AIR BREATHING COMBINED ENGINES
FOR SPACE TRANSPORTATION SYSTEMS

Alain Lardellier
SNECMA (France)
Marcel Pouliquen
S.E.P. (France)

ABSTRACT

For winged, horizontal take off and landing vehicule, the propulsion system appears as one of the key technologies. Based on the progresses in advanced technologies like cryogenic propulsion, high temperature materials, this paper will present progress on current concept studies of airbreathing/rocket combined engines with some consideration on questions raised by the vehicule / engine system integration (air inlet / engine performance / aircraft trajectory and thrust requirements).

I - INTRODUCTION

Space commercial activities are entering in a more and more competitive market. Space transportation systems grew up in Europe with ARIANE launcher family. ARIANE V launcher currently in development will significantly reduce the specific launch cost compared to ARIANE IV.

Beyond the era of ARIANE V, what new launcher concept could potentially offer reduction in specific cost with major improvements in versatility and mission flexibility ?

Winged horizontal take off and landing launcher concepts could offer this.

Two families of concepts are generally considered : single stage to orbit (SSTO) and two stages to orbit vehicules.

For such vehicules, the propulsion appears as one of the key element. Supported by the progresses in advanced propulsion technologies like cryogenic propulsion, high temperature materials (metallic, composite), turbomachinery systems, promising perspectives would be suggested by airbreathing propulsion.

Current concept studies on combined propulsion system for future launch vehicule are conducted under CNES (French Spatial Agency) and company fundings (SNECMA - SEP - ONERA in a joined team).

II - MISSION AND VEHICULE ASPECTS

On the contrary of rocket engines, which performance are only dependant on altitude , the airbreathing combined engines have characteristics strongly influenced by the integration to the vehicule (TSTO versus SSTO vehicle) and by the trajectory (wide range of Mach numbers and altitudes)

As a first step, we considered propulsion systems for a single stage to orbit with a pure rocket phase giving the final speed increment needed for low earth orbit injection.

Also the SCRAMJET operation theoritically able to deliver the orbital speed was not considered at this stage of the study.

Concerning the propulsion system, the fundamental parameters, in addition to transition mach number are :

- the specific thrust (F/W air) which gives the engine size for a given thrust.

- the specific Impulse (Isp) which is related to fuel consumption

- the thrust to weight ratio ($F/\bar{M}$).

III - ENGINE SELECTION OVERVIEW

From the basic families (Air turbo engines, Ramjet engines, Rocket engines) we have analysed the reasons of performances limitations.

For example a TURBOJET (or a TURBOFAN) is limited around M 4 by turbine inlet temperature and/or compressor discharge temperature (see fig. 1).

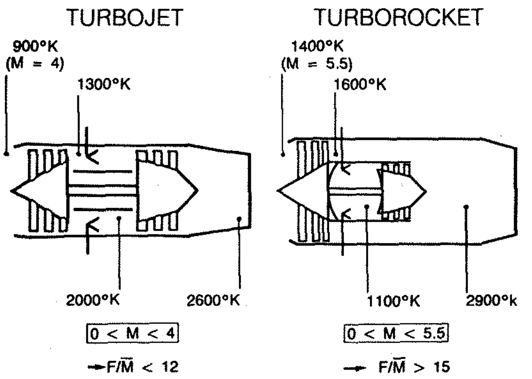

FIG. 1

Cooling the air flow at the inlet of the compressor will increase Mach number range but thrust to weight ratio will decrease dramatically ($F/\bar{M} < 12$ TO < 10).

As an improvement, the TURBOROCKET engine is such that turbines inlet temperature is decoupled from compressor discharge temperature (see fig. 1). Thus the liquid oxygen/liquid hydrogen mixture ratio in the gas generator controls the turbine inlet temperature. Such engine extends operation up to Mach 5.5 with temperature limitation at compressor discharge at 1600K (without cooling system) with :

- good thrust to weight ratio (> 15)
- capability to maintain high thrust during fraction of ascent (in corresponding Mach number range)
- specific impulse still 4 to 5 times the rocket Isp ($\approx$ 2000 s) (see fig. 2) but half of TURBOJET engines

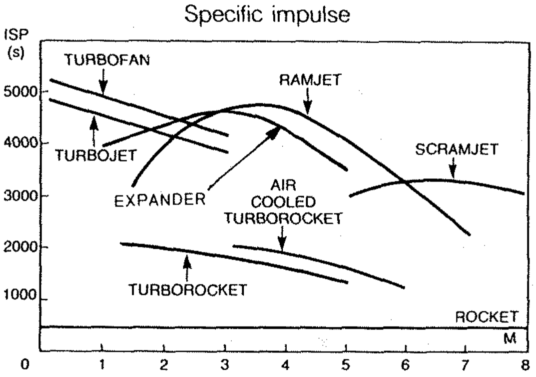

FIG. 2

A potential improvement is seen by considering replacement of gas generator cycle, feeding the turbine by an "expander cycle". Taking benefit of necessary cooling of engine structure with hydrogen (see fig 3) the idea is to use the corresponding enthalpy to feed the turbine with gaseous hydrogen. The specific impulse results is ranged from 3000 s to 4500 s as plotted on fig. 2. Currently studies are progressing in order to estimate the engine weight of this attractive cycle .

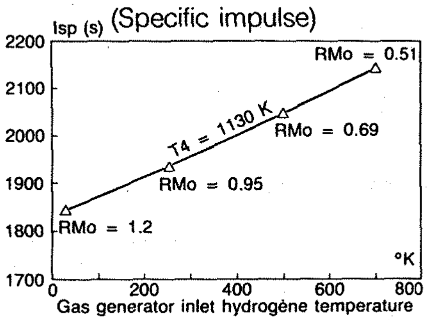

FIG. 3

Looking at RAMJET engines, they offer simplicity (thrust to weight ratio >15) since they do not contain rotating parts and consequently move up the threshold of temperature limits. In counter part, it is necessary to add a booster (a rocket for example) for take off.

To extend RAMJET engine operation over Mach 7 where high temperature in combustion chamber lead to dissociations, supersonic combustion technology needs to be developped : SCRAMJET engines. Because SCRAMJET cannot operate well below Mach 4 to 5, the ideal RAMJET should be dual mode RAMJET incorporating subsonic and supersonic combustion devices (extensive variable geometries : diffuser, combustor, chamber, nozzle throat...).

IV - PROPULSION SYSTEM STUDY : TURBOROCKET - RAM-ROCKET

The first step of our studies was based on single stage to orbit vehicule (SSTO). Over the numerous concepts and combinations of cycles, we focused on concepts meeting SSTO objectives with some pragmatic considerations :

1 - To have a ROCKET mode for vacuum operation.
2 - To have a high thrust to weight ratio for acceleration (> 15)
3 - To consider TURBO-ROCKET, which appears as one of the simplest concept with potential improvements.
4 - To consider RAMJET because of its simplicity althrough it needs to be combined with a booster for take off.

Associating a TURBO-ROCKET mode to the Ramjet mode allows to get an accelerator (TURBO-ROCKET) from take off to Mach 3 for the RAMJET with a good performance (Isp > 2000 s). The RAMJET mode will take over from Mach 3 to Mach 7. This combined engine is called a TURBOROCKET-RAM-ROCKET.

IV.1 - DESIGN CONSIDERATIONS

The general arrangement of the TURBOROCKET - RAM-ROCKET, presented on fig. 4, was designed with the following considerations :

1 - a single duct to reduce the weight, but assuming the compressor able to operate in windmilling during RAMJET operation with the penalty of getting only 30 % of designed corrected air flow through it.

2 - a rocket engine in the center body : a common nozzle for all engine operations was designed with a mecanism to assure variability of nozzle throat and exit area (three steps).

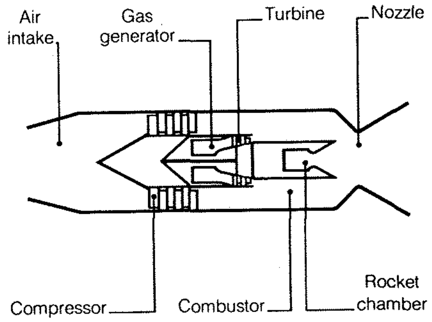

FIG. 4

3 - a low compressor pressure ratio :trade off between high specific impulse and high specific thrust (see fig. 5) leads to design a 3 stage compressor with pressure ratio of 3.75 at take off to get about 1 for ramjet operation at 3 < M < 4.

4 - a high turbine expansion ratio :trade off on specific impulse and turbine efficiency and number of stages leads to design a five stage turbine with 0.55 efficiency . As an example of sensivity of the efficiency : + 0.1 of efficiency provide 300 s of Isp.

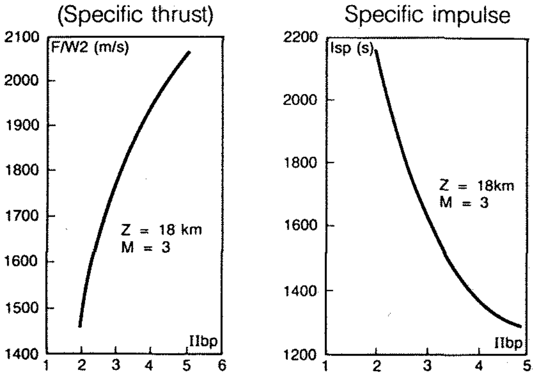

FIG. 5

5 - a single turbopump feeding system : for turbo-rocket mode, ramjet mode, rocket mode and gas generator . This configuration was made possible because flow rates and pressure requirements were compatible (see fig. 6).

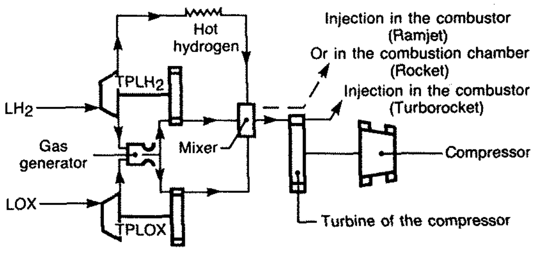

FIG. 6

IV-2 - MECHANICAL ARRANGEMENT

To estimate the weight of such an engine a mechanical design arrangement exercise has been conducted with 2 assumptions on material availability dates : 1995 and 2010.

The extensive use of composite materials in engine parts provides low weights (see fig. 7) We obtained a weight estimation of 2900 kg (1995) and 2450 kg (2010) which give the thrust to weight ratio along the trajectory $\rho.\frac{V^2}{2}$ = 0.6 bar of :

1995 : 10.4 $< F/\overline{M} <$ 15.5
2010 : 12 $< F/\overline{M} <$ 18

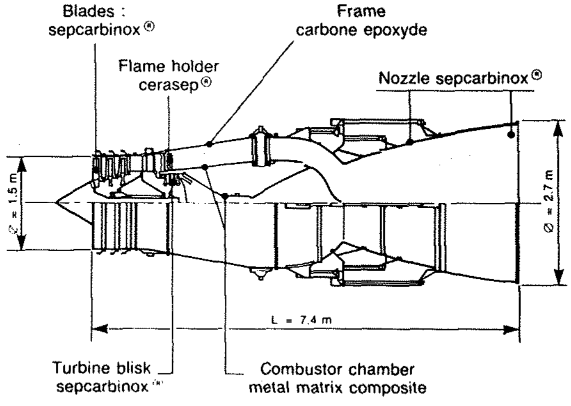

FIG. 7

V - INTEGRATION OF THE ENGINE WITH THE VEHICULE

In order to identify what is the sensitivity of engine performance with aircraft aerodynamic interfaces (air inlet and nozzle) we did an integration exercise with a defined air inlet and some simplified assumptions.

V.I. BASIC CONSIDERATIONS

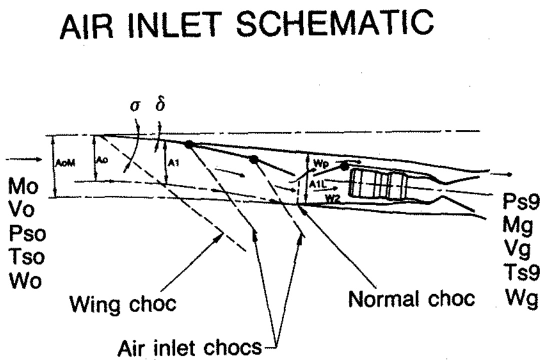
AIR INLET SCHEMATIC

FIG. 8

Thrust calculation with usual definitions are shown on fig. 8. We consider net thrust :

FN = W9.V9 - W2.VO + A9 (PS9 - PSO) as Gross thrust minus intake momentum drag.When the engine is installed, the thrust is lowered by some amount :

FINST = FN - (X inlet + X base - X I.B)

with :

X inlet : additive drag induced by the air inlet as a function of air flow, Mach number, angle of attack and air inlet caracteristics.

X base : drag induced by the nozzle base as a function of outlet/ambrent pressure difference, mach number, nozzle design.

X I.B : Drag due to the momentum losses of inlet boundary layer control bleed flow.

V.2. ENGINE ASSUMPTIONS

To compare the installation effects on engine performance, we use the same assumptions for net thrust calculation and installed thrust calculation :

- constant mechanical speed
- constant compressor stall margin
- compressor windmilling operation in ramjet mode (pressure loss factor of 0.15, corrected air flow 30 % of nominal)
- constant air inlet area (2.18 M2)
- pressure recovery factor (PRF) (basic characterictics of air inlet) as a function of Mach number, flow coefficient. (see fig. 9)
- variable nozzle throat and exhaust area

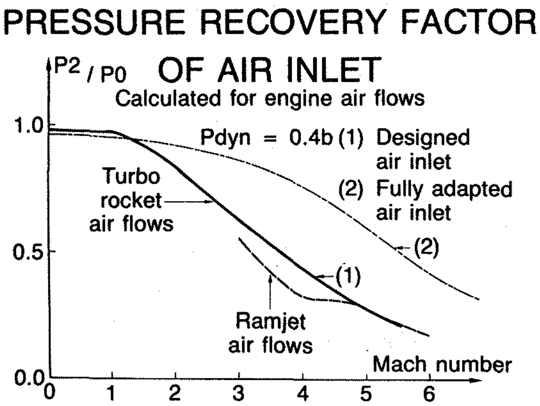

FIG. 9

V.3. ANALYSIS OF THE RESULTS

V.3.1. - Off - Design performance of the engine (net thrust)

1 - Over Mach 0.8 the net thrust decreases dramatically from 400 KN in TURBO-ROCKET mode (see fig. 10)

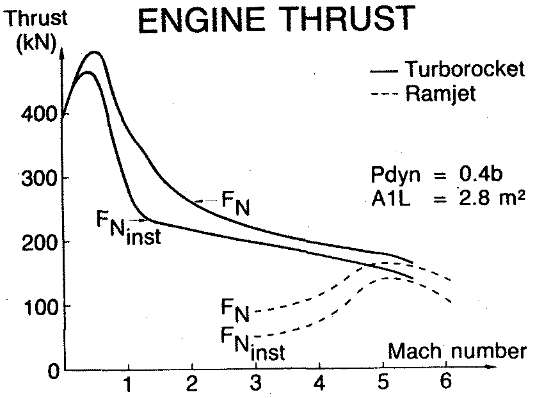

FIG. 10

The thrust reduction is due to the pressure recovery factor (PRF) of the inlet which decreases with Mach number also function of air flow coefficient of air inlet).

Above Mach 3 these combined effects are such that we have to derate the engine to be adapted to air inlet flow capacity.

2 - Below Mach 5 the thrust is also dramatically low for the RAMJET mode.

The two reasons are :
- same effects as above for the TURBO-ROCKET mode : pressure recovery factor and airflow coefficient of the inlet.
- the compressor windmilling operation provides only 30 % of corrected air flow in RAMJET mode. Both effects lead to reduce airflow and consequently the thrust.

V.3.2. - Installed performances analysis

The total drag penalty of the TURBOROCKET, in the transonic zone (35 % of the net thrust) is due to the air inlet drag for 75 % (see fig 11)

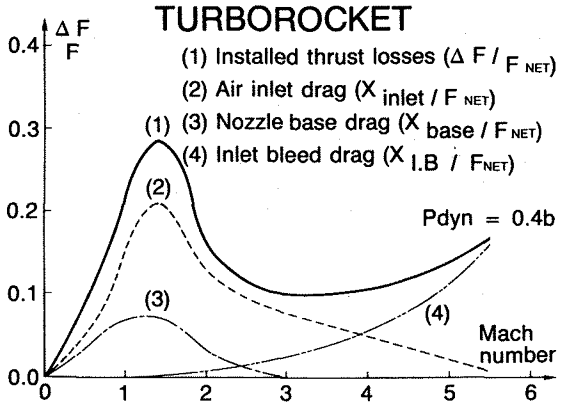

FIG. 11

Above Mach 4, the inlet bleed drag become a major effect. In addition, the larger the dynamic pressure is, the larger the losses of installed thrust are (compare fig 11 and 12 for dynamic pressure 0.4 and 0.6)

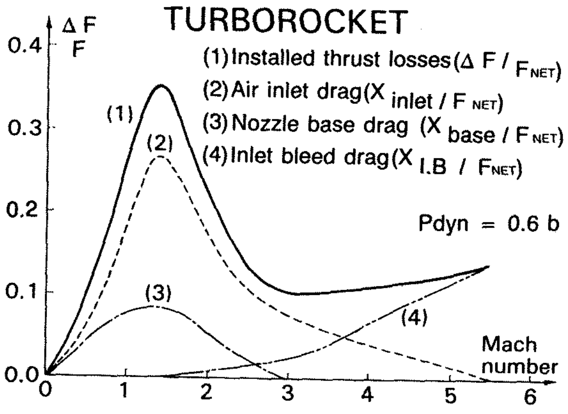

FIG. 12

In the RAMJET mode, the total drag penalty below Mach 4.5 is also due to air inlet drag (see fig 13). The effect is higher than for the TURBOROCKET mode at same Mach number because the air flow reduction due to compressor windmilling results in a more desadapted air inlet (spillage effect). Above Mach 5, the inlet bleed drag becomes major effect.

The thrust losses direct the specific Impulse penalties due to installation : (see fig 14).

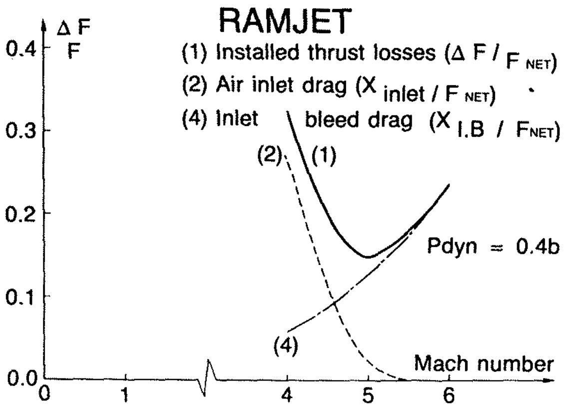

FIG. 13

V.3.3 comments

This exercise has revealed how sensitive the installed thrust and installed specific impulse are to the design of air inlet :

- pressure recovery factor
- ability to avoid spillage drag
- ability to recover part of the air inlet bleed momentum losses
- ability do adapt the inlet/engine flow capacity

Efforts have to be undertaken to improve air inlet design according to exchange coefficients between thrust, Isp, weight of the engine and complexity/weight of the air inlet through the various vehicule trajectories. Air inlet technology is already identified as one of the key technologies in a strong conjonction with the propulsion system.

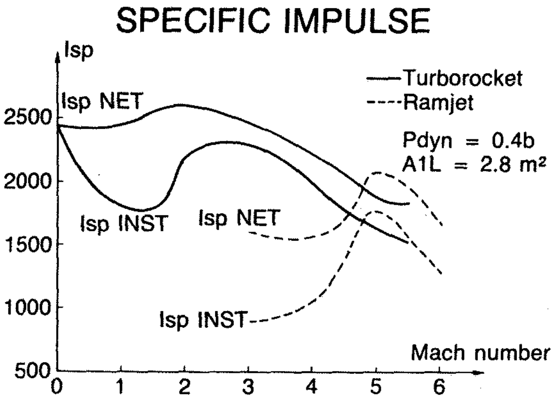

FIG. 14

VI - CRITICAL TECHNOLOGY AREAS

Through this system study, a number of critical items has already been identified, concerning the design and the development of airbreathing combined engines.

- mixing of supersonic / subsonic reactive gases (combustion)
- composite material : design, component manufacturing, high level of characteristics;
- high performance of air inlet and nozzle technologies (variability, aircraft integration).
- mechanical and functionnal integration of engine modes and cycles (expander cycles ...)
- turbine efficiency (aerodynamic)
- cooling systems and heat exchanger (material, performances, ...).

- windmilling operation of compressor
- full scale / flight condition testing (engine and components).

VII - CONCLUSION

This paper has presented the beginning of what is a long term effort.
The current studies are oriented to identify critical technologies, sensitivity of engine / vehicule integration parameters in order to prepare a research program for technology maturation to succeed further in the future European Launcher development.