Design Challenges for a Cost Competitive Hybrid Rocket Booster

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Abstract

The hybrid rocket concept promises very interesting safety, non-polluting and thrust control characteristics for the boost phase of a space launcher. However, frequently cited cost advantages compared to solid rockets are not so clear, taken in account the required liquid propellant feed system, the impact of low fuel-loading density and of solid fuel residuals on the mass of the hybrid rocket booster. In a primary study the cost competitiveness of a specific design of a hybrid rocket booster and its sensitivity towards improvements are examined. Using a turbopump fed liquid oxygen and a HTPB based solid fuel, the hybrid rocket booster model is based on the hybrid booster activities of AMROC and Lockheed Martin. Progress in some essential parameter compared to the baseline concept is considered. The cost estimation is exercised relative to a solid rocket booster and to a liquid rocket alternative on an exemplary mission defined by a required ideal velocity increment of 2.5 km/s. The hybrid rocket mass and cost model relies on commonality to Ariane's 4 and 5 liquid and solid rocket booster units. The result shows a cost disadvantage for the baseline variant compared to the solid rocket booster. However, an optimized advanced design may reduce the gap to a cost competitive hybrid rocket, where its other positive characteristic may become more important for selection of the hybrid rocket booster.

Nomenclature

ε	Nozzle area ratio A_e / A_t
Φ	Mixture ratio oxidizer/fuel
ρ_{load}	Fuel-loading density in the motor case, kg/m³
ρ_{solid}	Solid fuel or propellant density, kg/m³
ρ	Injector material density, kg/m³
σ	Injector material strength, N/m²
η_{c*}	Combustion efficiency, c^*_{ex} / c^*_{th}
η_{Isp}	Thrust efficiency
Δv	Ideal velocity-to-be-gained, km/s
Δp	Turbopump presssure rise, bar
c^*	Characteristic velocity, m/s
C_{over}	Cost of overhead (PM, SE and PA)
C_{int}	Cost of booster integraion, assembly and acceptance testing
C_{rec}	Reccuring cost of rocket booster
C_{sub}	Cost of functional unit
c_{rec}	Mass specific reccuring cost of rocket booster, cost unit/kg
c_{sub}	Cost index of functional unit cost, cost unit/kg
dm_{ox}/dt	Oxidizer mass flow, kg/s
F_{core}	Sea level thrust of core vehicle, kN
F_{vac}	Average vacuum thrust of booster, kN
F_{sea}	Average sea level thrust of booster, kN
G_{inj}	Injector LOX mass flux, kg/s m²
I_{sp}	Specific impulse, s
I_{tot}	Total impulse, MNs
k_{case}	Mass index of solid rocket motor case functional unit
k_{eng}	Mass index of liquid rocket engine functional unit
k_{eq}	Mass index of equipment functional unit
k_{feed}	Mass index of hybrid LOX feed functional unit
k_{inert}	Structural index of booster, m_{inert}/m_{pr}
k_{noz}	Mass index of solid rocket nozzle functional unit
k_{pro}	Mass fraction of propellant
k_{res_fuel}	Mass fraction of residual fuel, $m_{res-fuel}/m_{fuel}$
k_{res_ox}	Mass fraction of residual oxidizer, m_{res-ox}/m_{ox}
k_{res}	Mass fraction of residual propellant, $(k_{res-ox}\,\Phi + k_{res-fuel})/(\Phi+1)$
k_{tank}	Mass index of propellant tank functional unit
LOX	Liquid oxygen
m_0	Initial mass of launcher, kg
m_{case}	Mass of solid rocket motor case functional unit, t
m_{sub}	Functional unit mass, t
m_e	Final mass of launcher, t
m_{eng}	Mass of liquid engine functional unit, t
MEOP	Maximal expected operating pressure, bar
m_{eq}	Mass of equipment functional unit, t
m_{feed}	Mass of liquid propellant feed functional unit, t
m_{fuel}	Fuel mass, t
m_{inert}	Inert mass of rocket propulsion system, t
m_{noz}	Mass of solid/hybrid rocket nozzle functional unit, t
m_{ox}	Oxidizer mass, t
m_p	Payload mass, t
m_{pro}	Propellant mass, t
m_{tank}	Mass of LOX tank functional unit, t
m_{TP}	Mass of LOX turbopump, t
p_c	Chamber pressure, bar
r	Rocket mass ratio m_0/m_e
t_b	Burning time, s
TVC	Thrust vector control

I. Introduction

A. Motivation

Classical hybrid rockets use an "inert" solid fuel (e.g. a polymer) and a liquid oxidizer. A mixture of droplets and gasified oxidizer flows through the fuel grain ports during the motor operation and reacts in a boundary layer near the solid fuel surface with the gasified fuel, resulting in ongoing fuel regression and consumption (fig.1). The production of the solid fuel mass flow, made available for combustion, is coupled by the combustion process itself to the incoming oxidizer flow.

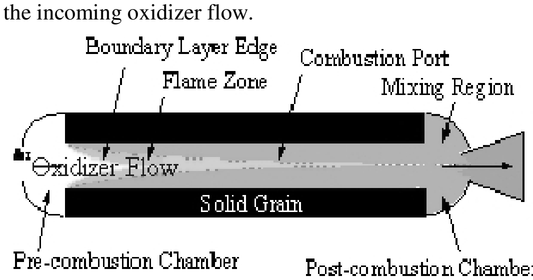

Figure 1: Schematics of Hybrid Rocket Motor Operation

The hybrid rocket has a clear safety advantage over all other rocket propulsion concepts: The stored propellant components cannot be mixed due to their separate phases, the solid fuel grain is insensitive to cracks and imperfections. The thrust can be easily throttled or stopped by controlling the oxidizer flow. The hybrid rocket operation is robust against a sudden energy release or regression fuel surface enlargement because of the controlling effect of the oxidizer flow. A solid rocket like chamber pressure runaway is not possible. The hybrid rocket also promises advantages concerning its non-polluting characteristics (chlorine and alumina free) compared to the solid rocket's toxic and corrosive exhaust.

In contrast, solid rockets are often questioned for safety concerns, because they contain massive amounts of hazardous solid propellant. Once ignited, they cannot shut down. They are also characterized by high levels of vibration and thrust pulsation. Limited specific oxygen content of standard solid rocket oxidizers like NH_4ClO_4 and its maximum achievable mass fraction in solid propellants set a limit for the specific impulse of actual solid rockets.

Combining a high performance oxidizer like LOX with a polymer solid fuel, theoretical the specific impulse of the hybrid rocket could be significant higher than solid rockets. The liquid rocket counterpart raises fears about high costs, which are up to three times more per kg launch mass compared to solids. Its higher performance (specific impulse, structural index) allows for a lighter booster, so that this can partially compensate.

Based on its promising properties the hybrid rocket booster has often been proposed for the replacement of the solid rocket booster of space launcher like Ariane 5 [7], [8], Scout [9], Atlas II [10], Titan IIIC [11] and the Space Shuttle [12], [13]. However, the safety and environmental features do not justify the replacement of the current systems alone. The hybrid rocket must display similar cost to its direct counterpart, the solid rockets, which are proven as a cost effective and reliable propulsion concept for the boost phase of a space launch vehicle.

Can a hybrid rocket booster as a combination of "both worlds" technologies or elements also combine their advantages, for example the high performance of the liquid systems and the low specific hardware cost of the solid rocket? Key questions for cost competitiveness are the required effort to feed the liquid oxidizer in the hybrid rocket motor, the fuel-loading density in the motor case, the complete solid usage of fuel onboard and its efficient combustion with the oxidizer.

The mass and cost prediction shall be demonstrated for a baseline and advanced hybrid rocket configurations relative to a solid and liquid counterpart. The baseline hybrid rocket booster reflects the status concerning design solutions, specific impulse, structural index, fuel-loading density and fraction of fuel residuals as represented by activities of the American Rocket Company (AMROC), the Hybrid Propulsion Demonstration Program (HPDP) and the Lockheed Martin Corporation between 1993-2002. For advanced configurations enhancements in fuel-loading density, fuel residual fraction and specific impulse are assumed, also if those not yet full proven in practice.

Using mainly Ariane 4 and 5 data, a cost and mass model is deployed, which is founded on technical commonality of hybrid booster functional units, to those that can be found in liquid and solid rocket booster. If necessary for mass modeling these functional units are broke down to components level.

B. Past Hybrid Booster Activities

There are only few experiences with larger hybrid rockets, even if demonstrator experiments are included. Serious activities concerning the application of the hybrid rocket for space launch started with foundation of the American Rocket Company (AMROC). This company conducted several hundred hybrid rocket firing tests during 1985 and 1993 up to the so called H-1800, which had a thrust level of 1100 kN [14], [15], [16], and [17]. A first development version DM-1 was tested four times. The H-1800 was foreseen to propel a sounding rocket HyFlyer with ~40 tons launch mass [18] and a small 4-stage launch vehicle Aquila [19]. Some subsystem hardware (e.g. hybrid rocket motor DM1, LOX tank, heated helium pressurization system) was build, but not fully qualified for space launch.

However, these projects were scrapped before a rocket was completed or even launched, because AMROC filed for bankruptcy in August 1995 after spending of ~ 25 Mill. $ private investor money [20]. The company SpaceDev, which supplied the SpaceshipOne hybrid propulsion and proposed a booster for its Streaker vehicle on the base of the H-1800/HyFlyer technology obtained AMROC's technical rights, proprietary data and patents in 1998 [20].

Another major achievement sparked by AMROC's work was the Hybrid Propulsion Demonstration Program (HPDP), supported by a consortium of industry, DARPA and NASA, [21], [14] and [22]. The HPDP consortium and its preexisting JIRAD consortium achieved significant subscale testing results, as demonstrated in [23] and [24]. Two examples of a hybrid rocket motor 250-K, similar in size and performance to the H-1800 motor, were tested four times between 1999 and 2002 by HPDP. Besides other problems, the tests did not achieve the targeted performance objectives, because the fuel regression was underestimated and in addition, low frequencies instabilities with very high-pressure excitations occurred [25].

Lockheed Martin Cooperation overtook the guiding role in the field of hybrid rocket activities of HPDP. In 1997, the company proposed the 250-K motor for an application as a strap-on booster for the Atlas IIAR (see fig. 2) at a time when only HPDP subscale test data were available [10]. Caused by these fundamental development problems the booster proposal was not realized in the end.

Together with Lockheed Martin, NASA MSFC started some years later the development of the HYPR sounding rocket; one of the, if not the largest, hybrid rocket (270 kN thrust, 31 s burning time, 2 feet diameter) that was ever launched. However, the mission of December 2002 missed their apogee target, due to hybrid rocket grain difficulties and the launch remained a single event. Nevertheless, a new helium heating system for the pressure fed hybrid rocket based on a small hybrid fuel grain was applied first time [26]. Lockheed Martin recent activities are the demonstration of a hybrid rocket propulsion with 105 kN thrust and a burning time of 170 s for the second stage a small launch vehicle in 2005 [27].

II. H-1800 and 250-K Motor based Boosters

A. Architecture

AMROC's and Lockheed Martin's selected booster architecture was an assembly of an aluminum alloy LOX tank and a hybrid rocket motor case. The H-1800 motor case was made of graphite/epoxy pieces (two endbells bolted to cylinder, sealed by fuel) and applied a kevlar phenolic insulation. Also nose cone, forward skirt, aft skirt, interstage section and heat shield of HyFlyer were made of graphite composite. The 250-K test motor case was made of steel, as proposed also for the flight version. An EPDM case insulation, a material known from solid rockets, was installed. AMROC relied direct on HTPB as fuel, whereas for the 250-K motor a 40/60 blend of HTPB and PCPD (polycyclopentadiene) was selected. The H-1800 motor had a 15-port wagon wheel grain shape; the 250-K based booster motor only eight ports. AMROC tested successful LOX injection (deflection 6°, up to 100 kg/s, 5-8 valves, at 1/3 nozzle downstream position) in the tape wrapped one piece silica/phenolic ablative nozzle for thrust vector control. Lockheed Martin decided for their proposal on a gimbaled nozzle design. Reliable hypergolic ignition was being achieved with injection of triethylaluminium for both motors. For the 250-K development motor an injector head design should be used, which contains 672 impinging elements in its copper faceplate to form a 45 deg solid-cone spray pattern [21]. AMROC relies on a showerhead type to spray 280 kg/s LOX in the hybrid rocket motor.

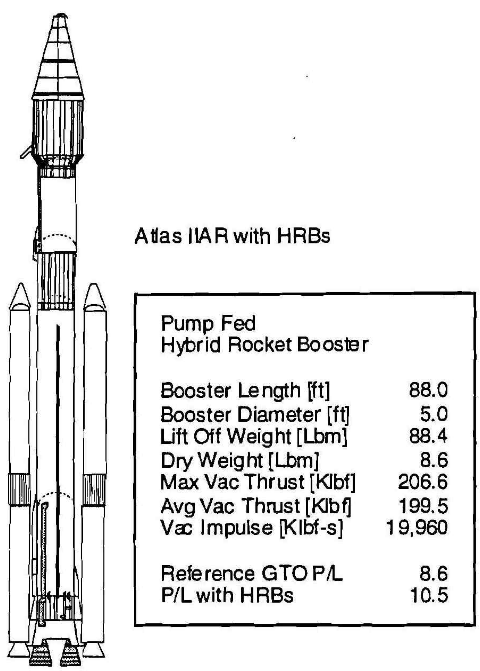

Figure 2: Hybrid Booster Concept for Atlas IIAR [22]

Both companies investigated a LOX pressure feed system as baseline (AMROC has used a "Tridyne" system for 41 bar LOX tank pressure) as well as a pump fed variant. Both designs exhibit a low chamber pressure around of 30 bar, also in case of turbopump feed. This may explained by the very low fuel-loading density, which results in very large mass penalties at higher chamber pressure for the motor case. The table 1 contains the summarized performance properties of both hybrid booster projects based on [19], [18], [28] and [10].

Table 1: Properties of Hybrid Rocket Boosters Proposal (Pump-fed Variant in Brackets)

Property	H-1800 based Booster	Atlas IIAR Booster
Length/Diameter (m)	24.1 / 1.88	27.5 / 1.53
Launch Mass m_0 (t)	39.2 (38.5)	40.3 (39.2)
Structural Index k_{inert}	0.192 (0.170)	0.163 (0.110)
Prop. Mass Fraction	0.839 (0.855)	0.86 (0.90)
Prop. Residual Fraction k_{res}	0.057	0.021
$I_{sp,vac}$ (s)	278	267 (262)
t_b (s)	78	98 (100)
Av.F_{vac} (kN)	1085	902 (887)
Av. / max. p_c (bar)	25.8 / 33.3	29.3 / 33.1

The AMROC hybrid rocket design which was not far away from flight status, is much heavier than the more theoretical (and maybe too optimistic) predictions of Lockheed Martin's study. The inert mass of AMROC's design pressure fed is also demonstrated by the need for four stages for the launch vehicle Aquila to reach low earth orbit. The H-1800/HyFlyer booster inert mass, initial fuel mass, propellant mass fraction and fuel residuals data were reconstructed from data found distributed amongst the several papers. The pump-fed proposal for the HyFlyer booster described in [28] was reduced in performance by the designer due to the needs of the sounding rocket application, the displayed data are corrected. An earlier AMROC's pump-fed proposal H-1500 is shown in fig. 3.

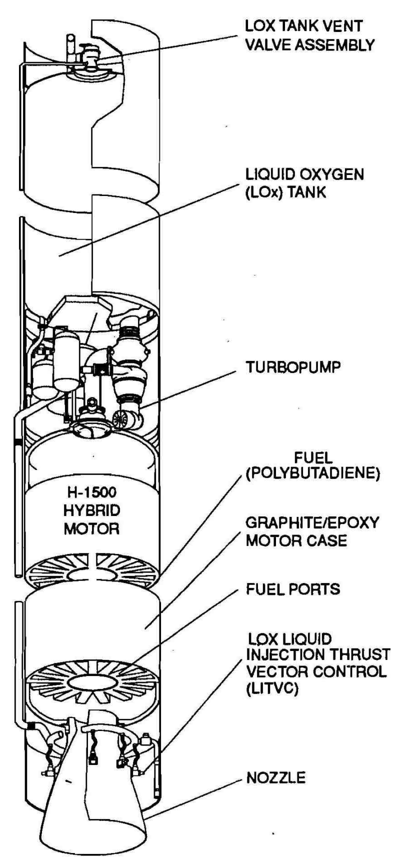

Figure 3: Early AMROC Pump-Fed Design [16]

B. Vacuum Specific Impulse

The HPDP hybrid fuel blend (HTPB/PCPD) in combination with LOX exhibits a theoretical specific impulse of 325 s (p_c 69 bar, equilibrium condition, mixture ratio of 2.3, 10:1 expansion ratio). This is approximately 50 sec greater than a HTPB/Al/AP solid rocket propellant with 69% AP and 19% Al, as stated in [23]&[21]. However the achieved average I_{sp} (vac) values of the H-1800 and 250-K-motor displayed in the table 2 are significantly lower and comparable to a solid booster. The average value of 278 s proposed by AMROC in a customer data sheet seems reasonable as baseline for pressure and pump-fed hybrid propellant booster.

Table 2: H-1800 and 250-K Motor Performance

Range of Average Values	H-1800	250 K
No. of tests	4	4
F_{vac} (kN)	1046- 1211	788 - 934
Φ (-)	1.59 - 1.89	2.3 - 4.5
t_b (s)	6.4 - 15	7.9 - 38.9
p_c (bar)	25.4 - 28.9	37.4 - 43.1
A_e/A_t (-)	3.7 - 8.33	
I_{sp} sea (s)	225 - 244	
I_{sp} vac (s)	262 - 286	249 - 277
$\eta_{Isp\ Vac}$ (-)		0.77 -0.92
η_{c*} (-)	0.86 - 0.93	0.79 - 0.98

C. Fuel-Loading Density

The HTPB-based hybrid rocket solid fuel regresses (typical 1 mm/s) with a low rate compared to a solid propellant. The required large wetted fuel surface results in complex voluminous fuel grain geometry with many individual ports to achieve the required fuel flow, which results in a low volumetric loading, see fig. 4.

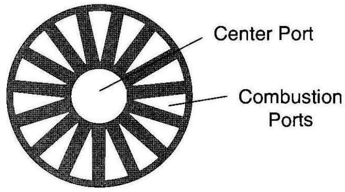

Figure 4: Section View of H-1800 Motor Grain

The fuel and oxidizer are not mixed and burned completely inside fuel grain port passages. A post mixing or combustion chamber is necessary to increase the combustion efficiency η_{c*} typically from 60-80% to 95%. An efficient gasification of the liquid oxidizer shall be achieved by a special vaporization chamber incorporated in 250-K motor (fig. 5). This added approx. 10-15% volume for each chamber, which lowers the fuel-loading density.

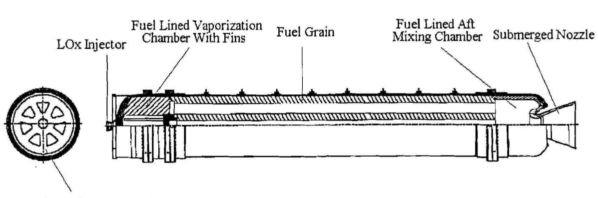

Figure 5: 250K HPDP Test Motor Layout

For a given hybrid propellant combination the fuel volumetric loading depends on required thrust-to-weight ratio and geometrical properties such as diameter and the L/D ratio of the motor case. Detailed information can be found in [2]. A high volumetric efficiency may be achievable as in the case of the upper stage demonstrator (fig. 6), due to a low thrust requirement, a low L/D ratio and a design which relies on a countless numbers of ports.

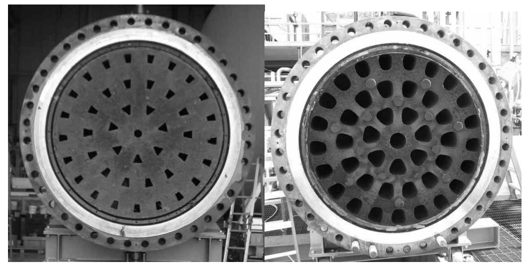

Figure 6: Upper Stage Demonstrator Fuel Grain Before and After 1/3 of Full Burn Duration [27]

As seen in table 3, the H-1800 and 250-K based hybrid boosters, which have a nearly one order of magnitude higher thrust per cross section area, display a much lower fuel-loading density in the motor case. The boosters have a high average vacuum thrust/initial mass ratio of 2.87 and 2.31 g.

Table 3: Hybrid Rocket Motor Parameter

Motor	H-1800	250-K based	Falcon Upper Stage Dem.
Fuel-Loading Density, Chamber (kg/m³)	450	480	750[1]
Volumetric Loading Efficiency	N/A	0.48[1]	0.75[1] (0.9 grain only)
In. Oxidizer Mass Flux (g/s cm²)	N/A	25	20[2]
Burning Time (s)	78	100	170
Thrust per Cross Section (N/cm²)	40	50	6
Av. Regression Rate (mm/s)		0.8	0.5[2] (t_b 60 s)
L* (m) Post Mixing Chamber	7[2]	20[2]	not available

[1]=includes 20% volume for pre-& post chamber, as in [10], [2]= accuracy ± 20%

D. Fuel Residuals

Specifically, the solid fuel residual is an important issue of hybrids, but it is often overlooked or not reviewed carefully. Residuals can not be avoided due to

– difficulties in predicting the O/F mixture ratio exactly,
– the complex geometry of many grains, and
– the non-uniform fuel regression.

Solid rocket propellant contains premixed oxidizer and fuel components the O/F mixture ratio is fixed during operation. In the case of the liquid propellant rocket, the flow of the oxidizer and fuel can be calibrated with good results by orifices or valves. Residuals due to O/F mixture ratio shift are in range of some 1/10 of a percent. In the case of the hybrid rocket motor, there are continuous changes of fuel regression rate, O/F mixture ratio, chamber pressure and thrust during operation, which can be predicted for an ideal motor configuration perfectly without additional residuals. In the case of the classical hybrid rocket, only the oxidizer flow can be controlled directly. Therefore, the O/F mixture ratio of the flight unit has to be predicted with high accurancy in advance by design measures. However, insufficient design tools (prediction of fuel regression rate, c* and nozzle regression) and unavoidable nominal tolerances in manufacturing process necessitate an appropriate fuel reserve to accomplish the dedicated mission profile. In [2] a value of 8 % is stated for a very small hybrid rocket. Complicated grain geometries as a three row wagon wheel type are proposed, as displayed in fig. 6, to achieve higher better fuel-loading density. However, structural grain instability of such multiport grains and port-to-port burnthrough shall be prevented. Therefore, grain designs have to be include a safety residual web thickness. The area between the dashed lines in fig. 7 illustrates the resulting fuel residuals for grain geometry similar to the 250 K motor. High strength polymeric fuel [47], a light but resistant fuel support construction and light burnable foam slivers as were applied in patents [61] and [60] were proposed to reduce the sliver mass. However, as demonstrated in [33] the most effective way to reduce this kind of fuel residuals is a single or double port grain configuration, which requires a significant fuel regression rate increase.

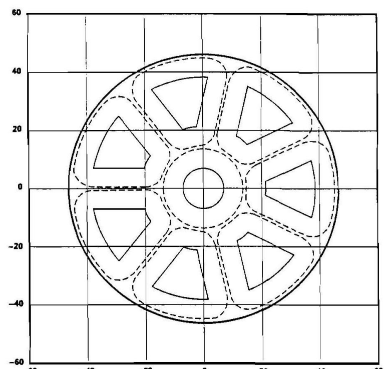

Figure 7: Grain Geometry Induced Fuel Sliver [33]

The regression can vary from channel to channel, caused by a nonuniform contribution of the oxidizer mass flow to each grain port. The uniformity of fuel regression depends on port internal flow and oxidizer spray characteristics, and it is likely to vary with grain length and in the circumferential direction. The length effect is demonstrated in fig. 8. Due to this uneven regression, some points of the hybrid motor case insulation may be earlier reached than others by the hot port flow. The insulation thickness has to be adapted or additional fuel residuals accepted to exclude these hazards from the hybrid rocket motor case.

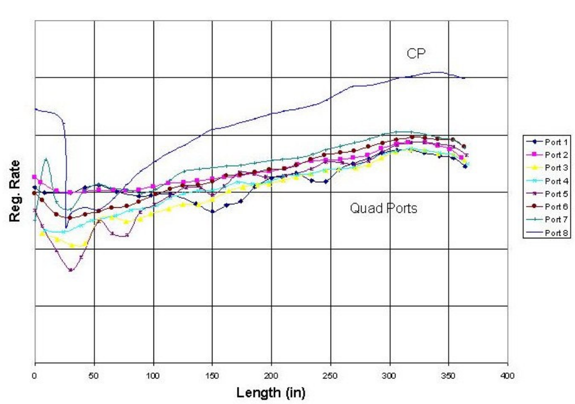

Figure 8: 250K Motor 2 Test 1 Regression Rates [25]

Fuel residual data from operational hybrid rocket propulsion systems such as that of SpaceShipone are not published, except that of two older drones [39], which are not comparable to a booster design. Table 4 shows data which comes from AMROC's experimental experience and from estimations made by the authors of design studies.

Table 4: Fuel Residuals of Hybrid Rocket Motors

Project	k_{res_fuel}	Remark/Reference
AMROC's HyFlyer (H-1800)	0.143	Build Motor k_{res} = 0.057 (Φ=1.94) [18] / [19] (k_{res_ox}=0.015)
Grain Design Payoffs Study	0.145 (8 port design)	Assumption of 1 inch fuel left [33]
Lockheed Martin's Booster Study	0.052	only uneven regression [10]
TNO's Scouts 1.Stage Repl. Study	0.05	estimated by original study's author [8]
Rockwell's Strap-on Booster Study	0.10	estimated by original study's author [11]
TU Munich's Space Tug & Sounding Rocket Studies	0.08 / 0.10	estimated by original study's author [3]/[42]
Douglas's Hybrid Terminal Stage Study	0.05	estimated by original study's author [43]

AMROC's statement in reference [18] of a propellant residual of 5.7% for the HyFlyer rocket, based on the experience made with the H-1800 motor, is interpreted as total propellant mass residual. With this value, a fuel residual (k_{res_fuel}) of 14.3% can be calculated. In [33] the residuals are calculated for a hypothetical booster design example similar to the 250-K motor, based on the assumption that one inch of fuel has to be left to assure grain stability, operation bandwidth and uneven regression, which results in a fuel residual of 14.5%. Determination of fuel residuals in Lockheed Martin's hybrid booster study [10] includes uneven burning behaviour, but there is no indication that fuel residuals due to nominal uncertainties in O/F-mixture ratio were included, so that this booster design study may underestimate the fuel residuals. This can also be assumed for the other referenced design studies. In this paper, a baseline fuel residual mass fraction of 15% has been taken.

III. Approach and Models

A. Reference Booster and Mission

The modeled parallel staged boosters are strapped on a core vehicle with a constant mass of 240 t. A core vehicle thrust is only considered for calculation of the required booster's liquid engine or solid rocket nozzle mass. The booster's mission is to produce an ideal velocity increment Δv of 2.5 km/s based on its vacuum specific impulse. For simplification a constant propellant mass flow it is assumed for all boosters. According to the baseline data base of the H-1800 and 250-K based hybrid booster, the average vacuum thrust-to-initial weight ratio is set for all three types of boosters to 2.6 g, also if this is not optimal to maximise the launch vehicle's payload (resulting total vehicle initial acceleration is 1.6-1.8 g).

A complete consumption of drainable LOX is assumed for the hybrid booster, because it is the much heavier propellant component. It is expected that 1.5% liquid be left in pipes, pumps and at the tank walls at burnout (data from liquid rockets). The same amount of residuals are assumed for the liquid rocket booster. For the solid rocket booster a complete propellant grain combustion is assumed but with residual alumina slag [32]. Using the basic rocket equation $m_0/m_e = e^{\Delta v/Isp}$, the definitions of the structural index and propellant residual mass fraction the required propellant mass for the specific booster can be calculated:

$$m_{pro}/m_p = (1-e^{\Delta v/Isp})/(e^{\Delta v/Isp}(k_{inert}+k_{res})-k_{inert}-1) \quad (1)$$

A sizing effect is neglected due to its smallness in the expected ranges of booster mass. Reference [5] shows a dependency between cost and propellant mass of -0.2 in the case of liquid rockets.

The solid and liquid rocket reference booster models rely on data from the Ariane 5 solid rocket booster EAP, from the Ariane 5 liquid booster study for the proposed EAL (Etage d' Accélération à ergols Liquides) using kerosene as fuel, and from the Ariane 4 liquid booster L36 and its second stage L33. Schmucker [5] has determined that the most cost effective design is the use of a liquid engine with a lower chamber pressure for the first stage or a booster. Therefore, for the liquid propellant reference booster, a hypothetical liquid LOX/kerosene rocket engine similar in I_{sp} and T/W-ratio to the F-1 engine is foreseen. Table 5 contains some major properties of the both reference booster models.

Table 5: Reference Booster Parameter

	Liquid Rocket Booster	**Solid Rocket Booster**
Φ	2.27	N/A
Fuel-Loading Density ρ_{load} (kg/m³)	N/A	1450
Max./Av. p_c (bar)	66/66	69/45
Av.vac./sea I_{sp} (s)	305/265	275/239
Thrust-to-Weight Ratio (vac.)	Engine: 954 N/kg	Nozzle 750 N/kg (incl: TVC)

B. Configuration of Hybrid Rocket Booster

Due to the high thrust mission requirement, its larger potential to reduce structural mass (the HyFlyer LOX tank mass could reduced to 1/3 by the use of a turbopump [28]) and greater flexibility, a turbopump fed system is being favored for the modeled hybrid rocket booster. Several proposals were published in recent years for the operation cycle of a turbopump-fed hybrid rocket. In [44] and [62] an expander Rankine cycle driven turbopump feed system were described, which uses vaporized LOX coming from a regenerative cooled nozzle. In [11] and [8] the hybrid rocket boosters employ a hydrogen peroxide gas generator to drive the turbine. In [56] the use of a hybrid propellant type of gas generator is patented, which produces steam by water injection to drive the turbopump. Lockheed Martin tested an oxygen rich hybrid gas generator, but experienced difficulties and has not yet reached a useable maturity [53]. Another patented idea is to use an expander cycle by a heat exchanger as an integrated part of the injection head to vaporize LOX for the turbopump propulsion [55].

To preserve the relative simplicity of the hybrid rocket the hybrid booster uses solid rocket technology as much as possible, i.e. an ablative cooled nozzle with hydraulic actuation. The hybrid booster relies on the open loop LOX/propane driven gas generator design, proposed by AMROC's turbopump variant study [28]. The LOX tank is pressurized by heated helium. The hybrid propellant booster modeled here shall have a comparable initial acceleration and L/D ratio as the HyFlyer and the Atlas booster, so that a representative fuel-loading density data of ~ 480 kg/m³ as baseline is be chosen, a low value compared to the EAP solid rocket motor value of 1450 kg/m³.

Faster regressing self-liquefying fuels (e.g. paraffin) are proposed in literature to increase fuel-loading density, to reduce fuel residuals and to simply grain geometries [58], also if same open design issues concerning combustion efficiency and mechanical grain stability exits. Tests on a smaller scale with paraffin show a regression rate of three to four times that of HTPB at same mass flux [52]. For an advanced option, which aims at fast regression fuel (paraffin is a candidate), an increase of the fuel-loading density by 50% to a value of 720 kg/m³ and a fuel residual amount of 7.5% has been assumed for this study.

Metal hydrides as AlH_3 and $LiAlH_4$ are proposed for to increase the specific impulse, see [8] and [66]. Recently Calabro predicts in [8] an increase of the theoretical vacuum specific impulse (A_e/A_t=20) of 23 s by the use of an Alane(AlH_3)/HTPB blend and an increase in fuel density by 15% compared to pure HTPB. The idea of metal hydrides in hybrid fuel is not new. Decades ago, they were intensively tested together with liquid fluorine or its mixtures with oxygen (FLOX), see [68] and [67]. More than thirty years ago the combination of lithiumborhydride with LOX was proposed by Schmucker and others in [3] and [4] for a space tug. However, grain mechanical properties, material compatibilities, handling, sensitivity to air and moisture and combustion efficiencies problems have to be considered carefully, before metal hydrides can be applied. It is assumed that the use of a high performance fuel shall increase the baseline vacuum specific impulse by the same amount (17 s) as a higher average chamber pressure of 50 bar. The following parameters are set for performance evaluation of the hybrid rocket booster for a baseline and future advanced versions.

Table 6: Hybrid Rocket Booster Parameter

Property	**Baseline Hybrid Booster**	**Advanced Parameter**
Fuel Residuals k_{res_fuel}	0.15	0.075
Φ	2.37	2.37
Fuel-Loading Density ρ_{load} (kg/m³)	480	720
Volumetric Loading Efficiency	0.48	0.77
Fuel Density ρ_{solid} (kg/m³)	997	930
MEOP (bar)	33	60
Av.vac./sea I_{sp} (s)	278/235 (25,8 bar average p_c)	295/256 (50 bar average p_c)

C. Concentration on Manufacturing Cost

For evaluation of booster cost competitiveness the major cost elements have to be identified. Development and insurance costs (cost of unreliability) are not taken into account. Only when competitive recurring costs of the hybrid rocket can be verified, should an investment in a development program be supported. The existing solid and liquid rocket propulsion units have already achieved a high level of reliability [6]. It might be difficult to increase it significantly by the hybrid concept, considering development experiences and difficulties.

As stated by Koelle [29], typically 75% of launch cost comes from the fabrication, assembly and verification of vehicle elements. Ground and launch pad operations to assemble, checkout, transport, tank and fill the vehicle, together with the launch and flight operations to plan, control, track and assess its flight account for 15%. The remainder will be caused by the management, marketing, customer relation, contracts office, technical support and launch site costs.

Large reductions in operating costs are often assumed with the hybrid rocket based on its safe nature and the simpler architecture, compared to liquid rockets. The high performance of oxygen and the existing experience and infrastructure at the launch sites determine LOX as the only realistic choice. Nevertheless, the hybrid rocket shares with the liquid rocket the LOX tanking and helium filling processes. The same precautions must be applied to prevent or reduce hazards caused by explosives for range safety, rocket motors for stage separation, the energy of a bursting high volume pressure vessel, the fire caused by LOX, the hazardous effects of the gas jet and the flying vehicle itself.

Any potential cost reduction realised by the propulsion units advantages in integration, testing and handling are limited by the 15% cost portion of the operations and by the fact that propulsion operations are only one part. Therefore, operating costs can be neglected as an issue for cost competitive decision making and the manufacturing costs will be estimated more in detail, because they contribute most to launch cost. Differences in transportation cost are not regarded.

The manufacturing cost C_{rec} of the booster is the sum of the units fabrication costs C_{unit} and the costs for integration, checkout and acceptance C_{int} and "overhead" costs C_{over} for project management (PM), systems engineering (SE) and product assurance (PA). Cost data are known for the serial production of the Ariane 4 liquid propellant booster L36, which displays C_{int}=0.077 ΣC_{sub} and C_{over} =0.162 ΣC_{unit} (C_{int} + C_{over} = 0.239 ΣC_{unit}). For the Ariane 5 EAP (Etage d' Accélération à Poudre) solid rocket motor the approximate combined integration and overhead costs for the stack assembly integration and acceptance of the solid rocket motor, which represents two of the four necessary subsystems are available, amount to 0.16 ΣC_{sub}.

The integration cost of the EAP stage equipment and of nose cone, skirts, nozzle actuation group etc. may be added to 5- 10% of C_{unit}. The system assembly cost comes in the same range as for the liquid booster. Based on these data no decision can be made, as to whether an integration of the solid rocket booster is significantly cheaper than for the liquid booster. The consideration of possible savings for the hybrid rocket booster integration compared to solid and liquid rockets - an open issue -should become relevant if the final resulting C_{rec} shows no great difference to the solid rocket. So for this study the summated subsystems or as they are later called "functional unit" manufacturing costs are being compared for the three types of booster as a representative for cost competitiveness.

D. Definition of Functional Units

Owing to its mixed nature, it is assumed that the hybrid rocket booster can be virtually assembled by functional units, which build up the liquid and solid rocket reference booster, see following table 7.

Table 7: Booster Definition by Functional Units

Functional Unit	Unit Index	Liquid	Solid	Hybrid
"Structure"	stru	●	●	●
"Equipment"	eq	●	●	●
"Tank"	tank	●		●
"Motor Case"	case		●	●
"Nozzle"	noz		●	●
"Engine / LOX Feed Unit"	eng/feed	●		●

These functional units are characterized as the minimum number of specific components summarizing units, from which the hybrid rocket can be built up, based on technical commonality to the equivalent functional units of the liquid and solid propellant rocket booster. The functional unit's principal functional requirements are the same for all three boosters so that comparable technical solutions and characteristics can be expected. Example: For fabrication of the functional unit "Tank" the hybrid rocket uses same materials, manufacturing procedures and verification methods as the liquid propellant counterpart. Therefore, the same mass specific fabrication costs

$$c_{unit} = C_{unit} / m_{unit} \qquad (2)$$

to deliver its in a qualified and accepted state to the booster integrator can be applied or expected, but the mass index can be different for the units, as later addressed.

The functional unit can be a self contained unit (as the full equipped propellant tank ("Tank") and the liquid rocket engine), a collection of comparable technology sharing elements as "Structure" or a class of very different components, which are built in all three boosters to operate it like the unit "Equipment". The following table 8 contains the detailed sorting scheme as applied to the boosters database.

Table 8: Components Sorting Scheme for Boosters Data Base

Functional Unit	Related Component
"Structure"	Nose cone, forward skirt, rear skirt, heat shield, interstage section, intertank section, forward and rear attachment system, pipe and harness ducts
"Equipment"	Power supply, harness, instrumentation, telemetry, commando unit, rocket motors for stage separation, pyrotechnics for separation and self-destruction
"Tank"	Equipped liquid propellant or oxidizer tank: Tank structure, isolation, propellant pipes, antivortex and -sloshing devices and tank pressurization system (not part of engine or LOX feed unit)
"Motor Case"	Rocket motor case incl. isolation, liner and igniter for solid fuel/propellant
"Nozzle"	Solid rocket like ablative nozzle with hydraulic actuated thrust vector control unit
"Engine" / "LOX Feed Unit"	Liquid rocket engine (incl. actuation system and control units) or technological comparable "LOX Feed Unit" of the hybrid rocket (turbopump, injector, valves, gas generator and its fuel tank)

E. Determination of Units Costs Indices

The fabrication cost data comes from the Ariane 4 program and the Ariane 5 solid rocket motor. For comparison, the cost models of Schmucker [5] were reviewed. All costs are referenced to the year 1995 and represent an advanced serial production experience on the learning curve of over 10 years. The confidential cost data are set in ratio to the mass specific cost of the "Motor Case" functional unit. The hybrid rocket solid fuel can be mixed cheaper and cast in the insulated motor case due to less strict regulations and precautions during manufacture. In addition, some process steps may be saved. Based on HTPB material and cast cost data given in [12] half of the specific costs for producing the solid fuel grain are reasonable. The following table 9 shows the cost indices for cost estimation.

Table 9: Cost Indices of Functional Units

Functional Unit	Cost Index c_{sub} (Cost Unit/kg)
"Structure"	4
"Equipment"	17
"Tank"	6
"Motor Case"	1
"Nozzle"	4
"Liquid Rocket Engine" / "LOX Feed Unit"	20
Solid Propellant	0.1
Hybrid Solid Fuel	0.05

F. Mass Index of Hybrid Booster Functional Units

Unit's mass indices are defined to enable the virtual assembly of the hybrid rocket booster from solid and liquid functional units and to reflect the influence of propellant mass as a booster's dimensioning parameter:

$$k_{unit} = m_{unit}/m_{prop}. \tag{3}$$

The structural indices for the liquid and solid reference booster are simply the sum of the unit's mass indices:

$$k_{inert} = \Sigma k_{unit}\ . \tag{4}$$

Accordingly, for the usage of liquid and solid propellant of the hybrid rocket, the oxidizer and the fuel mass are used to determine hybrid rocket "Tank", "LOX Feed Unit" and "Motor Case" functional unit indices. The structural index for the hybrid rocket is therefore:

$$k_{inert} = (1-1/(\Phi + 1))(k_{tank}+k_{feed}) + (k_{case}/(\Phi+1)+ k_{stru} + k_{eq} + k_{noz}\ . \tag{5}$$

The mass indices of the "Liquid Rocket Engine" and "Nozzle" functional unit are adjusted to the thrust level needed for a sufficient launch acceleration a_0, here shown for the liquid rocket engine, using its thrust-weight-ratio F_{sea}/m_{eng} parameter:

$$k_{eng/noz} = (((k_{inert}+1) + m_p/m_{pro})\ a_0 - F_{core}/m_{pro})/(F_{sea}/m_{eng/noz}). \tag{6}$$

The mass index of the "LOX Feed unit (without gas generator fuel supply) is adapted to the required LOX mass flow. The hybrid rocket booster "Structure" unit mass index is the sum of solid booster mass indices and that for the structural section that connects the LOX tank to the hybrid rocket motor. The added mass index of this intertank structure, which accounts for structural reinforcements to allow access and to support of LOX feed components (turbopump e.g.) and to connect a steel motor case to an aluminum LOX tank, is estimated to be twice that of the liquid booster section. Based on a given detailed mass breakdown of an elaborated EADS EAL liquid booster study [65], the mass index of the hybrid rocket LOX tank including heated helium pressurization system is determined to 71% of that the LOX-RP1-tank assembly, because the liquid fuel tank, the intertank structure for the two-tank solution and the long oxidizer feed line through the fuel tank can be omitted. The propane tank for turbopump drive including own helium pressurization system is estimated by 25% of the required propane mass, which is 1% of LOX mass. The propane mass is included as propellant in the specific impulse assumption.

The hybrid functional unit "Motor Case" mass is calculated from the solid rocket motor case index, material and design similar to the solid rocket booster assumed. Data of the solid motor case comes from the Ariane 5 EAP booster. For approximation the mass of the hybrid motor case shell alone is assumed to be a linear function of the product of chamber volume and MEOP divided by the material strength. This is proved by calculation on simple membrane theory and supported by empiric results [50]. Assuming constant thickness of the insulation and liner its mass is a linear function of the inner surface of the motor case. The solid and hybrid booster use the same the "Nozzle" functional unit, which includes also the thrust vectoring unit.

The major components of the "LOX Feed Unit" compromise a LOX turbopump, a LOX valve, a gas generator, an injector and a gas generator fuel (propane) tank. The last one is added to the hybrid "Tank" unit mass estimation. An empirical model [63], with pressure rise and LOX mass flow as input parameter is used to determine the LOX turbopump mass accordingly:

$$m_{TP} \sim (\Delta p\ dm_{ox}/dt)^{0.73}. \tag{7}$$

Reference LOX turbopump data (pressure rise, pump mass and LOX mass flow) come from AMROC's design. The injector faceplate mass is approximated by a simple model as can be found in [63], which is rewritten with the oxidizer injector mass flux G_{inj} and oxidizer mass flow dmox/dt to:

$$m_{inj} = 0.6\ \rho(4\ p_{inj}/\pi\ \sigma)^{0.5}\ (dm_{ox}/dt/G_{inj})^{1.5}. \tag{8}$$

From the 250-K test motor injector design shown in [21] an oxidizer mass flux G_{inj} of 1200 kg/s m² for an injection pressure of 62 bar can be calculated. For the baseline hybrid booster injector configuration the older H-1 (Saturn IB) liquid bipropellant engine's mass flux of 1900 kg/s is assumed (F-1 engine had a value of 3500 kg/s m²). The injector may be completed by a dome, which can be of light weight and simple construction compared to a liquid propellant engine dome, because no thrust has to be transmitted. The injector dome, the LOX valve and the gas generator mass are small compared to the turbopump and injector mass. There are added to an overall collection of pipes, hydraulic, pneumatic and electric components for actuation and control the LOX valve and turbopump, which is estimated at 50% of the summated mass of the turbopump and injector faceplate.

IV. Discussion of Results

A. Baseline Hybrid Booster

In previous chapters established cost and performance models are used to calculate mass and cost of the baseline hybrid and the liquid rocket booster compared to the rocket booster. For model verification, the ratio of manufacturing cost to fueled mass of the liquid and solid rocket booster was evaluated. The calculated cost ratio of 2.95 is comparable to a reference value of 2.76 [37] and to results found in [46]. The table 10 shows the determined mass indices for the three booster types and its functional units mass, assuming that a pair of boosters will be applied.

Table 10: Mass Data of Single Boosters and their Units

F_{vac}/m_0=2.6 g	Liquid	Solid	Hybrid Baseline
Launch Mass (t)	206	292	335
Structural Index	0.0980	0.1596	0.1534
Funct. Unit	**Mass (t)**		
"Structure"	5.1 (28%)	5.3 (13%)	8.5 (19%)
"Equipment"	1.5 (8%)	2.0 (5%)	2.3 (5%)
"Tank"	6.3 (34%)	N/A	5.1 (12%)
"Motor Case"	N/A	22.9 (57%)	14.8 (33%)
"Nozzle"	N/A	9.9 (25%)	11.6 (26%)
"Engine/LOX Feed Unit"	5.5 (30%)	N/A	2.1 (5%)
Inert Mass	18.4	40.1	44.4

The baseline hybrid booster shows a higher mass compared to the solid booster, caused by the significant fuel residuals despite is lower structural index. The "Motor Case" mass portion of 1/3 dominates the inert booster mass. The following table 11 contains the resulting cost distribution between functional units of the three types of booster.

Table 11: Cost Distribution between Functional Units

Functional Unit	Liquid	Solid	Hybrid
"Structure"	11%	15%	16%
"Equipment"	13%	23%	19%
"Tank"	19%	N/A	14%
"Motor Case"	N/A	16%	7%
"Nozzle"	N/A	28%	22%
"Engine/ LOX Feed Unit"	57%	N/A	20%
Solid Fuel/Propellant	N/A	18%	2%
Total Booster, relative	**135%**	= 100%	**149%**

The baseline hybrid booster cost are 49% and the liquid booster of 35% above the solid rocket booster. [54] and [46] confirm the cost advantage of solid rocket booster compared to liquid booster. Regarding the units cost portion the 57% cost of the liquid booster engine are consistent with other references, as the 18% share of the solid rocket propellant. The hybrid booster units display a relatively uniform cost distribution.

B. Sensitivity Analysis on Costs

Parameter, such as the ratio of liquid functional unit cost ("Tank" and "Engine") to the "Motor Case" unit, the fuel residual fraction, the fuel-loading density and the specific impulse are evaluated with regard to their effect on the baseline hybrid booster cost (table 12). All other parameters are constant, if one parameter is changed.

Table 12: Cost Sensitivity to Varying Input Parameter

Parameter	Cost, relative	Remark
Cost Ratio of Liquid Units to Motor Case Unit	149%	Liq.:135%
Decrease by 1/3	132%	Liq.:101%
Increase by 1/3	166%	Liq.:169%
Fuel Residuals, Baseline 15%	149%	k_{inert}=0.1534
1. Half of Baseline, k_{res}=7.5%	135%	k_{inert}=0.1521
2. As Liquid Rocket, k_{res}=1.5 %	127%	k_{inert}=0.1516
Fuel-Loading Density, Baseline 480 kg/m³	149%	k_{inert}=0.1534
1. Advanced Hybrid Fuel +50 %	139%	k_{inert}=0.1372
2. Solid Rocket Propellant +200 %	130%	k_{inert}=0.1201
Specific Impulse, Baseline 278 s	149%	k_{inert}=0.1534
1. Higher p_c = 50 bar (I_{sp} +17 s)	158%	k_{inert}=0.1874
2. New Fuel (I_{sp} + 17s), p_c=25,8 bar	128%	k_{inert}=0.1524

The data in table 12 shows that even a decrease of the liquid units cost compared to the solid rocket technology reference unit "Motor Case" by 1/3 still yields a cost penalty of 32% for the hybrid booster compared to the solid booster, while the liquid booster becomes similar. While fuel residuals of 7.5%, which yielded a cost decrease of 14% must be achievable, a further reduction to values comparable to liquid are deemed unrealistic and would only yield an additional 8% decrease. Increasing the fuel-loading density by a factor of 1.5 has an effect of 10% cost decrease, approaching a complete hypothetical value similar to that of the solid booster the added decrease is 9%. The structural index declines strongly. As expected, the most effective parameter is the specific impulse, i.e. an increase from 278 s to 295 s results in large cost decrease of 21%, if the chamber pressure is unchanged and a high performance fuel enhances the I_{sp} .

It is of interest, that the approach to increase specific impulse by higher chamber pressure results in a cost increase of 9% compared to the baseline hybrid booster and not in a decrease. There is also a large increase of the structural index. The gain by the higher specific impulse is more than offset by the impact of the chamber pressure on the hybrid rocket motor case, which exhibits a large effect due the low fuel-loading density, and on the "LOX Feed Unit" mass. This is the reason why AMROC and Lockheed Martin had selected a chamber pressure of only ~30 bar for its hybrid booster proposals with its low fuel-loading density.

C. Advanced Hybrid Booster

The calculation of the above-discussed results has been shown, that parameter like chamber pressure has to be selected carefully to get a cost optimized hybrid booster design. The optimal pressure is coupled to the fuel-loading density and to the material characteristics of the motor case. A cost optimization of the hybrid booster design goes beyond the objectives of this primary study. However, for an impression, what may be possible, three combinations of advanced hybrid booster parameter were selected (table 13). The case "A" combines advanced fuel-loading density and residual fraction, which may be achievable with reasonable development effort by new high regression fuel types. For "B" an increase of the I_{sp} by 17 s is assumed by a hypothetical new energetic type of fuel, without a chamber pressure increase. In addition to this case definition, "C" contains also an increase of 17 s for I_{sp} caused by chamber pressure increase to 50 bar.

Table 13: Cost of Advanced Hybrid Booster Variants

Combination of Properties	Cost	Remark
Baseline Hybrid Rocket Booster: 15%, 480 kg/m³, 278 s, 25,8 bar	149%	k_{inert}=0.1534
A.: 7.5%, 720 kg/m³, 278 s, 25,8 bar	127%	k_{inert}=0.1366
B.: 7.5%, 720 kg/m³, 295 s, 25,8 bar	110%	k_{inert}=0.1355
C.: 7.5%, 720 kg/m³, 312 s, 50 bar	116%	k_{inert}=0.1590

The cost decrease of 22% for case "A" is not sufficient to close the cost gap to the solid booster. However, in combination with the "new" fuel type, this cost disadvantage is reduced to only 10% for case "B". The previous experienced counteracting effect of the higher chamber pressure on case and "LOX Feed Unit" weight can be observed in "C", where the cost decrease is 6% smaller as in "B", despite the higher I_{sp}.

V. Summary and Conclusions

For a primary study of hybrid booster cost competitiveness, a mass and cost model based on commonality of hybrid rocket "functional units" to a liquid or solid rocket booster counterpart were developed, validated and tested with feasible results. The models were applied to a baseline and to hybrid booster configurations with some advanced properties. Based on properties as demonstrated by former hybrid rocket booster projects as those from AMROC, a cost level comparable to a solid rocket booster for a mission similar to Ariane 5 EAP (Δv=2.5 km/s) can not achieved by a hybrid rocket booster. In contrast, a significant cost increase is predicted.

However, a high performance and fast regressing hybrid rocket fuel together with an optimized design (e.g. selection of chamber pressure) may offer the solution to achieve a cost competitive hybrid booster, where other factors like safety and handling advantages or throttling capabilities may decide in favor of a hybrid against a solid rocket booster. Fuel components as paraffin and metal hydrides (AlH_3 and $LiAlH_4$) were proposed for this purpose in different references, which have to be reviewed carefully.

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