Overview on Hybrid Propulsion

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ABSTRACT

An historical survey shows aside of research works, propulsion used by students, for small satellites, for gas generation or for the Space Ship One, even if LOX/ was studied and tested in large motors for its potential very low cost, however this combination highlights a series of technical problems without any performance advantage over the existing LOX/Kerosene family and never been operational for ETO applications.

The particularity of hybrid propulsion is to use the state of the arts of both liquid and solids; the only Show Stopper is the propellant itself

The past work focused on LOX/HTPB or PE (selected for their low cost) appears to be a dead-end (combustion problems and global low performances resulting of a high level of residuals)

The solution that appears through the past experience is the addition of Hydrides to a binder (HTPB or other) or to a binder and a homogeneous fuel or a mixture of both, with or without others additives; within these solutions some will not present any manufacturing problem and some may have a low cost.

Nevertheless following phases studies have to demonstrate the compatibility of the potential regression rate range with a high performance global design of a Hybrid Motor and the manufacturing at a reasonable cost of a Hydride giving a high level of performances

Acronyms

ETO: Earth To Orbit

Chemical acronyms

AN: Ammonium Nitrate
AP: Ammonium Perchlorate
BAMO: 3, 3-Bis (azidomethyl) oxetane
CTPB: Carboxyl terminated polybutadiene
GAP: Glycidyle azide polymer
GOx: Gaseous Oxygen
HTPB: Hydroxyl-terminated polybutadiene
LOX: Liquid Oxygen
NP: Nitronium Perchlorate
NMTD: Metatoluene Diamine Nylon
PB: Polybutadiene
PBAN: Polybutadiene Acrylonitrile
PE: Polyethylene
PEG: Polyethylene glycol
PETN: Pentaerythriol tetra nitrate
PMMA: Polymethyl methalcrylate
PPG: Polypropylene glycol
PS: Polystyrene
PU: Polyurethane

INTRODUCTION

When one propellant is a solid and the other one is a liquid, a rocket motor is designated as hybrid architecture. Most of chemical rocket motors require at least two reacting media: a fuel and an oxidizer to burn and produce hot gases

The hybrid rocket may be classified into various types as shown on the following figure 1.

The standard hybrid arrangement consist of a pure fuel grain cast and cured in the combustion chamber (as a solid rocket motor) and of a liquid oxidizer stored into in a separate tank and injected under pressure in the combustion chamber (several configurations exists depending of the propellants and the application).

The solid state can also be obtained or freezing a fuel grain such as ethylene and n-pentane that has been tested at lab scale, or a gelled liquid fuel sustained by an internal matrix

The inverse hybrid uses a liquid fuel and an oxidizer grain; it works in the same way as the “standard” one.

Of all of the design concepts mentioned before, the standard hybrid rocket (scheme “a”) has received the most attention: from its first introduction during the 30s by L. Andrussow with O.Lutz and W. Noeggerarth, tested a 10-kN hybrid using coal and gaseous nitrous oxide (Work done for I.G.Farben)…………. to its use to win the Xprize

The inverse Hybrid, even if subject to some studies is not a solution: industrial manufacturing of an oxidizer solid grain is not easily feasible with the current techniques.

An historical survey shows aside of research works, propulsion used by students and for small satellites, some dead ends as the LOX/HTPB one for earth to orbit access were examined for its potential very low cost, however

this combination highlights a series of technical problems without any performance advantage over the existing LOX/Kerosene family.
Nevertheless if the combination of propellant is not only focused on the lower possible cost Hybrids may represent a potential breakthrough, using advanced Hybrids, for the Earth to Orbit (ETO) access.

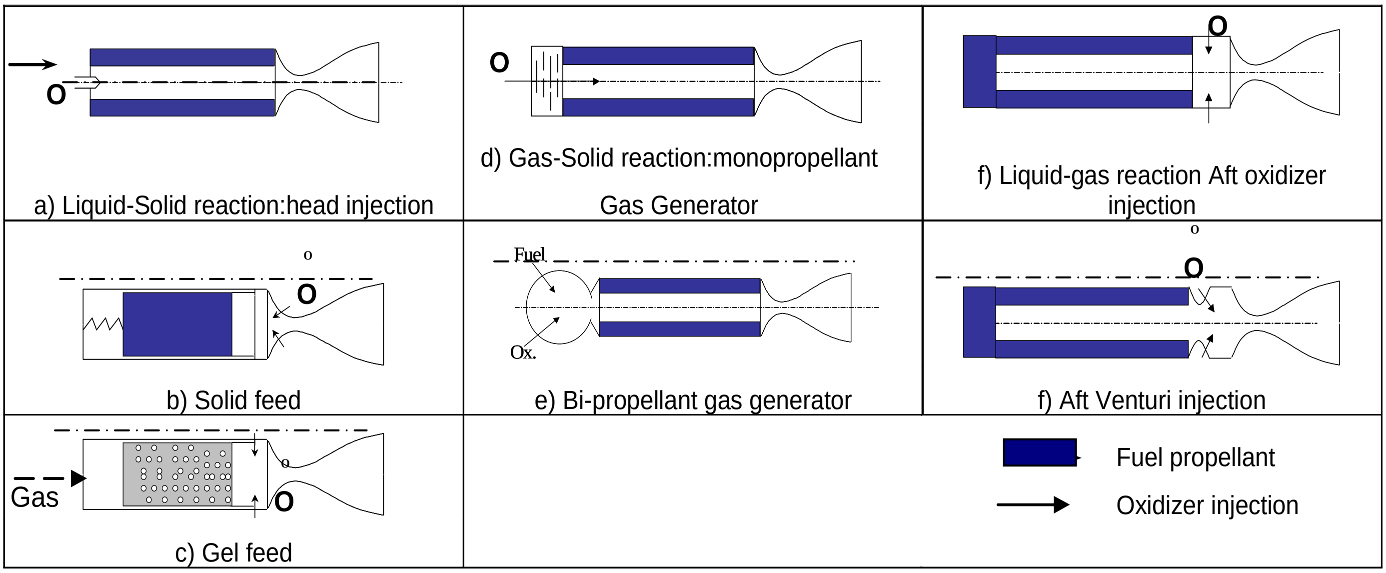


Figure 1: Typical hybrid concepts ([4] page 20-152)

HISTORICAL SURVEY/HIGHLIGHTS

This survey is limited to the experiences concretized with in-flight tests or large motors ground tests; for a more detailed history, the article of D.Altman and A.Holzman [5] and [1] will give more information.
The early developments date back to the 1930s: The first recorded flight of a GIRD-09 on August 1933 was reported by Sergei Korolev and Mikhail Tikhonravov (180mm of diameter, 500N thrust, it reached an altitude of 1500m). The propellants were a gelled gasoline suspended on a metal mesh and self pressurized LOX, refer to www.hybridracketen.de
In the mid 1940s The Pacific Rocket Society tested LOX with Wax/black Carbon, rubber-based-fuel and also wood (Douglas Fir), the most successful and the last (?) flight occurred in June 1951- XDF-23- using a rubber based fuel reaching an altitude of about 9km.
In the mid 1950s General Electric, under the sponsorship of the Army Ordinance Department, ran more than 300 tests on 90% Hydrogen peroxide (catalytic decomposition) and Polyethylene; the work demonstrate an easy throttling by means of a valve an a stable combustion but also a low burning rate that could not be varied significantly and practical problems to use Hydrogen peroxide resulting of its inherent thermal instability.
In the same period, both the Applied Physics Laboratory of the John Hopkins University, Thiokol and UTC (CSD) experimented reverse hybrids with various oxidizers; this solution was quickly abandoned running into difficulties
In the mid-1960s, UTC, sponsored by NASA, tested a FLOX (mixture 30/70 of liquid Oxygen and Liquid Fluorine) associated with a solid made of PBAN loaded with Li and LiH. This combination is hypergolic. The motor was 1.07m of diameter with an eleven port wagon wheel grain; the specific impulse was about 380s for an area ratio of 40 (Aviation Week- 26 January 1970)

Between 1960 and 1980, the US developed target drones with 2 levels of thrust:

- The Sandpiper conceived by UTC, using MON 25 and PMM/Mg fuel (10%Mg), the first of the 6 flight occurred in January 1968,(combustion duration 300s, throttling ratio 8/1, horizontal flight up to 160km, launched from an aircraft)
- The High Altitude Supersonic Target (HAST) using IRFNA fed by a turbopump and PMM/PB (20/80) fuel in a stacked cruciform grain (38 samples), thrust modulation was in a ratio of 10/1. While the Sandpiper was expandable, the HAST was recovered after flight; it used a CSD motor
- The Firebolt Target (with 40 samples) under development by Teledyne Ryan, manufactured by Beach Aircraft was a later version with a motor similar to the HAST. The Firebolt completed its evaluation period in 1984; however no production contract was ever given.

Table 1: Performances capability for several Fuel/Oxidizer couples [1]

Performance of hybrid propellants				
Pc = 3.5 MPa and Pe = 0.1MPa (Sea level)				
Fuel	Oxidizer	Optimum O/F	Isp, s	c*, m/s
HTPB	LOX	1.9	280	1820
PMM(C5H8O2)	LOX	1.5	259	1661
HTPB	N20	7.1	247	1604
HTPB	N204	3.5	258	1663
HTPB	RFNA	4.3	247	1591
HTPB	FLOX(OF2)	3.3	314	2042
Li/LiH/HTPB	FLOX(OF2)	2.8	326	2118
PE	LOX	2.5	279	1791
PE	N20	8	247	1600
Paraffin	LOX	2.5	281	1804
Paraffin	N20	8	248	1606
Paraffin	N204	4	259	1667
HTPB/Al(40%)	LOX	1.1	274	1757
HTPB/Al(40%)	N20	3.5	252	1637
HTPB/Al(40%)	N204	1.7	261	1679
HTPB/Al(60%)	FLOX(OF2)	2.5	312	2006
Cellulose(C6H10O5)	GOX	1	247	1572
Carbon	Air	11.3	184	1224
Carbon	LOX	1.9	249	1599
Carbon	N2O	6.3	236	1522
Cryogenic hybrids				
Pentane(s)	LOX	2.7	279	1789
CH4(s)	LOX	3	291	1871
CH4(s)/Be(36%)	LOX	1.3	306	1918
NH3(s)/Be(36%)	LOX	0.47	307	1967
Reverse hybrids				
JP-4	AN	17	216	1418
JP-4	AP	9.1	235	1526
JP-4	NP	3.6	259	1669

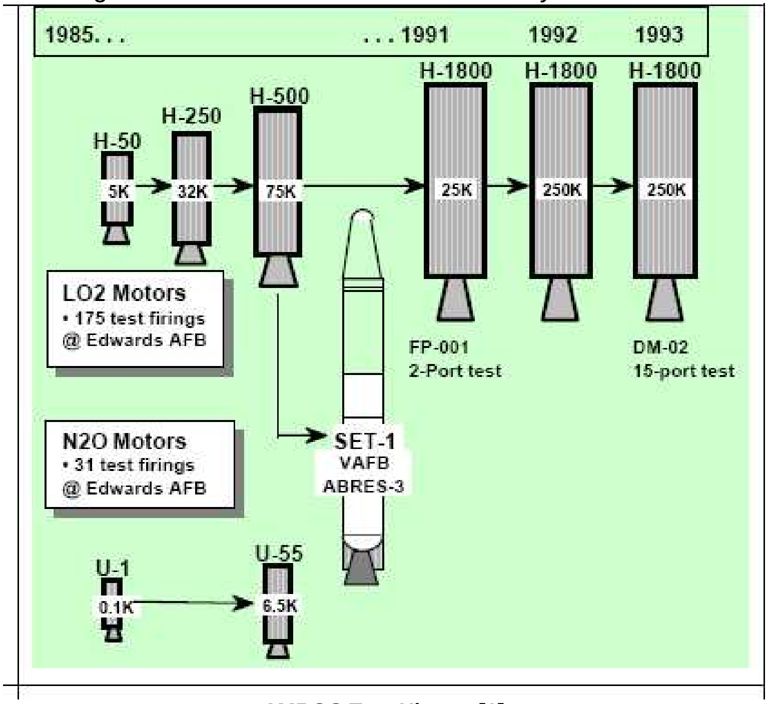
Note: JP-4 is Kerosene and nearly all of these combinations of the table have been tested at least at laboratory scale.

After 1995, there were 2 significant sounding rockets programs in the USA:

- The Hyperion using N_2O and HTPB (4 flights, the last in 1997),
- Lockheed Martin flew in 2002 a larger one using LOX/HTPB with an initial thrust of 267kN.

In Europe, ONERA developed the LEX **sounding rocket** with 8 successful flight between 1964 and 1967 - MON 40/NMTD (Metatoluene Diamine Nylon) – reaching an altitude in excess of 100km and then with SEP (Snecma today) and Nord Aviation ((Astrium Space Transportation today) a biggest version-the SPAL 30- for a drone (no in-flight test). The formulations have shown a relatively high burning rate and the propulsion system a very good overall efficiency. In Sweden, Volvo in-flight tested (1965) 2 HR-3 sounding rockets (IRFNA and PB/aromatic Amines), formulation very close to those of ONERA [6].
More recently, Nammo Raufoss conducted a static firing of their first full-scale hybrid motor, a part of the Norwegian Sounding Rocket (NSR). (30kN Thrust, 200kg of LOX), this development is leaded with in cooperation with Lockheed Martin (LM) Michoud Operations, New Orleans, USA.
The **large scale Hybrids** were tested only in the USA. First UTC with the HTM series motors in the 1960s under the US Air Force funding, tested a N_2O_4 and aluminized PB as the fuel (97cm in diameter; 180kN thrust)
The company Starstruck was created in 1981 to develop a large sounding rocket, The Dolphin, using LOX/PB and weighting about 8 tons; after 6 ground tests, a flight was a failure (1984). The company was reorganized and named AMROC, AMROC was an entirely private funded company. During the period 1985-1993, 139 motors of

different sizes were built and 240 firings were performed, mainly with LOX/HTPB, between 20 and 1100kN with a new flight failure in 1989, SET-1.A stuck valve by frozen humidity prevented the reaching of the thrust and after shut-down an external fire damaged somewhat the rocket in such away that another launch became impossible.



AMROC Test History [1]

In 1990-1993 AMROC mainly carried the design of Aquila, a small launch vehicle (900kg on a LEO); this development was based on the H-250K, a hybrid motor LOX/PB of 1000kN of thrust
The Hybrid Technology Option Project (HyTOP) including AMROC, CSD and Martin Marietta took the relay (large motors tested in 1993 and 1994 with low frequency instabilities problems) to demonstrate the low cost development of hybrid propulsion; in 1995, AMROC lost its sponsors, the cost to solve the problems was too high and ceased its activities . AMROC was bought by the SpaceDev society in 1998
Nevertheless a new program Hybrid Demonstration Program (HPDP) with Thiokol replacing AMROC was initiated. Configurations are still based on LOX/HTPB, wagon wheels grain solutions. 4 tests of a 1.1 MN thrust motor were performed with a lot of combustion issues.
AMROC, even if it was not successful, have demonstrated the capacity of Hybrid motors to be extinguished and reignited, the safety and the non explosive nature of hybrid.
“In summary, more than 15 years from the mid 1980s to the early 2000s were spent in development of large hybrids by three organizations, Starstruck, AMROC and the consortium mentioned above. All these programs were based on the LOX-HTPB propellants because of cost, good physical properties and performances. The major problem encountered by all these groups was combustion stability when scaled to larger sizes. [3]

Lockheed Martin HYSR Project: A large-scale hybrid rocket was successfully launched from the NASA WFF on 18 December 2002 as a technology demonstration for hybrid propulsion and related subsystems. The HYSR Program started in 1999. The overall goal of the program .was to develop a single-stage propulsion system capable of replacing existing two and three-stage sounding rockets, the hybrid rocket had a propellant combination of LOX and HTPB and produced approximately 60,000 lb of vacuum thrust. The three-year technology demonstration program was a collaborative effort between NASA and Lockheed Martin

Scaled Composites: SpaceShip One: The Ansari X Prize was a contest with a 10 million reward for the first commercial company to get 3 people to 62 n miles high and repeat within 2 weeks Composites built a two-stage airplane to win the prize with the second powered by a N2O/HTPB hybrid rocket with a 80s maximum burn. N_2O was self pressurized
The in-flight use of a N_2O/HTPB motor by Rutan on the Spaceship one to win the X prize closed happily the US hybrid History (even if it experienced some combustion instabilities). The History will continue with a larger vehicle the Spaceship 2

Figure 2 : Space Ship 2 overview Credit: Virgin Galactic

ADVANTAGES AND DRAW-BACKS OF HYBRID PROPULSION

Resulting of its characteristics (i.e. separately stored fuel and oxidizer), hybrid propulsion systems may offer important advantages over their liquid and solid competitors.
The following advantages for the classical hybrids are commonly recognized in the propulsion community and will be discussed:

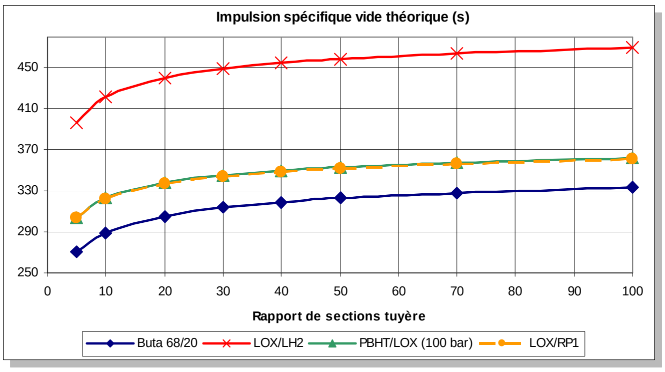
- Higher performances than liquid and solid rockets.
- A very safe fabrication, storage and testing.
- A better operability for a lower cost
- A minimal environmental impact.
- A much lower propulsion system cost
- A high reliability (half the pumps and plumbing of a liquid propulsion system; a insensitive solid-propellant grain, tolerant to cracks).
- Stop-start-restart capabilities
- A controllable thrust shaping on demand

Propulsion Performance

The performance of a propulsion system has to be appreciated doing comparative stages designs. Nevertheless, several parameters are useful to have a first idea of propellants comparison

- The theoretical specific impulse,
- The combustion efficiency, the interesting system parameter being the practical specific impulse
- A reasonable throat erosion
- The equivalent density; this parameter is of first importance when an hybrid have to replace an existing system with lay-out constraints
- The amount of residuals

Theoretical Performance



Theoretical Specific Impulse: comparison between a HTPB, HTPB/LOX, LOX/RPI and LO2/LH2 versus area ratio [7]

<table>
<tr><td colspan="2">Propellant</td><td>Mixture Ratio</td><td>Equivalent Density (kg/m3)</td><td>Isv th (Pc 7MPa, Σ=40)</td></tr>
<tr><td colspan="2">Solid (HTPB)</td><td>68/18/14</td><td>1750</td><td>315</td></tr>
<tr><td colspan="2">Hybrid (LOX HTPB)</td><td>72/28</td><td>1060</td><td>354</td></tr>
<tr><td rowspan="5">Liquid Bi Prop</td><td>NTO/MMH</td><td>2.37</td><td>1200</td><td>341</td></tr>
<tr><td>H2O2/RP1</td><td>7.0</td><td>1320</td><td>314</td></tr>
<tr><td>LOX/RP1</td><td>2.77</td><td>1030</td><td>358</td></tr>
<tr><td>LOX/CH4</td><td>3.45</td><td>830</td><td>369</td></tr>
<tr><td>LOX/LH2</td><td>4.8</td><td>320</td><td>455</td></tr>
</table>

Theoretical Isv: comparison between current propellant and LOX/HTPB[8]

This table illustrates the comparative performances of one of the most studied hybrid –LOX/HTPB- with conventional solid and liquid formulations, Hybrid is potentially better than solids and better than storable bi propellants and competitive with semi storable propellant

A fair comparison have to be made through a comparative global analysis for a given mission, less dense that solid, a hybrid stage is more cumbersome *but amazingly could be lighter than a solid solution* ,the higher Isv is largely giving the advantage over solid and also over NTO/MMH, The competition between LOX/Kerosene or LOX/ Methane with LOX/HTPB or PE , all "green propellants" is questionable : The Specific impulse is not better and the high level of residuals handicap this Hybrid solution

From the point of view of the Specific Impulse better combinations exist that will be examined latter, nevertheless no classical fuel (i.e. PE, Wax, Nylon/MNTD) associated to the better potential oxidizer in competition is able to deliver a much higher Isv than LOX/methane

Combustion efficiency

Hybrids burn differently from either liquids and solids, for classical HTPB hybrid propellant mixing and combustion occur in a diffusion flame zone that is in the same range of length as the inner bore length ; a very strong research effort have been made on the subject . G.A Risha from Penn State University ref [1] mentioned C^* star efficiencies in the range 72-91 %

Several measures could be taken (separately or combined) to have a reasonable or even a good efficiency level:

- A special design of the grain
- The oxidizer injection techniques
- The fuel grain formulation

A *special design of the grain*, whose aim is to create and organize turbulent zones -all along the inner bore-will have a dual role:

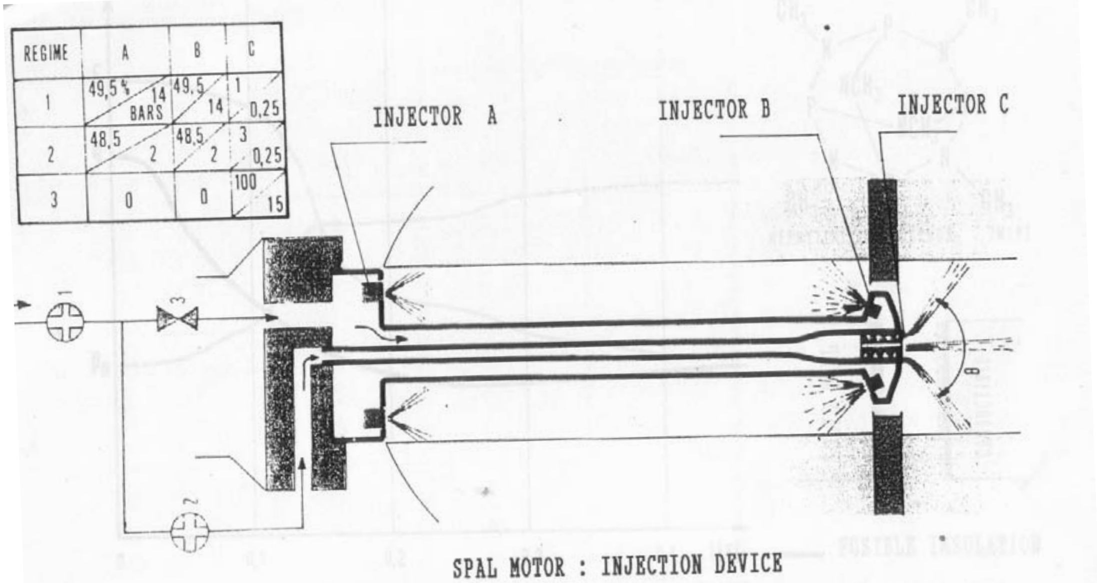
- the combustion efficiency increase
- a lower risk of combustion instabilities (medium frequency=acoustic coupling)

A solution widely proposed is to create a premixing chamber and a post combustion chamber, including or not a secondary injection of oxidizer; all the AMROC stages for Aquila and HyFLYER , the LEX of ONERA were designed with theses chambers another way could be to have distributed slots [9] or a central cavity (on very long solid grains the ASSM-POP Cnes program showed the interest of that solution by tests and computations for solids ; the efficiency of these solutions have to be demonstrated for Hybrids)

Another solution is to include turbulence generators including metal or plastic screen in the fuel grain so that after regression obstacles are created all along the inner channel [10], *localized turbulence*-or to include crystalline loads to increase the roughness surface being vaporized and ejected–*distributed turbulence*

Injection Systems

In the early developed hybrids in France (Sounding Rocket LEX, SPAL30 for the C30.C Target Drone, ONERA was paying a special attention to the injection system to avoid losing room with large premixing and post combustion chamber. The injection design resulted from a strong experimental work and led to specific impulse efficiencies greater than 0.95 [6] that means taking into account the C_F a very high efficiency, C^* in the range of those of liquid (0.99 for the acceleration regime). The basis of this design was to have no laminar combustion zone at all but to have from the beginning a pre mixed turbulent diffusion combustion

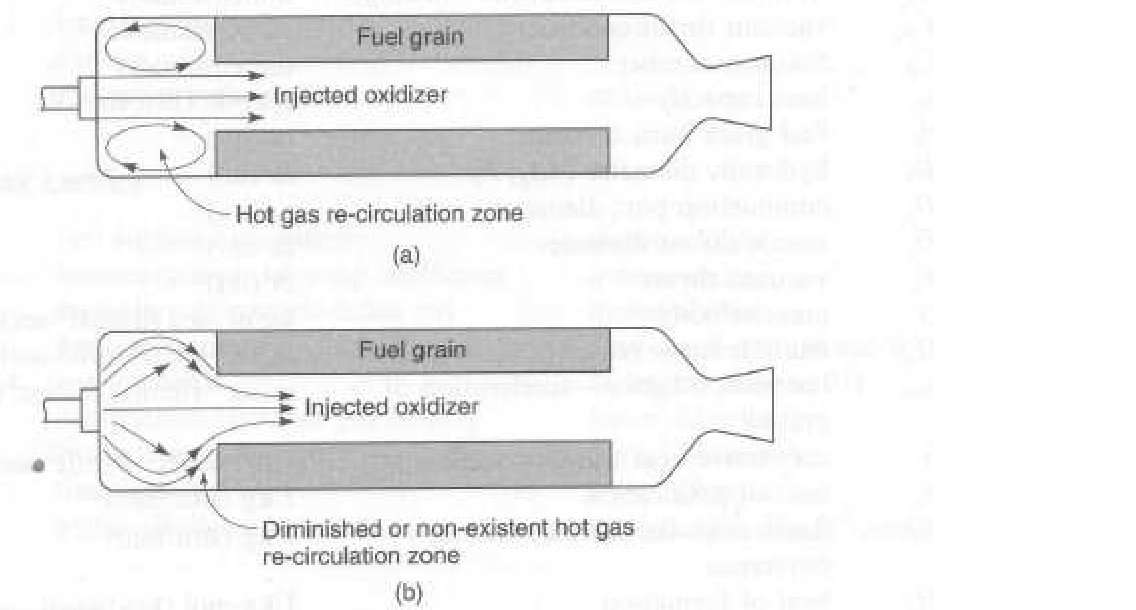


SPAL MOTOR : INJECTION DEVICE

AIAA - HYBRID PROPULSION LECTURE SERIES - 29 TH AEROSPACE SCIENCES MEETING JANUARY 10, 1991. RENO, NEVADA

The combustion chamber was divided in two part, a first one ended by an elastomeric diaphragm The first Chamber Injector was constituted of 6 Tubes/.30 Vortex Injectors .(injector A) The Diaphragm Injector of 108 elementary Vortex Injectors(injectors B and C), the main grain was a 6 Branches Star with a MON 40/NMTD (Metatoluene Diamine Nylon) combination. This combination is not hypergolic, the self ignition was obtained with an ignition liner of Paraphenylene Diamine (8 successful LEX flights, 3 SPAL 30 ground test, configuration with 3 channels and 16kN thrust) .The measured Specific Impulse Efficiency was of 0.95 taking into account the C_F losses, it means that it is possible to have C^* efficiencies at the level of the combustion of liquids. From this period vortex injection was subject to many experimental studies and modeling works (i.e. Majdalani[1])

AMROC U.S. Patent 5794435



More classical injector head was used by AMROC with LOX HTPB such as theses described in the US Patent 5794435, or classical shower head one with or without diverging jets (the (a) configuration lead to a stable combustion resulting of a strong recirculation z, the (b) is to proscribe) , this kind of injector is associated to a premixing chamber (Story ref .[1] pages 529 and following, [2] Sutton 7th edition page 603), nevertheless ; it was probably not so simple ; in fact AMROC added in the premixing chamber a finocyl grain and a deflector: the fins and flow deflector are designed to promote flame holding in combustion ports here also the C^* efficiency may reach 0.98 without combustion instabilities

In conclusion on this point, it is possible playing on several parameters to reach a good efficiency without combustion instabilities the counterpart being or a more cumbersome motor or a more sophisticated design

Throat material Erosion rate

The nozzle of a hybrid motor uses the same technologies from the self than used for solids; the exhausts gases are very chemically aggressive for the throat materials; so the thrust efficiency have to take into account for the same combustion pressure of a lower average area ratio and so a lower average specific impulse

	Solid (HTPB)	Classical Hybrid
Carbon/Phenolic resin	0.252 mm/s	0.65 mm/s
Silica/Phenolic resin	0.42 mm/s	1.12 mm/s
Carbon /Carbon	0.13 mm/s	0.24 mm/s

Comparison of erosivity [11]

Some Advanced Hybrids (including Hydrides) whose exhausts gases composition is close to the solid ones, will have a much better behavior and will not show significant differences with the solids

The effluents of typical hybrids (excluding afterburning in the exhaust plume); could have a very low erosivity: A potential low cost formulation (LOX/Wax/MgH2) will show a lower erosivity than a classical solid (see the table here under) with its large amount of Hydrogen and without water and CO2.

moles/100g	LOX-CH4	SOLID	Wax	Wax MgH2
H	0.161	0.156	0.035	0.016
H2	0.398	1.136	0.074	2.955
OH	0.359	0.024	0.278	0.000
H2O	2.112	0.035	1.255	0.005
O	0.085	0.002	0.076	
O2	0.178	0.000	0.506	
CO	0.824	0.847	0.455	1.404
CO2	0.562	0.032	0.961	0.000
N2		0.288		
AL2O3		0.337		
HCl		0.467		
MGO				1.090

The equivalent density effect

Without any constraints of lay-out , the effect of a lower bulk density than solid may only be appreciated by a complete design of a stage , the launch vehicle for the same payload will be bigger but with a lower lift-off mass[12] .For example, the replacement of the shuttle booster by conventional LOX/HTPB would require 59 tons less propellant but with an increased diameter from 150in. (3.81m) to 180in. (4.57m)with an increased length of more of 5 meters, it was equivalent in size and propellant mass than a LOX/RP1 booster

Classical hybrid when studied to replace a solid one with lay-out constraints need an improved solution (more energetic fuel) to be really competitive (Example of the MPS Ariane 5 replacement [9] where with the lay-out constraints (launch-pad, and Ariane itself), only a maximum of 2x210 tons can be loaded but may increase the performance of the launch vehicle of 2 tons with the use of an improved Alane Hybrid)

The residuals

Solids have a negligible amount of residuals and liquids less than 2%, Classical Hybrid with a low regression rate associated to Wagon Wheel geometry will have a much greater level of residuals, the regression of the surface is not regular, taking into account that stopping the engine on a full consumption of the fuel will be a hazardous procedure

The hybrids have not a regular regression of the surface and mainly for multi ports the amount of residuals is very important, the LEX with its single star central port had a level less than 5%, The 1100KN AMROC motor (see figures above) has a high level residuals (>15%?); to obtain a very low and reproducible level on a multiple ports will be a hard point. This mass has to be considered as a dead mass and penalize the performance of a hybrid motor

On the other hand if Hybrids with an high regression rate exist, with a single port geometry, an efficient internal insulation, a low erosive formulation the amount of residuals may be very low

Fabrication, Storage and Testing

Handling – Virtually all hybrids fuels are considered inert (Class 1.4c propellant – zero TNT equivalent), that is they can be transported via normal shipping techniques with no additional safety requirements. This is a significant benefit when compared to traditional solids, where any processing is considered a hazardous operation and special handling considerations must be observed.
Fabrication: manufacturing an inert grain is a major parameter on the production cost, via a lower security cost. Classical hybrid motors can be cast in light industrial facilities using the techniques of traditional solid propellant casting
Moreover for relatively small motors (solid grain less than around 10 tons) the composite case can be directly wound on the grain (the grain itself replacing the sand mandrel used to wind with the solids)
Hybrid rockets are much less sensitive to cracks and imperfections in the solid-fuel grain. Even though the oxidizer and combustion product gases can penetrate into crack cavities, reactions in the cavity regions are limited and unable to generate any significant local pressurization and grain damage.
The level of safety is increased: "In liquid-bipropellant systems, leakage of propellants or structural failures due to mishandling or excess loads, whether on the launch pad or in flight, could lead to a catastrophic conflagration if the leakage or failure results in a fuel/air fire or mixing of the fuel and oxidizer. On the contrary, there is much lower probability for any violent energy release hazard involved in the event of leakage or structural failure in the hybrid's liquid oxidizer system
These safety features represent the most desirable characteristics of hybrid rockets. Their safety characteristics will definitely have a strong impact for reducing future propulsion hazards to the payload of unmanned missions, launch facilities, and manned flights" [1].

So when looking for advanced Hybrids, solutions as including some Ammonium Perchlorate or to replace HTPB by an energetic binder to increase the regression rate have to be proscribed , the propellant losing its low cost and its safety characteristics.

Operability, Reliability

Compared to liquid rockets, the relative simplicity of hybrid rockets offers important benefits in prelaunch operations due to their fewer components and operational steps.
The prelaunch operations when the vehicle is fueled could be shortened, the number of controls decreasing dramatically to become closer of solids, (some weeks less of launch campaign).
Hybrid rockets are more complex than solids due to the need for an oxidizer delivery system, with an associated oxidizer tank pressurization system and pump if necessary. Although hybrids are more complex than solids, they use only one fluid system, which make them less complex than bi-liquid systems (liquid rocket engines).

Cost

The handling and casting process costs should be significantly lower than that of a solid. Since there is only one liquid (oxidizer) used, the system costs should be significantly less than that of a liquid system.
When using an advanced hybrid, the use of a toxic or hazardous additive has to be proscribed being the origin of a cost increase

Environmental Impact, Toxicity= "Green" propellant

LOX/RP1 or other "classical" Hybrid are comparable with "green" liquids: The exhaust gases don't contain any Hypochloric acid nor alumina : there is no risks of local pollution by acid rain or alumina or toxic products
Rocket launchers are identified to have four types of effects on the atmosphere, Including stratospheric ozone depletion, acid rain, reduction of local air quality due to dispersion of toxic compounds, and global warming.
The subject is very controversial on the effect on Ozone depletion between solid and liquid competitors. The following major points may be noticed:

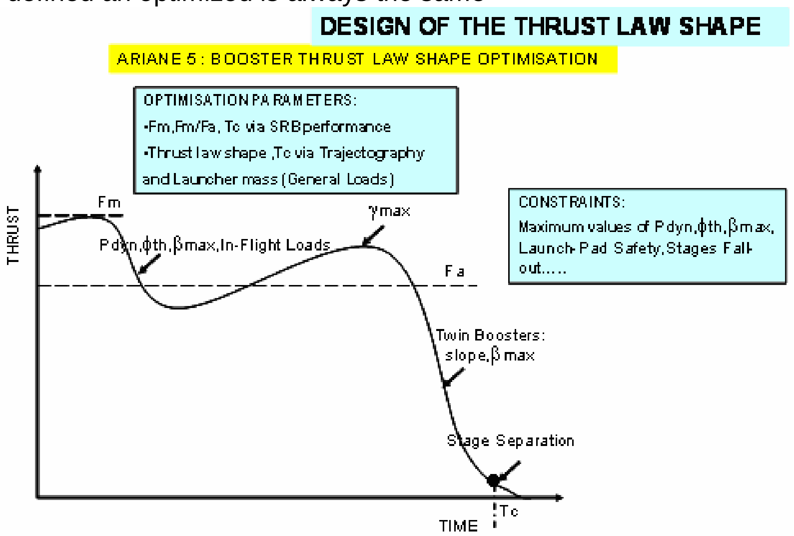
- With the current number of flight per year, the effects are completely negligible [Chiaverini, McDonald] in comparison with other human activities and natural sources. In a long term perspective and regulatory demand to reduce the pollution to a minimum , the classical solution is a good answer versus storable propellants or solids
- Advanced Hybrids have to complies with this requirements, that means that some additives such as Beryllium whose oxide is highly toxic species will be prohibited

Stop-start-restart capabilities

The most important point is the ability to stop the motor, that may solve many safety problems, for example the hybrid project for the Shuttle, it would be the only solution to save and recover the astronauts during the boost phase (need to stop the propulsion before astronauts ejection); on a conventional launch vehicle, it is the only solution with liquids to be able to respect the safety zones
The stop-restart capabilities is mainly required for upper stages, it result of the Launch vehicle optimization in term of cost and performances For example a GEO mission the Ariane Upper Stage has to deliver several separated impulses, the two first one are interrupted by a ballistic phase resulting of a trajectory optimization, the last one to clean the orbit. Generally speaking on a two stages launch Vehicle (low cost architecture), its design include a capability of restart for the upper stage, the trajectory of the Vega includes ballistic phases and it will be very beneficial to replace the Z9 upper stage and the Avum by only one Hybrid upper stage [SNPE paper Eucass 2009)
This advantage on solids is also highly appreciated when designing small launch vehicles where solids are generally the best answer in term of cost efficiency

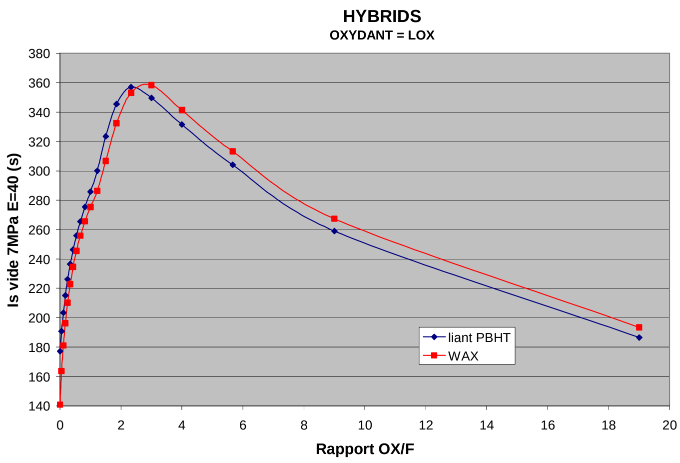
Throttling capabilities

A great number of authors emphasize the flexibility given by the throttling capabilities of hybrids.
This capacity allow to tailor the shut-down and obtain an accurate delivered velocity increment (DV) and so an accurate position, as the liquids are able to do
From a system point of view, a versatile tailoring is of first interest for some military applications, for a civilian launch vehicle to shape the thrust law is only important for the boosters; as Ariane 5 designed for a given mission; so, this shape one time defined an optimized is always the same



Thrust Law shape optimization and design criteria [13]

Practically, this throttling capability is not a real advantages versus solids where the thrust can be tailored as required without losses in specific impulse For a solid, mixture ratio is an invariant by nature, for hybrid with a constant oxidizer mass flow rate the thrust will decrease and the mixture ratio increase leading as counterpart to an average specific impulse loss that will depend of the motor design



Nevertheless, with long grain and oxidizer flow regulation (to stay at the maximum specific impulse (the thrust law shape is naturally decreasing, that a better compromise than a liquid engine with a constant thrust

CHALLENGES IN HYBRID PROPULSION

Hybrid propulsion could clearly presenting an interest .so, the question is: why it was never fully developed for large boosters for an earth to orbit use
Versus liquid propulsion, the specific impulses of classical hybrids are not better. Develop and create a new propulsion family is costly in terms of financial and human investments; the propulsion industry is sharply divided with their experience in liquid or solids This technology don't took any benefits of military involvements: solid propellant propulsion is currently quite the only technology used (even for very special systems, battleships generally forbid the use of liquid propellants)
More important are the technical problems:
The regression rate is really too low, it results a complex design of the solid part with a multi port grain, a combustion difficultly mastered (the regression rate depends on many parameters) and so a great amount of residuals may handicap Hybrids.
The challenge is to find a new fuel with a regression rate higher in a ratio of a minimum 5 versus these of LOX/HTPB to allow a single port grain as on solid
The specific impulse level have to be better than the liquids (except LOX/LH2), giving to this kind of propulsion a definitive advantage both on solids and liquids whatever the application could be
Nevertheless the objective to obtain the same level of the LOX/Methane or to be a little better in term of Isv could be an interesting objective if a target of very low cost can be reached without any technical problem

NEW ENERGETIC HYBRIDS

So, what could be an improved hybrid?
The choice of the oxidizer, for every body, seems obvious, the more energetic high density, non toxic, cheap to produce with a capacity of self pressurization and eventually nozzle cooling is the liquid oxygen.
For application or mission asking a long term storage into space or an easier handling; hydrogen peroxide and nitrous oxide (MON) are the best candidates
The major problem is to select a new fuel with the two major objectives:

- Increase significantly the regression rate,
- An higher specific impulse,
- Or both,

without losing any specific advantages of hybrids. So, the solid grain has to be constituted of combination of a basic polymer , a fuel (no oxidizer at all).and an additive (metal or Hydride) The formulation used on the LEX could be taken as reference(Nylon/Metatoluene Diamine with a regression rate between 3.5 and 5 mm/s)
Note: when reading the literature, many tests have been made at low pressure, so some laboratory results may be not relevant. In a modern motor the combustion pressure will be in the range 6 to 10 Mpa for the point of view of regression rate

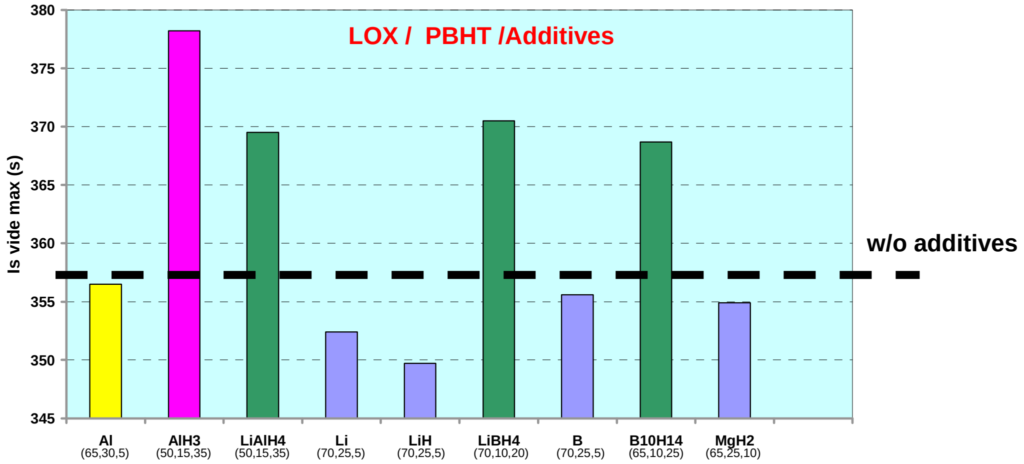
The choice of the basic polymer or fuel

For many years HTPB was a likely candidate for hybrid motors for ETO applications: the overall reaction with oxygen is taken as:
$C_4H_6 + 11/2\ O_2 \rightarrow 3\ H_2O_2 + 4\ CO_2 + 6.8$ kcal/g [Lengellé]
HTPB has a high endothermic heat of ablation, the pyrolised fuel vapor is transported to the flame zone by convection and diffusion, where it mixes with the oxidizer and burns, but the fuel flux due to the pyrolisis block some of the heat transfer to the surface which is the cause of a low regression rate [Chiaverini]
Moreover, if looking the way to incorporate additives, some hydrides may react with the isocyanates (USP 2003/0164215, September 4, 2003) used for HTPB manufacturing even if the problem is yet solved
So other binders have to be considered:
An energetic binder as the GAP is. GAP has a low heat of ablation (70cal/g versus 800 for PE and HTPB), the regression model is different, GAP possess an autonomous burning rate and so the regression rate may reach 15mm/s instead of 1 mm/s and may be envisaged as ballistic additive taking care to keep the self extinction capacity of the solid
Dicyclopentadiene (DCPD) polymer was subject of studies because it has the useful attributes of being hydrophobic and capable of encapsulating reactive fuels such as $LIALH_4$ (LAH) [Heister]

Wax used in hybrids is a mixture of n-alkanes (non polymeric saturated hydrocarbons) and as DCPD or PE doesn't contain oxygen, it is well capable to encapsulate reactive loading, with a better ratio carbon/ hydrogen. Its

performance associated to LOX is better than DCPD and equivalent to HTPB, so wax could be an ideal candidate to replace HTPB. The major advantage on HTPB is to have a basic regression rate (without any additives) greater in a ratio 2.5-3.5 [Chiaverini]
The choice will not be done not on a criterion of high Isv but on criteria of safety, combustion properties and compatibility with solid reactive fuels or additives

The choice of an additive/Reactive fuel
The effect of additives on the performance
From the stand point of performances, the following table shows the interest of some additive often studied at small scale levels .this table shows that if aluminum is studied, it is not for its effects on the specific impulse that is lower than a pure LOX/HTPB combination, boron and magnesium hydride are also not better, Li and LiH are giving a lower performance
Alane (ALH_3), LAH ($LIALH_4$), $LIBH_4$, $B_{10}H_4$ and Magnesium Borohydride are good candidates
The effect on the global density is also always positive these additive being denser than the binder (HTPB or wax or others)



SNPE computations (reference LOX/HTPB 357s, LOX/WAX 359 s)

The effect of additives on combustion and regression rate

Preliminary note: most of the studies have been made with polymeric binders and often at low pressure, the effect of pressure is generally not mentioned
The basic reference document on the subject is Risha in [1] pages 414-456

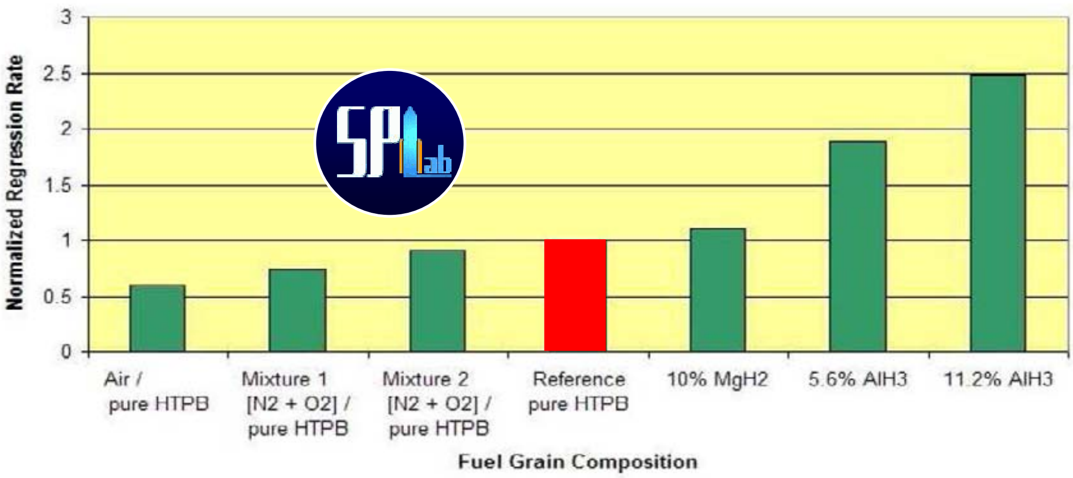
Conventional ballistic catalysts
The increase of burning rates through addition of catalysts (CuC_{l2}, $K_2Cr_2O_7$, Ferrocene) is the range 5 -25%.

Aluminum
In the 1960s, the U.S. Air force made a significant effort to develop hybrid rocket, as a viable alternative to liquid and solid rocket propulsion systems [14] [28] and tested aluminized fuels
The sizes of the particles traditionally used in the early development of hybrid rockets were usually on the order of micrometers, with the smallest being 2-5 μm. The greater energy release from the oxidation of the metal particles substantially increased the regression rate compared to nonmetallized solid fuels. With this apparent benefit in mind and recent advances in nanotechnology, nanosized particles possess the ability to release the energy in a shorter time and closer distance from the regressing fuel surface. There are many others direct advantages for incorporating nanosized particles into solid fuels and fuel-rich propellants
Nevertheless, the major conclusion is that aluminum is not the good solution to increased dramatically the burning rate that remains at the level of 1 mm/s with oxygen associated with HTPB (62% burning rate increase [Chiaverini]or with any polymeric binder
There are few results with waxes where the basic burning rate is greater in a ratio 2.5-3.5[Chiaverini [1]] “Regression rate appear promising for an operational use” (Evans)

Hydrides

One major advantage of Hydrides is the fast deshydrogenation under a thermal flux , then the hydrogen will burn with the oxidizer and the binder gazes in the primary flame zone ," the deshydrogenation of α-Alane takes place on a time scale of at most 100 microseconds" (9-IWCPLerici ,Glumac &Krier). So, it will lead to a good combustion and a high regression rate

The work of the Politechnico di Milano confirms this trend



The above figure shows the very important effect of addition of hydrides on the burning rate , addition of 11.2% of Alane to the fuel (5% of the global amount of propellant) increase the regression rate by a ratio of 2.5 , the optimum amount is 70% of the Fuel (35% of the propellant)

EUROPEAN HARDWARE STATE OF THE ARTS

The hardware needed to realize a Hybrid booster in perfectly in the state of the arts of the European Industry:

The technologies of liquid part: depend of the stage size and of the selected oxidizer, the practical possibilities of choice for the oxidizer are very limited:

The family of Nitric Acid and MON used at the beginning of the development for Sounding rockets and now generally discarded for safety reasons

The LOX is the most powerful cryogenic oxidizer excepted Fluorine whose mixtures and compounds are too dangerous to use

The Hydrogen Peroxide may be useful for missions requiring long term storage in space

N_2O Nitrous Oxide, storable, Non Toxic, relatively friendly to use and so preferred for the Space Ship One

So, the technologies for the liquid storage are coming from the shelf

Small and Most large scale hybrids have been tested with pressure-fed systems (LEX, Volvo, NAMO, Firebolt, Space Ship One) with metallic tank or for the Spaceship One a composite tank

Larger stages may need to be powered by pump fed system; only in the US were developed such a system:, AMROC, Allied System Aerospace, and NASA SSC

In terms of hardware, the metallic tank solutions are the same than used in Europe on the Ariane program, In case of a pressure fed large composites tanks can be realized by several companies (with metallic liner). The Ariane 5 industrial partners have all the Know how to realize the liquid storage (pressurization system, tank, turbopump if any, injection valve)

For the solid storage/combustion chamber a composite tank is generally to use as for modern large solid Stages (use of a metallic case is interesting for only the very small diameter rockets)

As for the liquid part, among the potential players, the Ariane industrials in charge of the P250 have the technologies needed for a development

CONCLUSION

The particularity of hybrid propulsion is to use the state of the arts of both liquid and solids; the only Show Stopper is the propellant itself

The past work focused on LOX/HTPB or PE (selected for their low cost) appears to be a dead-end (combustion problems and global low performances resulting of a high level of residuals)

The solution that appears through the past experience is the addition of Hydrides to a binder (HTPB or other) or to a binder and a homogeneous fuel or a mixture of both, with or without others additives; within these solutions some will not present any manufacturing problem and some may have a low cost.
Nevertheless following phases studies have to demonstrate the compatibility of the potential regression rate range with a high performance global design of a stage and the manufacturing at a reasonable cost of a Hydride giving a high level of performances

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