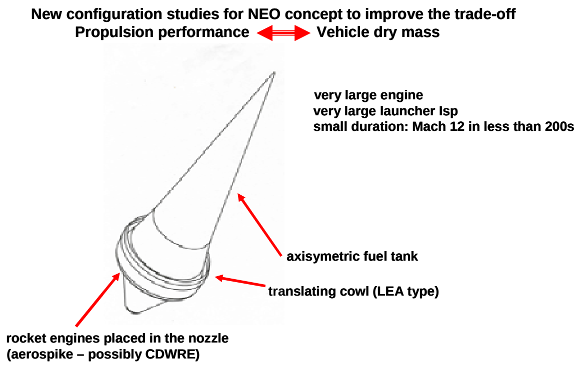


Fig. 15 – Axi-symmetric micro-space launcher

Conclusion

The ramjet/scramjet concept constitutes the main air breathing propulsion system which can be used in a very large flight Mach number range up to Mach 10/12 and then could allow developing future fully reusable space launcher and military systems.

Beside international activities, mainly in USA and Japan, a permanent Research and Technology effort has been pursued in Europe since twenty years. Today, the effort led in France 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 the two possible application within the next five to six years (2012/2013).

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