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New Materials for Composite Cases: A Possible Revolution for Launcher Propulsion?

Max Calabro- EADS-LV

ABSTRACT:

Solid Propellant Propulsion was initially developed for military applications (strategic and tactical missiles) for which:

- for a long duration (20 years its operational availability,
- its suitability year storage period,

makes it absolutely necessary.

The fields of launchers where solid boosters have found naturally an application are:

- large segmented boosters (ARIANE 5, H2, SHUTTLE, TITAN...),
- conventional monolithic motors used on small launchers or as strap-on boosters on the launchers PEGASUS, LLV, M5, DELTA II, ARIANE 4... the largest of which, in process of development, is the booster of the HII A (60 tons of propellant).

As a matter of fact, this type of propulsion has shown a very great reliability while highlighting some specificities which are particularly interesting - a simple architecture, a small number of components- these facts combined with an optimized definition for a mission, can lead to a very interesting cost/effectiveness if the required series exceed a few units per year. High cost effectiveness of solid propulsion is mainly due to the use of composite cases , roughly five time better than metallic tanks for withstanding internal pressures

In the present context which tends to favor very low cost access to space, there are question marks on the following problems:

- Conventional liquid propulsion solutions (with turbopumps) do not allow to reach the cost objectives, so why not design a liquid booster as a solid one? As simple as a solid booster , could a liquid solution cost half the price with better performances? Do we have to push composite tank, blow-down mode pressure fed solutions?
- Can emergence of new structural material for tanks and skirts using very high strength carbon nanotubes introduce a revolution in favor of very simple and reliable solutions for liquid propulsion?
- Is such a revolution applicable both to expandable and reusable launchers?

INTRODUCTION:

Upper stages for heavy or super-heavy launchers require a very high level of performance and a high level of reliability for a reasonable cost.
Based on the ideas developed by M. Truax [R1] on the advantages of pressure-fed stages, the study revisits the Beal project, to day cancelled, and will show 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, and the potential breakthrough due to new composite materials

taking the benefits of "low cost" and mass production of carbon nanotubes mainly developed for electronic applications.
Conventional liquid propulsion solutions (with turbopumps) do not allow to be cost effective in future Launch Vehicle competition, so why not designing a liquid booster as a solid one?
As simple as a solid booster, a liquid solution cost could probably reach half its price with better performances by suppression of costly components such as flexseal, carbon/carbon, internal insulation and use of very low cost liquid propellant.
But, we have to push very a simple solution: composite tank, blow-down mode pressure fed solution without costly pressurization system.

Note: It is surprising to note that composite tanks are being considered first in the USA, 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) and the Japanese choice of an upper stage for a new version of a small launcher seems more appropriate.

An incremental approach seems more logical, less risky and more fruitful:
Upper stages for heavy or super-heavy launchers require a very high level of performance and a high level of reliability for a reasonable cost.

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, reduced margins
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 (lower margins)

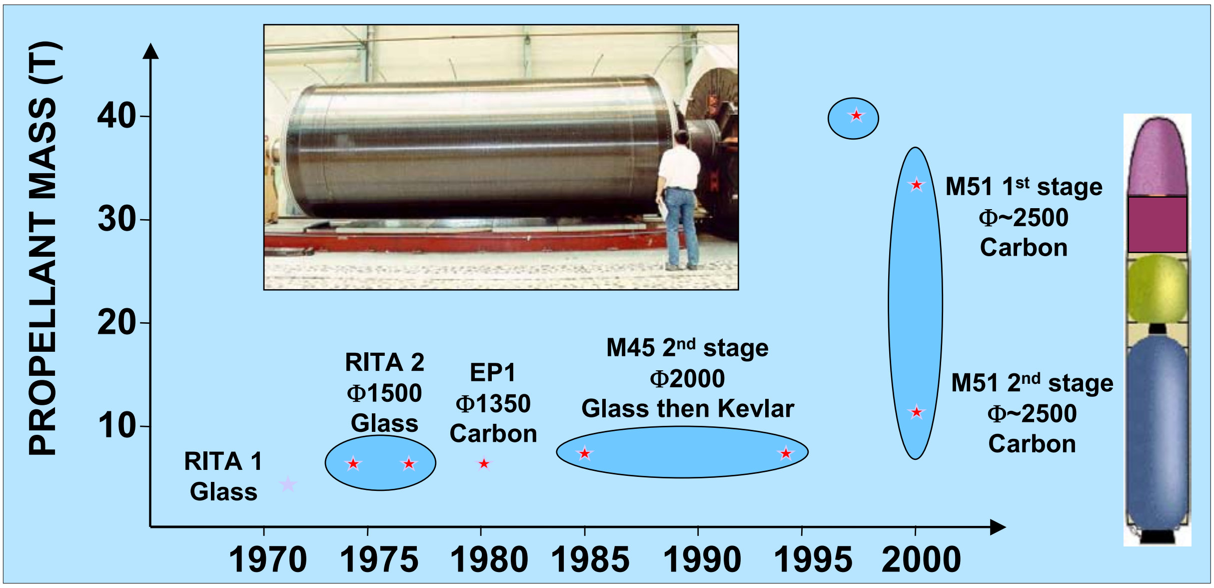
EADS LAUNCH VEHICLES BACKGROUND EXPERIENCE FOR COMPOSITE TANKS

EADS-LV has been a leader for a long time in the development of launch vehicles and military missiles, re-entry vehicles and other complex systems and thus possesses a wide range of experience in system architecture.

As the industrial prime contractor of the French deterrent missile force, EADS-LV develops, manufactures, tests and delivers the missiles and the non-nuclear parts of the re-entry bodies. In addition, EADS-LV is the industrial architect of Ariane 4 and Ariane 5 and is the stage contractor of the Ariane 5 EPC (Cryogenic Core Stage) and of the Ariane 5 P230 SRM.

For more than 40 years, the Industrial Directorate of EADS-LV has developed more than 15 types of solid propellant motor cases, mainly for military programs : Diamant, Europa, M20, S3, S4, M4, M45 and currently M51.

Fig. 1. EADS tank realizations



All of these developments and mass productions represent more than 600 manufactured motor cases and about 150 tons of filament wound composite combined mass from 1970 until today :

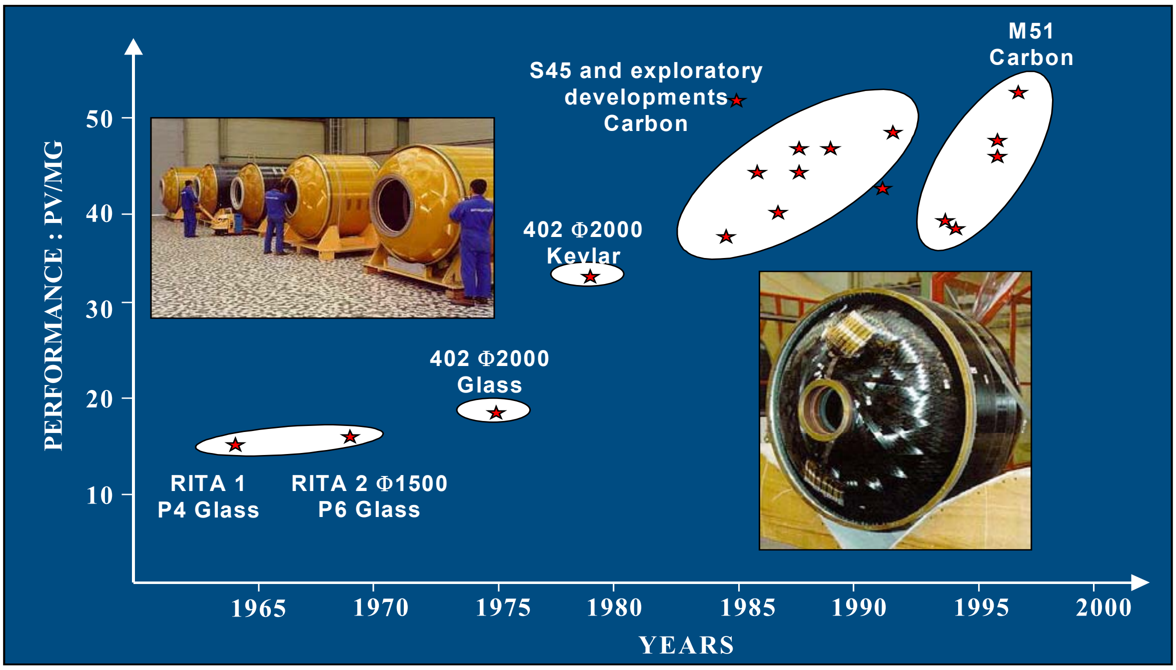


Fig. 2. Improvement of the performance in the course of time

The motor case dimensions have steadily increased (up to about 2300 mm in diameter and 5700 mm in length : M51 1st stage is currently the largest composite motor case in Europe) and the use of glass fibres, then kevlar fibres and finally carbon fibres, has enabled a constant and remarkable increase in tank performance. Most of these propellant motor cases were made with epoxy resins which, for the most part, have been developed in EADS-LV's facilities.

The Fig. 2. presents the improvement of the motor case performance in the course of the time since 1965 .

Yet, EADS-LV's skills and experience on solid propellant motor cases are not limited to the field of composites but also cover each part of the structure, such as polar bosses, polar bosses/motor case attachments, motor case/skirts attachments, skirts/metallic frames attachments, external fittings, internal thermal protection and external thermal protection (due to its background experience on re-entry vehicles, EADS-LV has a complete range of materials which meet propellant motor cases requirements).

EADS-LV has integrated design and manufacturing including drafting, designing, sizing and CAD/CAM, which enables propellant motor case design optimization. These design skills are rounded out by manufacturing and curing machines fitted to mass production, non-destructive inspection facilities and testing facilities :

Manufacturing Capacities :

- filament winding and fiber placement
- horizontal helicoïdal winding + 1 carriage for filament winding + 1 carriage for fiber placement
- 4 axis for filament winding carriage (5 axis altogether) and 6 axis for fiber placement carriage (7 axis altogether)
- accuracy (processing head / structure) to within 1 mm for filament winding and to 0.5 mm for fiber placement
- max diameter = 5.65 m / max length = 12 m
- max inertia = 70000 kg.m²
- 30 spools max (max fiber band width ~ 90 mm)

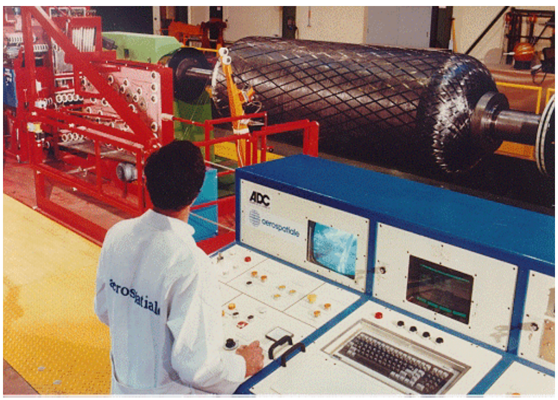


Fig. 3. TITAN

Fig. 4. SATURNE

Curing facilities :

- 200°C drying oven for 10 m length / 3,5 m diameter structures
- 250°C and 20 bars pressure-sealed for 5 m length / 2,3 m diameter structures
- UNIPOLIS Electron-Beam curing facility which is the largest electron-beam curing facility in Europe:
  - max diameter = 5.6 m / max length = 12 m
  - electron or X-Ray curing (X-Ray target = Tungsten + cooling system)
  - beam energy = 10 Mev / beam power = 20 kW
  - pulsing frequency = 50 – 500 Hz
  - concrete mass = 9000 t / max wall thickness = 3.2 m / door mass = 350 t

Non-destructive inspection facilities : X-Ray (160 KV and 420 KV), Ultrasonics, Infra-Red, acoustic emissions, water proof test

Testing facilities : internal pressure tests (300 bars x 25 m^3), static and thermal tests (5000 KN / 1.6 MW Infra-Red oven) and vibrations tests (250 KN)

Fig. 5. UNIPOLIS

Fig. 6. Internal pressure test facility at EADS-LV

Due to this mastery of all stages (design / sizing / CAD/CAM / materials / manufacturing / inspection / testing), these technologies have found applications in many fields : high pressure vessels for satellites and for Ariane 4 and 5, cryogenic composite tanks, oil pipes, struts for Airbus planes or military applications etc…

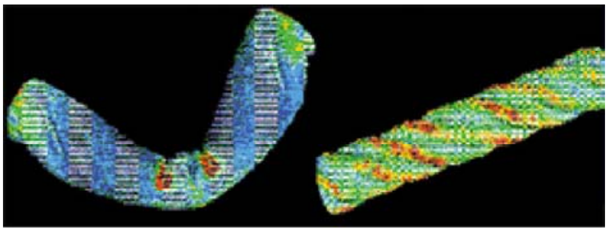
Fig. 7. High pressure vessels

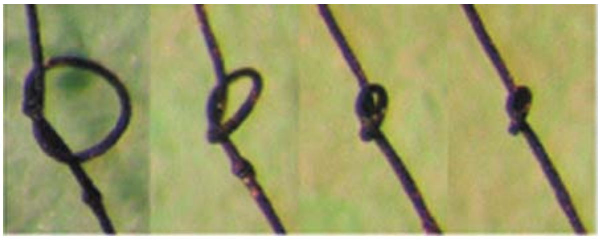
Fig. 8. Struts for Airplanes

These technologies could also be applied to tanks for liquid stages or boosters of a launch vehicle

A POSSIBLE BREAKTHROUGH IN THE FIELD OF MATERIALS

	Aluminum	Carbon Fibers	Carbon Nanotubes
Density	2.7	1.8	1.4
Young Modulus (Gpa) (axial stifness)	70	200 – 800	1000 - 1500
Poisson Modulus (Gpa) (transverse stifness)	26	100 – 300	Very low
Ultimate Stress (Gpa) (traction)		2 - 7	10 – 50
Ultimate Strain (%)		0.4 – 2	20





Carbon Nanotubes were Discovered in 1991 by the Japanese Sumio Iijima: CNT is a tubular form of carbon with diameter as small as 1 μm and Length as few μm to microns.
CNT is configurationally equivalent to a two dimensional graphene sheet rolled into a tube.
CNT can be metallic or semiconducting, depending on chirality.

From this time, as possible breakthroughs are possible in numerous field of activities, including high strength, light weight composites; so extensive research on the electronics, mechanical and other properties of nanotubes an their manufacturing have been undertaken by different countries including the NASA Ames nanotechnology group (In 2001 R&D programs were funded by NASA for $M 495) .

Carbon nanotubes exhibit remarkable mechanical properties, for example, a Young's modulus of over 1 TPa and tensile strength of about 200 Gpa (see table above).

A breakthrough is possible with revolutionary new materials[R4], with a strength several times higher than the current carbon fibers.

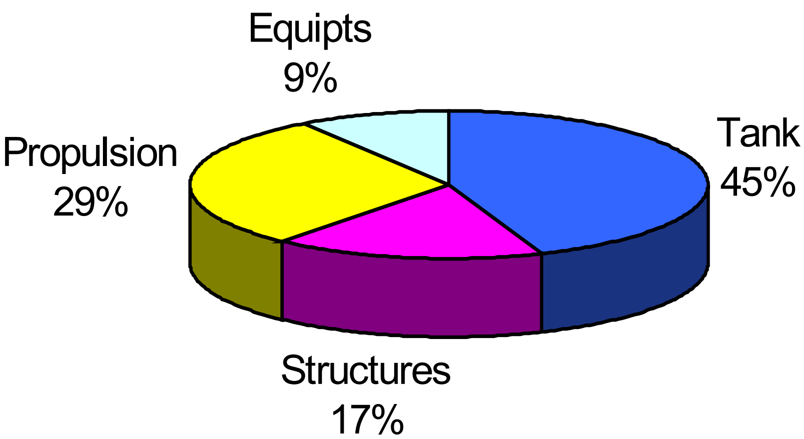
Nevertheless, a great deal of work is to do to go from SWT of decimeter[R3], fibers of bad qualities to very high qualities material available in bobbin yarn of several kilometers length for filament winding or in clothes for primary structures composites.

PRESSURE-FED PROJECT STAGES

To illustrate the potential advantages of current state of the art composite tanks associated to pressure-fed stage, we will present two different type of applications.

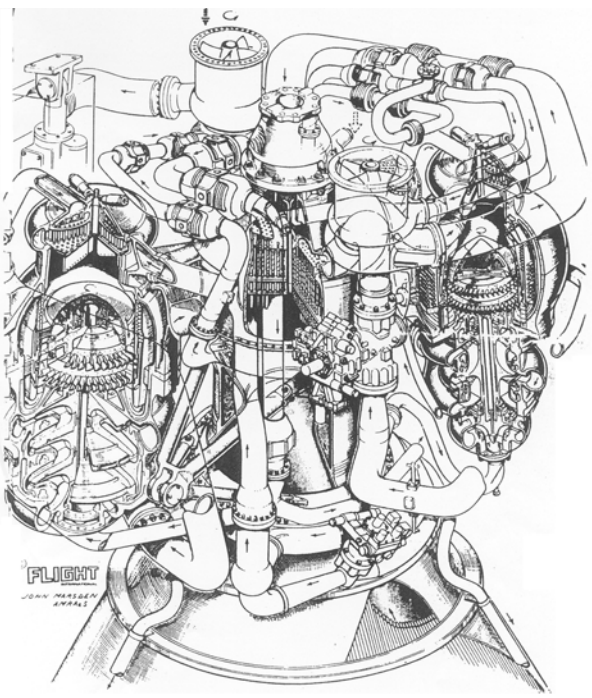
Launch Vehicles are mainly Propellant Tanks- for solids or liquids - sized by their internal pressures, or primary Structures sized by buckling or flexion loads

ARIANE 5- EPC - Mass Sharing



A Launch Vehicle uses rocket propulsion, i.e combustion hot gas mass ejection at the maximum possible velocity:

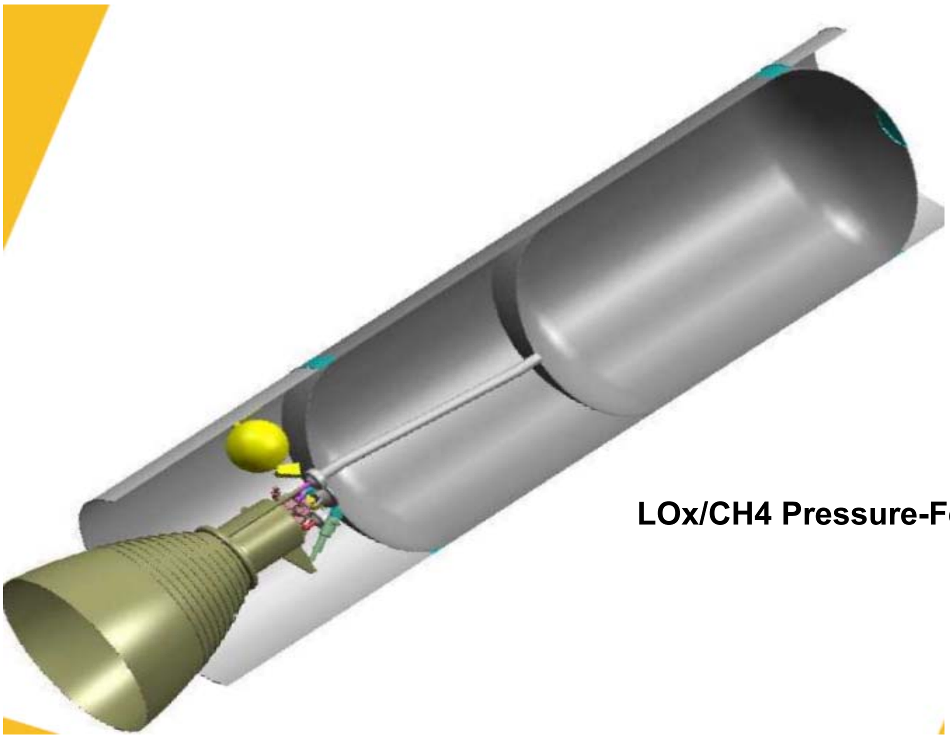
- Combustion pressures have to be high enough to limit kinetic losses (upper stages)
- Combustion pressure is a major performance parameter for high thrust stages (stages0 and 1)
  - SotA: heavy metallic tanks➡ minimum MEOP ➡Pressure increase by Turbopumps for *liquid propulsion*
  - SotA:Tank= combustion chamber for *Solids*, pressure level results from an optimisation Pc increase with material properties



For Liquid stage an engine is costly due to the high cost of turbopumps(=30 to 50% of engine cost, the engine may represent 50% of stage cost) . Moreover, complexity equals loss of reliability.
Is it possible and interesting to make Liquid Stages as simple than Solids ones?
The answer seems to be: Pressure-Fed with a Controlled Blow-Down
Pressure-Fed Systems are more simple and less expensive but to be competitive, they need high performance tanks: low mass for high internal pressure:

- a first step is to use carbon filament winding, currently used for Solid Rocket Motors
- a second step is to use improved fibers (with carbon nanotubes)

Boosters projects:



A pressure-fed liquid stage will be better than a turbopump one if with the same specific impulse(same combustion pressure), its structural index is better than a turbopump one.
Reference (Turbopump):Stage LOx/Kero Propellant Mass 280 tons Struc. Index =8% with a

Staged Combustion Engine : Isvac =333s Average on trajectory 320s
It seems possible with a Pressure-Fed solution to reach a Structural index close to 10% for average Is on trajectory of 305s: It is not enough to be competitive in terms of performances with a turbopump-fed stage but it will cheaper. Such a solution will be better than a solid stage solution.

Upper Stages:

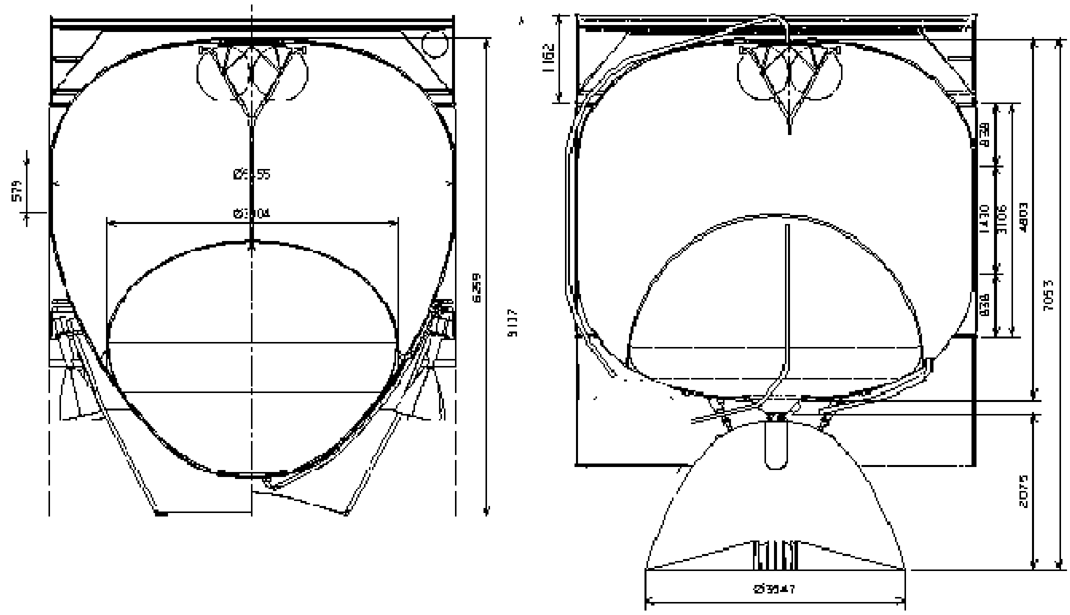
Examples of architectures were presented in AIAA-2001-3692-Innovative Upper Stage Propulsion Concepts For Future Launchers:

- ❖ With a cluster of engines associated with a truncated plug nozzle.
- ❖ With a reversed E-D nozzle

It was compared in terms of performance to a reference architecture, in this case, an EADS in-house study of Ariane 5 Upper Stage. Like Centaur stages, this stage will use a (VINCI) LH_2/LO_2 Expander engine equipped with an Extendible Exit Cone (EEC), currently under development, so as to have as high as possible a specific impulse level.

These alternate solutions that are not yet state-of-the-art (SOTA) in Europe but may benefit from more than 30 years of experience on SRM wound cases and from all European R&D work on new hot composite materials (EADS-LV, Astrium, SNECMA).
In such an application, the specific impulse of an engine was assumed to depend mainly on its area ratio and not on its combustion pressure (but in fact the effects of the 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 were not negligible).

Tank pressure was arbitrarily chosen as low as possible, corresponding to the minimum thickness of a composite tank of this size: to limit the penalty on the mass budget, a blow-



down operating mode is considered at the end of the mission. The tank pressure was assumed to decrease from 1.85 to 0.7 MPa.

	ESC-B GTO	ESC-B Multiboost	ESC-plug multiboost	ESC-ED multiboost
ΔCU Isv	0	0	- 880	- 760
ΔCU masse	0	- 803	+ 340	+ 570
ΔCU propergol	0	- 425	+ 100+X	+ 100+X
ΔCU total	0	- 1 230	- 440	- 90

The previous table shows the low potential difference with the reference solution for a GTO mission and its advantage for a multiboost mission (non sensitiveness of pressure-fed solutions to mission profile).

A new winding material allowing to double the MEOP with the same tank mass will have the consequence to double the combustion pressure and quasi suppressed the performance penalty due to a lower specific impulse (kinetic losses due to a low pressure operating mode)

With a new material, theses solutions will be potentially greatly better in every uses.

Material breakthrough:

What could be reasonable material specifications? :
Increase the ultimate fiber strength (traction) up to a ratio of 3 or increase up to 2, both winding fibers and material for primary structures?
For the upper stages, the tanks were sized at the minimum feasible thickness: such an improvement will lead to double the average operating pressure and so to largely increase the specific impulse , it should result in a total payload increase of some hundred kilograms resulting of lighter primary structures and of 500 kg or more due to an higher specific impulse

For boosters, a combination of lighter tank and primary structures (skirts) and a reasonable increase of the operating pressure (function of the material properties and of the engine technologies) could lead to an important performance improvement.

Material Specifications :

Temperature range: 20-350K
Utilization: yarn bobbin
Roving Length (bobbin ϕ 60/250 mm fitted to winding machine): 2,5 km, extension to 6 km max.
Elementary Width : roughly 3 mm
Needs per year: some hundred of tons
and need of R&D to learn to use it:
Either with Pre-preg winding

- **Storage: lifetime from 1 to 1.5 year inside a freezer**
- **Lifetime after storage when used : average value from 1 to 6 months**

Or wet winding

CONCLUSION :

R&D on new materials may offer- perhaps- the breakthrough needed for a low cost access to

Space leading to come back to simple an cheap solutions such as pressure-fed propulsion systems.

Europe cannot be absent of the competition, and has to fund research on nanotubes and their uses.

REFERENCES:

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[R2] AIAA-2001-3692 Innovative Upper Stage Propulsion Concepts For Future Launchers M.Calabro et all, EADS LV, 37th AIAA JPC Conference 8–11 July 2001- Salt Lake City

[R3] Science vol. 296 May 2002- Direct Synthesis of long Single-Walled Carbon Nanotube Strands- H.W.Zhu et all
[R4] SAMPE Journal,Vol.38, N°3 May 2002 Carbon Nanotubes and nanofibers in Composite materials- B. Maruyama -AFRL