Innovative LOX/Methane Upper Stage for Future Launchers

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Abstract

The trend is today to research easy to use and cheap solutions for the propulsion of future expendable launch vehicles but also with a high level of performances.

Another point is to look for non toxic propellants but able to operate in space for long duration mission and with a high level of performances: LOx Methane is a good compromise.

A way could be an extensive use of composite materials both for the structures, the tanks and the engines with use, as much as possible of automatic processes. In a near future a breakthrough or improvement of the fibers strength may increase the interest of such technologies.

Liquid composite wound tanks can weigh three to four times less than a metallic one under the same operating conditions, the same results can be obtained for the chambers; So these technologies give a new interest to pressure fed solutions (as a first approach Vacuum Specific Impulse depends mainly on engine area ratio and less on operating pressure)

It could lead to a stage easy to operate, reliable, needing no costly solutions (Expander engine, Turbopumps, Boost pumps).

. On an upper stage with a full diameter tankage system (with a common bulkhead),the use of composite tanks is enabling creation of room, or all around the aft dome of the tank or in length (moreover mass of composite tanks is less sensitive than metallic ones to the shape).

Creation of thrust depends mainly on the possibility of implementing nozzles divergent surfaces.

On another side, thermal fluxes depend greatly on the operating pressure: low pressure engine no longer needs regenerative cooling system (radiation+ film or transpiration cooled ceramic engines could be used) Increase of throat area ratio is not a major problem with respect to the available room.

Moreover stage without turbomachinery is much less sensitive to the mission profile and become much more competitive with a multi-boost mission

As a previous study [R4] showed the interest of these solutions with cryogenic upper stage, the aim of this presentation is to demonstrate the performance improvement by replacing a conventional low pressure-fed NTO/MMH upper stage by an all composite designed LOx/Methane pressure fed stages and so the interest for R&D on this field.

Introduction

The trend is today to research easy to use and cheap solutions for the propulsion of future expendable launch vehicles but also with a high level of performances using a non toxic propellants able to operate in space for long duration mission: LOx Methane is known as a good compromise.
Upper stages for heavy or super-heavy launchers require also a very high level of reliability, mandatory for a commercial success.

Based on the ideas developed by M. Truax [R1] on the advantages of pressure-fed stages, our study shows that such stages may greatly benefit from using emerging new technologies such as:

- Liquid composite wound tanks with an internal liner, which can weigh three to four times less than a metallic tank under the same operating conditions;
- New materials for radiation + film or transpiration nozzle cooled engines

It is surprising to note that composite tanks are being considered first for RLVs, which require a dramatic upgrading of the airframe to be feasible and competitive with expendable launch vehicles (ELVs). From a technological standpoint, such an application is the most difficult case for the operational use of this new technology:
It is better to choose and begin by its own domain of excellence (basically composite tanks are able to withstand high pressures)
An incremental approach seems more logical, less risky and more fruitful:

Step	Description	Why
1 .ELV Upper Stage	Storable propellants High pressure tanks (pressure-fed) Reasonable size Shapes of revolution Expendable launcher	No thermal problems Best use for very high strength materials Minimum technological problems No aging, no cyclic strain
2. ELV Upper Stage	Cryogenic tanks	Introduction of thermal problems
3. ELV Boosters	Large tanks	Introduction of size (and assembly) problems
4. ELV Upper Stage	Low pressure (turbopump-fed)	Search for minimum thickness
5. RLV Wing & Body	Large, shape of revolution tanks	Introduction of aging and cyclic strain requiring better knowledge

To illustrate the potential advantages of composite tanks associated to pressure-fed stage, an example of architecture will be presented:

It will be compared in terms of performance to reference architecture, in this case, the Ariane 5 EPS (pressure-fed).
This paper presents this alternate solution that is not yet state-of-the-art (SOTA) in Europe but may benefit from more than 30 years of operational experience on SRM wound cases and from all European R&D work on new hot composite materials (EADS, DLR, Snecma, Onera).

Interest of a pressure-fed upper stage/Stage Architecture configurations

Concerning the tank, wound composite tanks are able to withstand a much higher level of internal pressure for a mass lower than for metallic ones. Such a solution presents only a marginal interest (from the performance standpoint) for a turbopump-fed system but may greatly increase the performance of a pressure-fed system [R4].

The specific impulse of an engine depends mainly on its area ratio and not on its combustion pressure (some % between 1 MPa and 7 MPa for an area ratio in the range 200-300 for the ODE Specific Impulse and Kinetic losses variations).
A pressure-fed upper stage may have a specific impulse of the same order of magnitude as a turbopump-fed stage if its engine may have a large area ratio.
Contrary to the Isv, the thermal fluxes depend greatly on combustion pressure ($P^{0.8}$), the choice of a combustion pressure close to 1 MPa enables the use of simple, lightweight radiation or transpiration cooled engines (CMC, columbium or other). By comparison with an engine operating at 7 MPa, fluxes are reduced by a ratio of 6.
When looking at the reference solution (all metallic), it appears that to obtain a short layout associated to reasonable mass and costs, a four tank with a single engine was selected. Nevertheless the mass is relatively important.
Alternate solution with a cluster of 4 small engines and only one tank may use the allocated space better (same length), will be cheaper (only 2 tanks instead of 6).

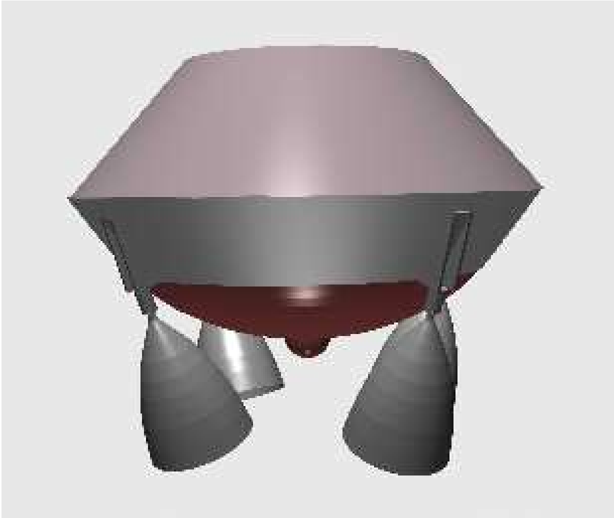


Fig. 1 ARIANE 5 EPS

Fig. 2 EPS Alternative

The 4 engines may be implemented in the annular space, between the tank aft dome and the conical stage structure, their unit thrust will be low enough and they can be directly attached to the conical skirt of the tank, locally reinforced avoiding a heavy thrust cone. There is a large amount of available space, enabling the use of high area ratio engines.
Moreover, clustered low-pressure engines with allow an attitude control and thrust vectoring by on-off modulation or thrust throttling (no need for movable engines) (a trade-off between 4 nozzles with one degree of freedom have to be made but its results will not change the order of magnitude of the performance increase)

Solutions that do not use turbomachinery, nor regenerative cooling circuit will have with the following major advantages:

- They do not need a heavy specific thrust frame as previously mentioned;
- Better potential reliability,
- Easier in-flight re-ignition,
- No need to satisfy any pump NPSP, so thermal management of propellants is much less critical and may lead to a lower amount of pressurant .

These two last points lead to a better fit to multi-boost mission (relative insensitivity to the mission profile)

For competitive performance levels, there are a few major drawbacks but for cryogenic use, composite tanks are not in the European SOTA. A first step at the LOx temperature seems an interesting intermediate step

<u>Operating conditions/ basic hypothesis</u>

The basic hypotheses for this study are:

- Stage lay-out consistent with the allocated space or shorter if possible;
- Roughly 1,2 MPa combustion with transpiration cooled engines;
- End of mission blow-down operating mode to minimize pressurizing gas masses and therefore the end of mission mass
- Same thrust as Reference Stage, except for the end of expulsion (blow-down mode), ratio of about two on the thrust, and a slow decrease in the acceleration level.

<u>Tanks</u>
The internal tank pressure is 2 MPa. (Burst 2.8) corresponding to minimal thicknesses. The pressure has to be a little higher in the Methane tank than in the LOx tank due to the selected configuration (LOx Tank is around the Methane tank). This can lead to the requirement for special propellant and pressure management during the stage mission (ballistic phases).
The external liquid tank is an axi-symmetrical composite structure with 2 domes and a cylindrical part. It is made of one piece by filament winding. This cryogenic tank is equipped with an external cold

insulation and with an internal liner (so microcracking in composite walls are acceptable) fabricated using two thin layers of aluminum foil bonded together (see [R2]): As this liner system is not load-carrying (sized only to prevent from leakage), high strength carbon fibers must be used in order to optimize stage mass, T1000G fibers have been selected.

Fig.3 : Large Composite Tank

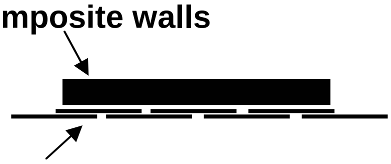


Fig. 4. Liner system

The external tank is equipped with only one metallic polar bosses (bonded closure on the other one). The interface between composite walls, the liner system and the bosses is one of the major singularities. One of the best concepts is the packing gland-type boss with reinforced domes. Three of the main metal selection criteria are the chemical liquid oxygen compatibility, mechanical characteristics at 90K and the thermal contraction at 90K.

To connect the tank to the conical stage structure, one conical skirt is implemented, locally the tank will be conical..
This skirt will be bonded on the tank without rubber. The objective could be to absorb relative strains between skirt and tank, but which is not compatible with a very low temperature. In order to do without a rubber, the strains of the composite envelope in the skirt attachment area must be limited by axial reinforcements made by hand lay-up or tow placement.
Except for the part bonded to the tank, the technology of the skirt is assumed to be the current technology used for composite skirt
The Methane tank, inside the LOx tank, is made of 2219 aluminum with a thin rigid insulation layer to avoid any risk of methane freezing (subcooling of Methane during the tank filling and during the first stages flight) . This insulation is on the inner side of the methane tank wall (compatibility with oxygen)

<u>Structural materials of tanks</u>
The main characteristics are:

	2219 T87 Aluminum	**IM-T1000 Composite**
σ_R (MPa)	**441(293 K)**	**2270(20K)***
σ_R weld. (MPa)	**220**	
E (MPa)	**70,000**	**180,000**

Tank Thermal Insulation

The selected solution for the tanks is an external configuration (Klegecell Insulation material is expanded tight polyurethane foam (Klegecell 51 kg/m^3) used to insulate the cryogenic Ariane Stages. The thickness will be 15 mm; an additional MLI (Multi-Layer Insulation) is added to meet the payload cooling requirements (front dome) or to protect the aft part from the engines fluxes; Aft dome tank is protected against engines plume fluxes by a blanket (Internal Multi-Screen Insulation) composed of some layers (metallic radiation shield –0.25 μm- covering a 20 μm ceramic sheet). Spacers are made of alumina ceramic felt. This multi-layer is covered with a 0.4 mm protecting bag made of Nextel 440 ceramic fiber.
So the main characteristics of the tank are:

External Diameter: 3625mm
LOX Tank Diameter: 2250mm
Overall Length 2300mm
Mass 300 Kg (without equipments)

Engines

4 engines of 8000N thrust with an area ratio of 150 (15°canted) are directly hooked on the conical skirt They operate to a 1.25 MPa chamber pressure.
The injector could be of the pintle type to enable thrust modulation, if this solution is preferred to on-off modulation for attitude control.
The engine chambers (basic solution) are made of ceramic/ceramic.
Min. Thick.= 1,5mm
Density =2800 kg/m^3
Θmax =1800K
The engines would be partly insulated with a rigid silica felt:
Density =70 kg/m^3
Θmax =1650K

Note: Metallic cooled structures could afford the engine heat loads, but need efficient then complex and costly architectures.
Pin fins circuit are generally preferable to channels.
Composite materials have a good benefit in weight, temperature, cooling loads, and hopefully cost.
Fastening the skins and the components of the engine duct has to be carefully addressed.
Woven and assembled preforms techniques are available at EADS-ST (especially in French Aquitaine plant) to complex shapes and would reduce the mass, the cost and the risk particularly associated with bounding (gluing, brazing, ...).
Several manufacturing process can be used for the transformation of the preforms to composite complete structures (C/C or C/SiC, CVI, LPI, LSI routes, ...).
With this background, the PTAH-SOCAR technology was developed to drastically increase the performance of the cooled engine structure while decreasing the manufacturing cost, the weight and the performance of ramjet. The PTAH-SOCAR technology will be really well fitted to transpiration cooled chamber. The internal wall thickness will be of 1.5mm with an adjusted porosity and may whistand wall temperature p to 1800K (cf[R5])
The divergent part of the nozzle is assumed to have a 1.5 mm stiffened ceramic SiC structure (2.5 D developed by EADS-LV) or other material with the same performance. The structure will be coated with thermal protection (40 mm for an aluminum silicate felt. Other materials such as IMI would probably lead to a lower thickness and better performance).
Its main characteristics are:
Throat Diameter: 65mm
Exit Diameter 800mm
Total Length 1180mm (without valves)

With these hypotheses, the mass of one the engine is estimated to 24 kg. (Including Injection valves)

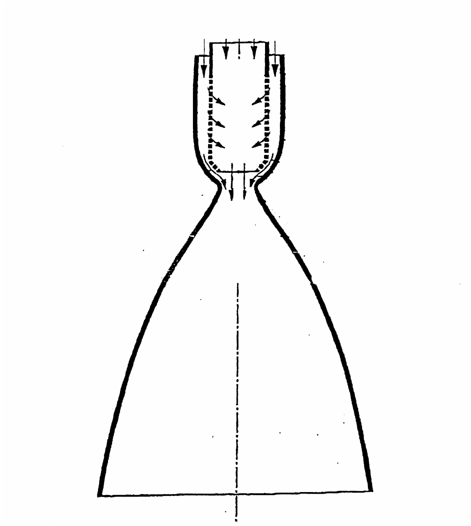


Fig.5: Transpiration cooled Chamber principle using PTAH-SOCAR [R6]

Fig.6: One of the first large nozzle perform woven at EADS

Pressurization system

The pressurization requirements are the drawback of such a propulsive system. To limit the penalty on the mass budget, a blow-down operating mode is considered at the end of the mission. The tank pressure is assumed to decrease from 2 to 1 MPa.

Fig.7: EADS Carbon vessel with Titanium Liner (80 liters- 17,7 Kg)-

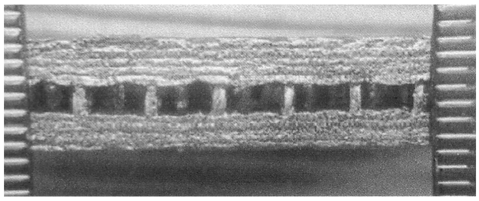


Fig. 8: PTAH-SOCAR Sample [R5]

Both tanks are pressurized with helium gas stored in high-pressure vessels at methane temperature; the helium tank is made of carbon composite like those of Ariane 5. The feasibility of such a tank (operating temperature 110K) has to be demonstrated.

Before injection in the tank, helium is heated to 300K through a ceramic heat exchanger located on the center of the aft dome of the tank, zone heated by the 4 rocket plumes.

The main characteristics of the system are:

Helium mass: 26 kg
Bottle diameter 480mm
Bottle mass 115 kg
Misc. 30kg (heat exchanger, Pressure reducer, valves,…)

Overall Characteristics

The following table presents an estimate of the mass budget (kg)

		EPS	New EPS
Propellant		NTO/MMH	LOX/METH
Propellant mass	Kg	9800	9800
Thrust	kN	29	34
Isv	s	321,2	368
Pc	Mpa	1	1.25
O/F		2.05	3.5
Mass Flow	Kg/s	9.5	9.4
As/AT		83	150
Engine(s) mass	Kg	115	100
Dry mass	Kg	1254	900
Diameter max	m	4.0	4.0
Length	m	3.4	3.4
Structural Ratio		0.13	0.09
DV	m/s	2000	2250

Performance Comparison

Specific Impulse

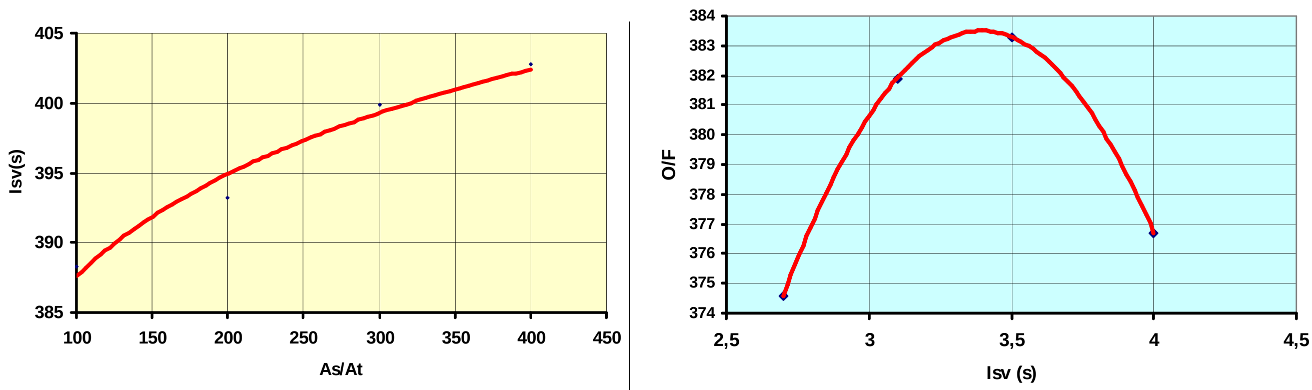


Fig. Isv Lox-Methane Pc 1MPa

The above figures explain the choice of the mixture ratio (optimum) and he interest of a very high area ratio. With an area ratio of 150, the practical specific impulse was estimated to 368 seconds

Payload increase:

With a lighter stage (of 350 Kg) and a specific Impulse increase of 45 seconds, it would result a payload increase of 1500 Kg (20%)

Conclusion

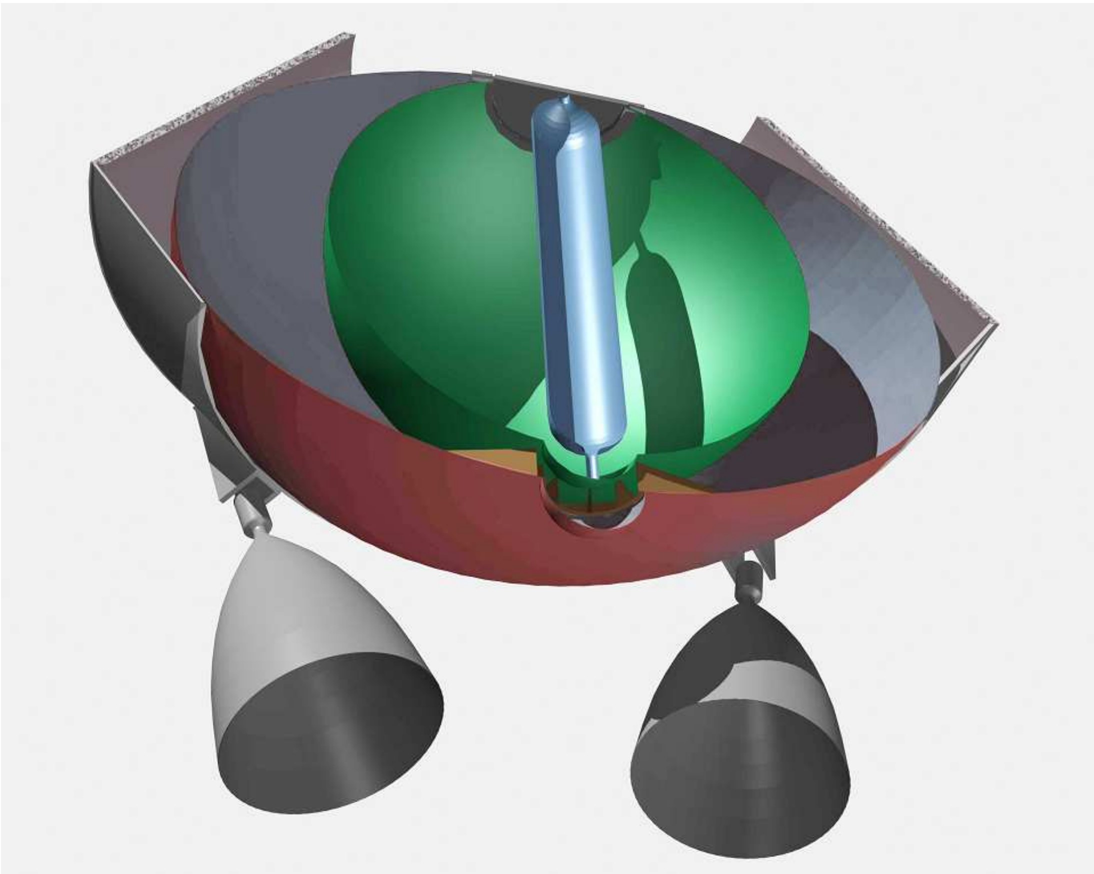
The results of this preliminary study show that, if a development effort is done on modern composites jointly to the use of a LOx/ Methane (non toxic, good compromise performances/in space storability) an intermediate way is possible for upper stages versus LOx/LH2 stages with expander engines

Such technical solutions could give much friendly stages to use at system level:

- No movable engine, thrust vector control (TVC) by modulation
- No Exit Cone to extend
- Easy to re start
- Simple engine(s)/systems (reliability)
- Better suited to the ballistic phases (relative insensitiveness to mission profile)

Actually, the major questions are whether the recurring cost of the stage could be as low as expected. Achieving the mass and cost targets will be of prime importance for such a solution.

Because of the high performance levels of composite tanks, they should be considered for use now on an ELV stage instead of waiting for an eventual RLV.



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[R5] AIAA 2004-3653: PTAH-SOCAR Fuel-cooled Composite Materials Structure for Dual-Mode RamJet and Liquid Rocket Engines Marc Bouchez, *MBDA France et all*

[R6] Patent WO 03/074859 A1 Rocket Engine

[R7] Brevet FR 2840384 Réservoir pour fluide sous pression comprenant deux compartiments et procédé de fabrication d'un tel réservoir