Long-Term / Strategic Scenario for Reusable Booster Stages

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The basis of this paper's investigation is a partially reusable space transportation system under study within the German future launcher technology research program ASTRA. It consists of dual booster stages, which are attached to the expendable Ariane 5 core (EPC) at an upgraded future technology level. The design of the reference liquid fly-back boosters (LFBB) is focused on LOX/LH2 propellant and a future derivative of the Vulcain rocket motor. The preliminary design study is performed in close cooperation between DLR and the German space industry. The paper's first part describes recent progress in the design of this reusable booster stage.

The second part of the paper assesses a long-term, strategic scenario of the reusable stage's operation. The general idea is the gradual evolution of the above mentioned basic fly-back booster vehicle into three space transportation systems performing different tasks: Reusable First Stage for a small launcher application, successive development to a fully reusable TSTO, and booster for a super-heavy-lift rocket to support an ambitious space flight program like manned Mars missions. The assessment addresses questions of technical sanity, preliminary sizing and performance issues and, where applicable, examines alternative options.

Nomenclature

D	Drag	N
M	Mach-number	-
T	Thrust	N
W	weight	N
l	body length	m
m	mass	kg
sfc	specific fuel consumption	g/kNs
q	dynamic pressure	Pa
v	velocity	m/s
α	angle of attack	-
γ	flight path angle	-
δ	deflection angle	-
ε	expansion ratio	-
η	control surface defection angle	-

Subscripts, Abbreviations

CAD	computer aided design
CFRP	Carbon Fiber Reinforced Polymer
EAP	Etage d'Accélération à Poudre (of Ariane 5)
EPC	Etage Principal Cryotechnique (of Ariane 5)
ESC-B	Etage Supérieur Cryotechnique (of Ariane 5)
EUS	Expendable Uper Stage
FEI	Flexible external insulation
FEM	finite element method
GLOW	Gross Lift-Off Mass
GTO	Geostationary Transfer Orbit
H2K	Hypersonic Wind Tunnel (at DLR Cologne)
JAVE	Jupe AVant Equipée (forward skirt of Ariane 5)
LEO	Low Earth Orbit
LFBB	Liquid Fly-Back Booster
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MECO	Main Engine Cut Off
RFS	Reusable First Stage
SHLL	Super Heavy Lift Launcher
SRM	Solid Rocket Motor
SSO	Solar Synchronous Orbit
TMK	Trisonic Test Section (at DLR Cologne)
TSTO	Two Stage to Orbit
TVC	Thrust Vector Control
cog	center of gravity
sep	separation
s/l	sea-level

1 INTRODUCTION

A reusable booster stage dedicated for near term application with an existing expendable core is under investigation within the system studies of the German future launcher technology research program ASTRA. To date, analysis shows that such a winged fly-back booster in connection with the unchanged Ariane 5 expendable core stage is technically feasible and is a competitor to other reusable and advanced expendable launchers.

Realizing the fact that a single launch system application alone might not be sufficient to justify the development of a reusable stage, the options for continuous operation of such stages or of their derivatives in a timeframe of at least 50 years should be investigated. A major constraint for such a roadmap is that it is only viable if a flexible operational scenario exists.

The basic design philosophy of the reusable booster is to choose a robust vehicle which gives a relatively high degree of confidence to achieve the promised performance and cost estimations. In the second part of the research study 'lessons learned' from the first phase and previous investigations (e.g. ref. 1 and 2) are integrated. In as far as it is possible the applicability of existing and already qualified parts should be assessed for integration in the booster stage.

2 A PROPOSED SEMI- REUSABLE LAUNCH VEHICLE IN COMBINATION WITH ARIANE 5

The examined partially reusable space transportation system consists of dual booster stages which are attached to the expendable Ariane 5 core stage (EPC) at an upgraded future technology level. The EPC stage, containing about 185000 kg of subcooled propellants, is assumed to be powered by a single advanced derivative of the Vulcain engine with increased vacuum thrust. A new cryogenic upper stage (ESC-B) should include a new advanced expander cycle motor of 180 kN class (VINCI) at the end of the decade.

Two symmetrically attached reusable boosters, replacing the solid rocket motors EAP in use today, accelerate the expendable Ariane 5 core stage (Figure 1).

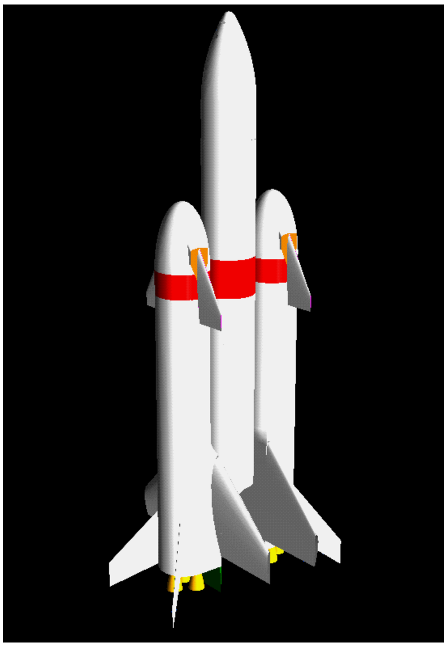

Figure 1: Semi-reusable launch vehicle with Ariane 5 core stage and two attached reusable fly-back boosters

2.1 LFBB Geometry Data and Lay-Out

The reusable booster stage is based on the same advanced version of the EPC's Vulcain engine, but employs an adapted nozzle with reduced expansion ratio. Three engines are installed in a circular arrangement at the aft of each vehicle. The total LFBB length is 42 m. A fuselage and outer tank diameter of 5.45 m is selected so as to achieve a high commonality with Ariane's main cryogenic EPC stage.

Three air-breathing engines, for fly-back, are installed in the vehicle's nose section (see Figure 2), which also houses the RCS and the front landing gear. The nose is of ellipsoidal shape with a length of 6.7 m. The three turbo-engines, in close proximity to each other, are located in the nose's upper part for thermal and integration requirements. A 500 kg buffer / trim spherical tank to feed the turbofans is arranged in the center below the inlets. The complete RCS is also positioned in the nose to provide sufficient torque with respect to the vehicle's cog.

The nose section is followed by an annular attachment structure. The structure for canard mounting and actuation is provided at the center of this attachment ring. The cylindrical tank is integral and with respect to the EPC core stage it has the same diameter, shorter length, and similar lay-out. This geometry constraint might reduce manufacturing costs if realized, and enables to better compare expendable with reusable structures within this investigation. LOX is stored in the upper portion of the tank, and is, separated by a common bulkhead from the first LH2 tank. The ascent propellant mass reaches 167500 kg when subcooled as this allows a density increase of LOX to 1240 kg/m^3 and to 76 kg/m^3 for LH2. It is assumed that both the cryo- and thermal insulation are installed externally. This approach is preferred to any internal arrangement, as this allows a better accessibility of the tank walls for inspection between flights. The integral tank section is followed by the wing and fuselage frame section. A second, non-integral LH2 tank is mounted above the wing attachment frames. This tank is interconnected with the main hydrogen tank and it is currently foreseen that engine feed be performed through this second tank.

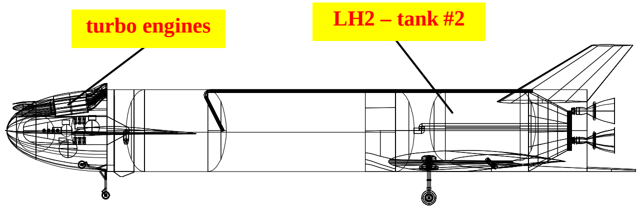

Figure 2: LFBB projection in the x-z-plane

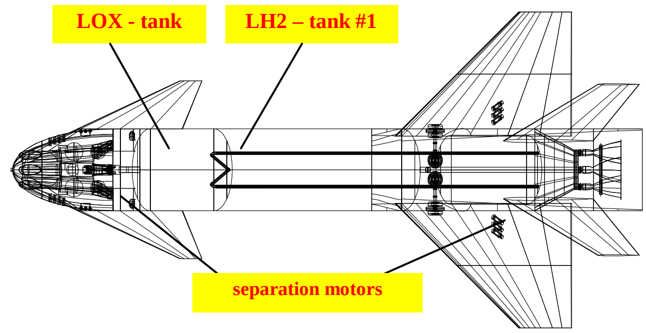

Figure 3: LFBB projection in the x-y-plane

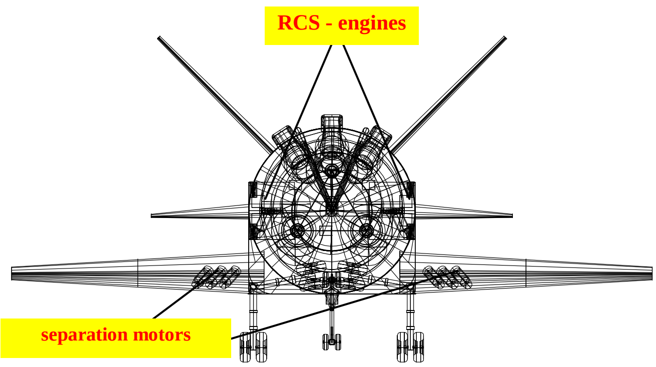

Figure 4: LFBB projection in the y-z-plane

The main wing lay-out has been changed from last year's flat lower surface configuration[3] to the transonic RAE 2822 airfoil. This new aerodynamic configuration comprises also increased canard leading and trailing edges, for improved aerodynamic stability in subsonic cruise flight. Checking of the required canard deflection angle and of the vehicle's trim performance during the full return flight are addressed in Section 2.3. The wing spans more than 21 m and the exposed area is about 115 m^2.

The rocket engines are mounted on a conical thrustframe. A full 2D gimballing of all engines is required to obtain sufficient controllability of the launch vehicle (see ref. 3). The engines are protected on the lower side by a body flap, also necessary for aerodynamic trimming and control. Two vertical fins are attached to the upper part of the fuselage, and inclined at 45 deg. (see Figure 4). The structural support of the complete launch vehicle on the launch table has to be provided by the two LFBB.

2.2 Propulsion System

An advanced more powerful version 3 of the European Vulcain family of large cryogenic engines is currently undergoing definition studies. It might include an increased mass flow, a higher chamber pressure, and a larger expansion ratio. Although no technical data is yet fixed, the results presented in this paper, and in the ASTRA-study are based on assumptions concerning the performance of this motor. Engine data of the advanced Vulcain variant with reduced expansion ratio to be used in the LFBB configuration is given in Table 1.

Cycle	open gas-generator	
propellant combination	LOX / LH2	
nominal thrust (s/l)	1412	kN
nominal thrust (vacuum)	1622	kN
specific impulse (s/l)	367.23	s
specific impulse (vacuum)	421.7	s
chamber pressure	13.9	MPa
mixture ratio	5.9	-
nozzle area ratio	35	-
length	2890	mm
diameter	1625	mm
dry weight	2370	kg
T/W (s/l)	60.7	-
T/W (vacuum)	69.8	-

Table 1: Proposed Vulcain 3 (ε= 35) main engine characteristics as used in the study

To reduce the mass of fly-back fuel, turbo engines which use hydrogen should be implemented. The feasibility for replacement of kerosene by hydrogen in an existing military turbofan (EJ-200) investigated within the ASTRA-study shows promising results and no show-stoppers. The engines will be installed without afterburner and will have a nozzle with a fixed throat.

The reaction control system (RCS) thrust requirements are defined with regard to the only flown RLVs: The Space Shuttle and the Buran orbiter. The sizing of the Space Shuttle RCS thrusters is based on the yaw acceleration for re-entry attitude control. At maximum vehicle mass about 0.5 $°/s^2$ has to be achieved [4]. In case of the LFBB configuration these requirement leads to 10 thrusters on each side of the vehicle with a thrust level of 2 kN per engine. Currently different propellant combinations are looked upon. Besides the classical but toxic N_2O_4 / MMH, the environmentally friendly GO_2 / Ethanol and GO_2 / GH_2 are being studied. (see ref. 3)

2.3 Aerodynamic Design and Analysis

The aerodynamic design is an integral part of a winged reusable stage. The applied aerodynamic and flight dynamic simulation of the return flight requires trimmed aerodynamic data sets for the complete trajectory from separation at M=6 down to the landing phase at M=0.27. The resulting configuration has to comply with tight margins concerning longitudinal stability and trim and the behaviour of the booster has to be robust over the complete Mach number range. Another demand is the analysis of the transonic flight regime.

The aerodynamic work is done at DLR's Institute for Aerodynamics and Flow Technology, based on unstructured Euler simulations for M < 2 and surface inclination methods for M > 2. The already performed steps in the vehicle's aerodynamic design process are described in references 6 and 7.

An assessment of the aerodynamic interactions between Ariane 5 core stage and the LFBB's during mated ascent has been studied as an engineering approach by Euler calculations using unstructured mesh calculations. (Figure 5) The aerodynamic interactions in the configuration's aft region including attachment structure between rocket and booster are of special interest. The calculations are preliminary, since the shock-boundary layer interaction and engine flow has to be introduced in future investigations.

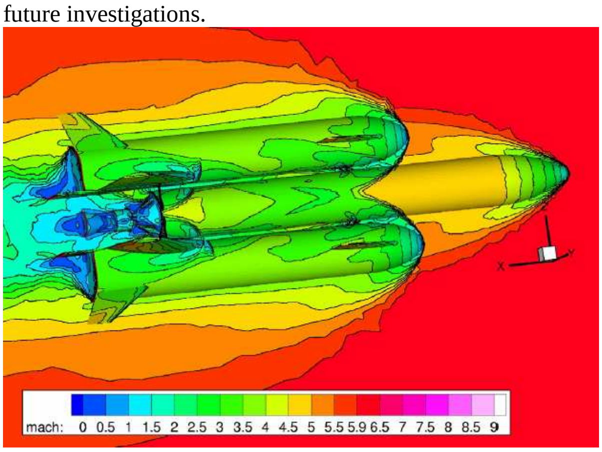

Figure 5: Flowfield and Mach number contours around the Ariane 5 and two attached LFBB at M= 6, α=0°, η_{can}=0° (Euler calculation)

The first phase of the aerodynamic design studies, summarised in reference 6, showed the essential need of canards to increase the static margin and to enable the trim of the vehicle. The resulting vehicle with canards is the basis for the definition of a wind tunnel model. In the meantime this model has been thoroughly investigated in the DLR wind tunnels TMK and H2K (see Figure 6). The force measurements at Mach numbers between 0.6 < M < 7 have been used to verify the aerodynamic approach and the experiments delivered valuable data for an update of the vehicle's shape.

The analysis of that early "Y7"-LFBB showed its robust behaviour concerning the trim. The canard deflections may be limited to $\eta_{can} \approx 8°$ for subsonic flow and they are always smaller than $\eta_{can} = 5°$ for super- and hypersonic flow conditions. The comparison of the neutral point position and the center of gravity points to the main problem of configuration "Y7", its lack of longitudinal stability during the dominating sub- / transonic cruise flight[3].

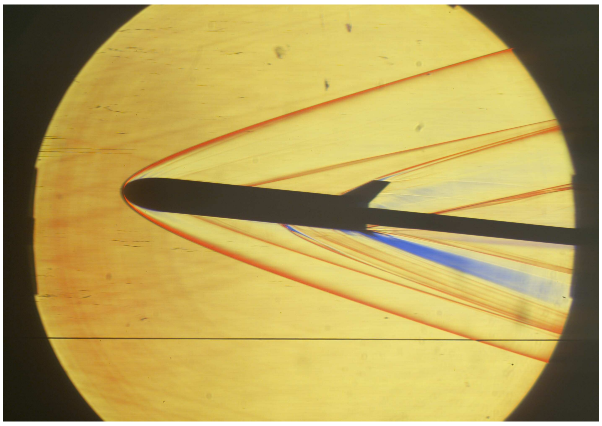

Figure 6: Color Schlieren-technique photo of LFBB model in DLR wind tunnel at M=6

Therefore, the focus of succeeding work is the definition of adaptations which enable to increase the static margin and to preserve the robust trim behaviour. A numerical and experimental analysis presented in reference 7 demonstrates that the canard most dominantly influences the static margin of the configuration. Based on these findings a refined aerodynamic configuration of the LFBB could be defined. The advanced design has a canard with an increased leading edge sweep of 65° and a trailing edge sweep enlarged to 22°. The size is reduced to 90% of the original projected area of 15 m^2. The vertical position and the axis of rotation are kept unchanged. Additionally, an asymmetric NACA 3408 airfoil is used for the canards. The planform of the large wing is kept unchanged but a 'rear loading' RAE 2822 airfoil is applied to increase static margin.

Taking into account the booster's updated mechanical architecture and the fuel trim tank located in the nose, which together have slightly moved the cog forward, the new aerodynamic configuration show an almost neutrally stable behaviour for M< 0.8 and is stable at higher Mach numbers. The results of ref. 7 additionally indicate a potential for a further reduction in canard size which may lead to a LFBB configuration which is stable along the complete return flight and which has a very robust trim behaviour.

2.4 Mechanical lay-out of vehicle structure

A preliminary mechanical design of major structural elements is performed. This work is executed by the German launcher industry Astrium and MAN. The wing, thrust frame, tanks, and fuselage are dimensioned according to the operational loads calculated from flight dynamic and aerodynamic analyses.

The main function of the booster structure is to transfer the thrust to the EPC-stage. Load transferal is foreseen at the forward attachment, in order to keep the same structural architecture as for the EPC of the present Ariane 5. The booster thrust is routed from the thrust frame via the rear fuselage, through the LH2 and LOX tank to the attachment ring structure into the EPC.

At the LFBB's top the nose cap structure is attached, which is an aerodynamic cover and is completely removable for easy accessibility in case of maintenance.

The basic design of the booster attachment ring should be analogous to the Ariane 5 EPC forward skirt, but it is especially equipped to satisfy the requirements of a reusable re-entry vehicle. This ring is located between the forward end of the oxygen tank and the LFBB's nose section. It is one of the main structural elements of the booster with very high loads and several interfaces like the canard support and the main attachment fitting, introducing the thrust loads to the expendable core stage. The length of the ring is 2.5 m with the booster's external diameter of 5.45 m.

The basic design is similar to the Ariane 5 EPC forward skirt. But as the booster skirt is unsymmetrically loaded, it has a strong section around the attachment fitting and a considerably thinner and lighter region on the opposite side. The nose landing gear is located inside the nose assembly close to the ring structure. Therefore, it is possible to attach the gear's strut support to the same major frames of the ring, which already transfer the thrust loads during ascent. (see Figure 7) The multiple use of structural elements during different phases of the booster mission enables considerable weight savings.

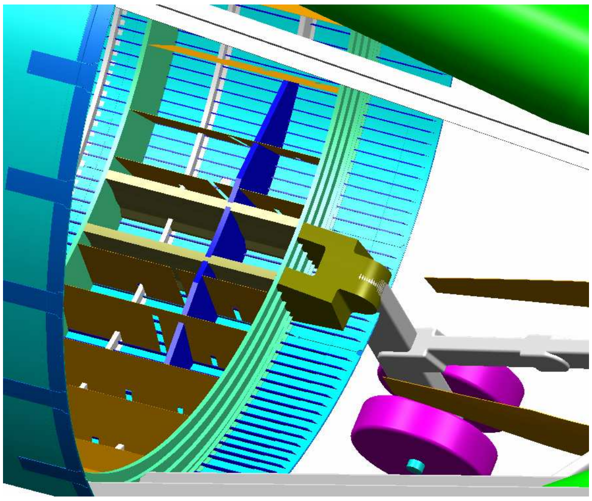

Figure 7: Preliminary design of LFBB attachment ring showing the internal lay-out including the support structure of the nose landing gear

The load carrying LH2 and LOX tank as part of the forward fuselage as well as the attachment ring structure, are designed similar to the Ariane 5 EPC tank and front skirt JAVE. The cylindrical tank parts are integrally stiffened with the stiffeners place on the outer tank surface. Since the insulation is foreseen to be external, an internal inspection of the tank skin is possible. The tank sizing is made for the two materials Al 2219 (as used in Ariane 5) and the aluminum lithium alloy Al 2195.

The rear fuselage is proposed to be made of CFRP, locally reinforced against buckling. (see Figure 8)

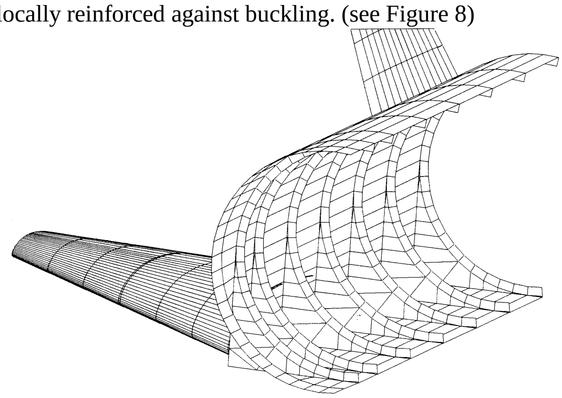

Figure 8: Static system model of the rear fuselage

The structural concept of the wing consists of a wing box with four spars stiffened with ribs. The shear panels are designed as CFRP sandwich panels, reinforced by T-sections at the lower and upper end.

For the thrust frame a trade-off between a truss structure (CFRP struts) and a conical shell has been performed. It turns out that the shell structure, also made of CFRP, has more advantages. A stress plot of the selected thrust frame for the three Vulcain 3 engines is shown in Figure 9.

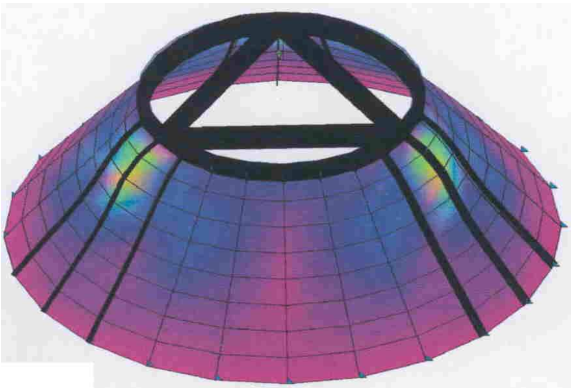

Figure 9: Stress Plot of the Thrust Frame

Stiffness requirements, which can influence the structural mass, are not defined yet. They have to be derived from dynamic and aeroelastic investigations, which are foreseen in the next study phase.

During the re-entry flight the booster is subject to moderate aero-thermal heating, never exceeding 100 kW/m^2 at the stagnation point. Nevertheless, the outer skin of the integral tanks with cryogenic insulation and the CFRP body and wing have to be protected against this heat flow. A first analysis of the thermal protection selects a flexible insulation like FEI of different thickness on a large part of the vehicle's surface. Another feasible option for the LFBB is a hot structure. However, this alternative approach would require a different mechanical architecture than that described above.

2.5 Launcher System Performance

The usual mission of commercial Ariane 5 flights will continue to be operated from Kourou to a 180 km x 35786 km GTO with an inclination of 7 degrees. This orbit data and a double satellite launch including the multiple launch structure SPELTRA are assumed. The overall ascent trajectory of Ariane 5 with LFBB is similar to the generic GTO flight path of Ariane 5 with SRM. After vertical lift-off the vehicle turns during a pitch maneuver, and heads eastward to its low inclined transfer orbit. This trajectory has to respect certain constraints, which are close to those of Ariane 5+ ascent. Throttling of the Liquid Fly-back Booster is not performed, since the Ariane 5 acceleration limit is not reached.

Some characteristic mass data of the investigated LFBB configuration as of August 2003 is listed in Table 2. The dry mass is incorporating the results of the structural and thermal protection analyses. The separated satellite payload mass in double launch configuration exceeds 12.4 Mg. The fully cryogenic launcher (boosters, core, and upper stage) is able to deliver almost 2 % of its gross lift-off mass into GTO.

	kg
LFBB dry mass:	**46200**
GLOW LFBB mass:	**221200**
GLOW launcher mass:	**695775**
GTO payload mass:	**12450**

Table 2: Characteristic mass data of the Fly-back Booster for GTO mission with Ariane 5 core stage

A complete flight dynamics simulation of the atmospheric re-entry and fly-back trajectory is run. Lift-, drag-, and pitching moment coefficients with regard to canard and bodyflap deflection are used in combination with a calculation of center of gravity movement, to perform a flight dynamics and control simulation. The trimmed hypersonic maximum lift-to-drag ratio reaches a value of about 2.0. In the low subsonic and cruise flight regime trimmed L/D is slightly above 5.0. Hypersonic trimming is performed by the canards and supported by the RCS. A stable condition is achievable at least up to angles of attack of 35 degrees.

A quasi-optimal trajectory is found by parametric variation of the initial banking maneuver. The return of the LFBB should start as early as possible, but is not allowed to violate any restrictions. The banking is automatically controlled to a flight direction resulting in a minimum distance to the launch site. After turning the vehicle, the gliding flight is continued to an altitude of optimum cruise condition.

An elaborate method is implemented to calculate the fuel mass required by the turbojets for the powered return flight to the launch site. The complete flight is controlled along an optimized flight profile. Aerodynamic data, vehicle mass, and engine performance (available thrust and sfc) are analyzed in such a way as to determine the stable cruise condition with the lowest possible fuel consumption per range (g/km). This is not a trivial task, since engine performance is dependent of altitude and Mach number, and the equivalence of drag-thrust respectively lift-weight is usually not exactly found at maximum L/D.

The changing booster mass due to fuel consuming, and a minimum necessary acceleration performance have also to be taken into account.

Including 30% fly-back fuel reserves to take into account possible adverse conditions like head winds, the booster needs about 4.0 Mg hydrogen for its more than one hour return leg.

3 EVOLUTION-SCENARIO FOR THE REUSABLE BOOSTER STAGE

The second part of the paper assesses a long-term, strategic scenario of the basic fly-back booster vehicle. The general idea is the gradual evolution of the above outlined LFBB into at least three space transportation systems performing different operational tasks. If the reusable booster can support satellite launches from the lower end to the very high upper end efficiently with virtually the same type of vehicle, production can be surged to numbers otherwise not realistically achievable by a reusable stage. In combination with further operational synergies considerable cost reductions should be reached.

Starting with the heterogeneous expendable launcher family of Vega, Soyuz, and Ariane to be operated from Kourou within the next few years, a reusable and potentially common element can be introduced with the LFBBs replacing the EAP of the Ariane 5 ECB. Assuming an operational capability of the LFBB in combination with the expendable Ariane 5 core stage at mid of next decade, one can imagine an evolution of the reusable booster stage as shown in Figure 10. In a next step, the reusable boosters extend their application as a reusable first stage (RFS) in the class of small and medium size launchers like Vega and Soyuz. Possible options have been analyzed and some of the first results are described in section 3.1. The second direction of evolution is the upper segment of a super heavy-lift launcher (SHLL). Payload should be close to the capability of the famous Saturn V and Energia boosters to support an ambitious space flight program like manned Mars missions. The design and performance constraints of this configuration are investigated in section 3.2. Eventually, the partially reusable system with Ariane 5 core might evolve into an RLV TSTO still relying on the (upgraded) LFBB as the first stage element (section 3.3). To date the analysis of such systems, when compared to the Ariane 5 LFBB study presented above, has been performed to a lesser degree of detail.

3.1 Reusable First Stage (RFS)

A single reusable first stage derived from the LFBB design described in chapter 2, is the common element of the considered RFS-options. Three major alternatives have been investigated for the expendable upper stage(s) so far:

- Zefiro 23 + Zefiro 9 + AVUM of Vega
- H-25 derived from Ariane 4's H-10
- H-170 to H-185 similar to the future EPC-core of paragraph 2

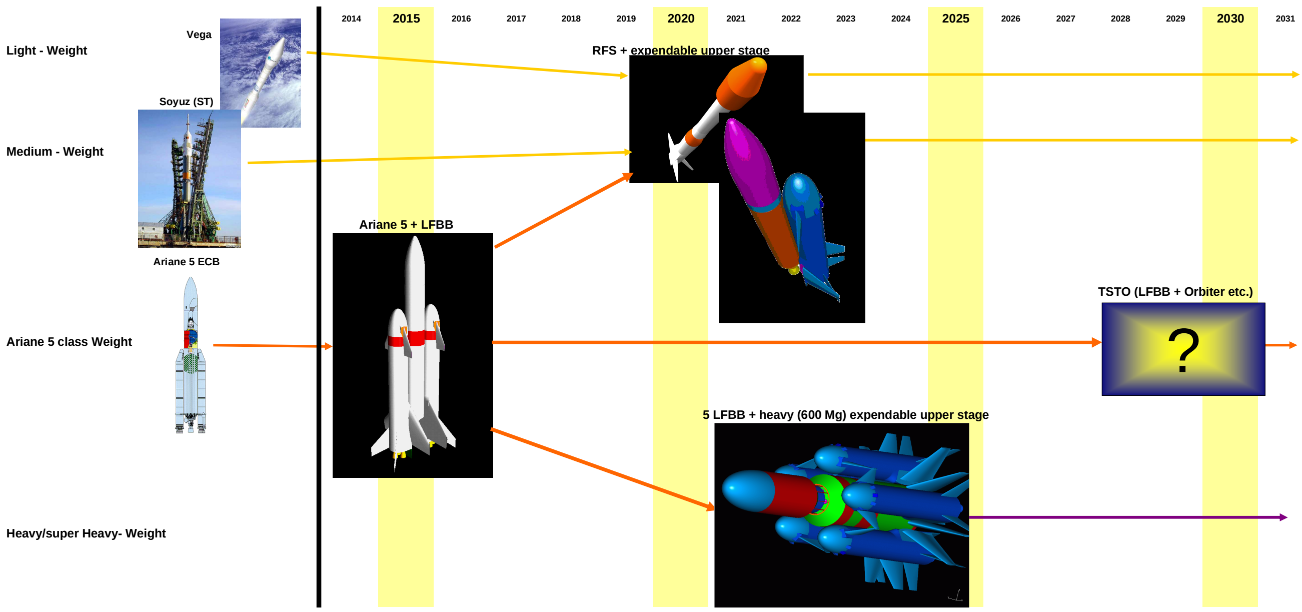

Figure 10: Future launcher scenario for Europe based on reusable booster stage

kg	RFS + Zefiro 23 + Zefiro 9	RFS + H-25 (propulsive deceleration)	RFS + H-25 (aerodyn. deceleration)	RFS + H-185
GLOW RFS mass:	193600	206600	207800	221500
GLOW launcher mass:	233900	238650	241050	438000
SSO payload mass:	1882	1481	2788	5000

Table 3: Characteristic mass data of the investigated launchers with reusable first stage for SSO mission

The common reference orbit of these launcher configurations is assumed to be a SSO, which might be their preferred, but not only destination. In case of the small upper stages like Zefiro and H-25, RFS-propellant is unloaded to keep separation conditions within the re-entry load limits of the already designed LFBB stage. Of-course, it has to be checked in the later selection process of possible RFS options, if such unloading is acceptable from a structural-dynamic and launcher control point-of-view. Although this approach does not seem to be an optimized solution for the RFS-launcher itself, it leads to a favorable reduction in the development effort for the LFBB's secondary application and is acceptable for the limited mission numbers of the small launcher.

As a basic requirement, the separation velocity and flight path angle must not exceed considerably the nominal conditions of the LFBB configuration (approximately 2 km/s and 23°). Otherwise a new and dedicated design would be obligatory. Additionally, two unusual design options, intended to keep the reusable stage's re-entry condition sufficiently low will be investigated while examining their performance impact.

In the lightest RFS configuration, the LFBB replaces the proposed P80 first stage motor of Vega. The upper stages, assumed to be unchanged, are mounted on a large interstage structure above the LFBB nose. The Z-9 solid upper stage is injected in a Vega-like 150 km x 170 km transfer orbit, to be circularised to 800 km SSO by the AVUM module. By replacing the solid first stage with the reusable booster, an injected payload mass increase of about 20 %, with respect to the original Vega launcher, can be achieved (Table 3). Although the RFS separation velocity is increased to values above 2 km/s, the re-entry loads stay within acceptable limits because γ can be hold in the low twenties at this point. The growth in return flight propellant is easily accommodated by off-loading of ascent propellant.

The second RFS option has already been subject to investigations in earlier studies[2], and has now been adapted to the most recent LFBB configuration. An advanced cryogenic upper stage charged with 25 Mg of cryogenics and a Vinci engine might be developed with some expertise from the well known H-10 of the former Ariane 4. Although a thrust increased VINCI expander-cycle engine of 200 kN is selected, it is found difficult to reach sufficient acceleration performance at staging conditions below 2 km/s. Flight path angle or velocity at stage separation must be considerably augmented above LFBB conditions, to successfully reach the 160 km x 800 km transfer orbit. Two innovative methods to actively decelerate the reusable stage are investigated to keep re-entry loads within the limits defined by the vehicle's main role.

The first option uses a booster rocket engine for active deceleration of the RFS after separation. Re-ignition of a hot engine shortly after MECO (approximately 50 s has to be assumed for booster re-orientation by RCS) is judged as too risky. Actually, such a re-ignition can only be avoided by using two of the three LFBB engines for ascent and the remaining one for deceleration. This approach is made possible by the good acceleration performance of the LFBB, but is restricted in propellant loading by the requirement of a sufficient thrust-to-weight ratio at lift-off. A full trajectory simulation of ascent, deceleration, and return shows that a workable solution exists. By using 10 Mg of fuel, the RFS' velocity can be reduced by 300 m/s while re-entry loads remain acceptable. On the downside, the payload mass does not exceed a value of 1480 kg, i.e. about 400 kg less than that provided by the solid upper stages Z23+Z9. It has to be noted that for the H-25, a heavier and larger Ariane 4 class fairing is chosen, while the solid stages use the Vega shroud.

The second alternative exploits aerodynamic forces for reducing velocity. Since it is not an easy task to considerably increase the drag of an existing vehicle in a controlled manner, something like a parachute has to be used. Hypersonic parachute design is a complicated and costly endeavor for reusable stages with a size comparable to that of an RFS. A more robust solution for atmospheric re-entry deceleration might be found in the *Ballute* proposal. The word implies a combination between balloon and parachute. Several Ballute lay-outs have already been investigated by JPL and others for extraterrestrial planetary probe atmospheric entries [8]. For the RFS application a Ballute with a cross section of 45 m^2 is found most promising in the flight dynamics simulation. A smaller or larger design will increase the loads exerted on the vehicle exceeding the LFBB design case. In the first instance the deceleration through drag force will be too low, in the latter it is not possible to aerodynamically control the RFS' angle-of-attack, hence increasing dynamic pressure. The Ballute rope will be cut at around Mach 2 since it is afterwards no longer required and could even have severe impacts on flight stability. The payload mass to SSO of the aerodynamically decelerated RFS in combination with H-25 significantly increases to above 2700 kg because the separation velocity is allowed to reach 2.25 km/s (Table 3).

The last launcher in the RFS class investigated so far is an asymmetric configuration with a single LFBB and an adapted cryogenic EPC core already used in the primary application of chapter 2. The two stages are mounted and operated in parallel up to RFS separation. The expendable stage is first injected into a 180 km x 800 km transfer orbit before releasing the payload and controlled de-orbiting executed by small forward mounted solid motors follows. The large Ariane 5 fairings should be used for this launcher. Circularisation of the payload is performed by an injection module with storable propellants not further investigated here.

The separated mass in the transfer orbit including injection module and propellant is 7360 kg, while about 5000 kg payload are delivered in SSO. Payload mass to LEO exceeds 10000 kg. RFS separation is as low as about 1.5 km/s due to the configuration's relatively high lift-off mass Therefore, re-entry loads and fly-back fuel demand of the reusable stage are benign.

A more severe constraint on the RFS with parallel-operating upper stage arises from the unsymmetrical thrust load and the cog-movement perpendicular to the flight direction. Most important is to achieve a moment balance at each instant of the trajectory which can be fulfilled by thrust vector control, though this automatically increases the angle of attack. This undesired but unavoidable behavior is especially critical for the winged stage, because strong aerodynamic moments arise. A flight dynamics simulation of the ascent trajectory found the resulting moments to be at or beyond TVC limits. The maximum engine deflection in normal (z-) direction reaches at least 6.5° (Figure 11). Actually, the wing as an eminent part for reusability causes serious problems during the ascent phase.

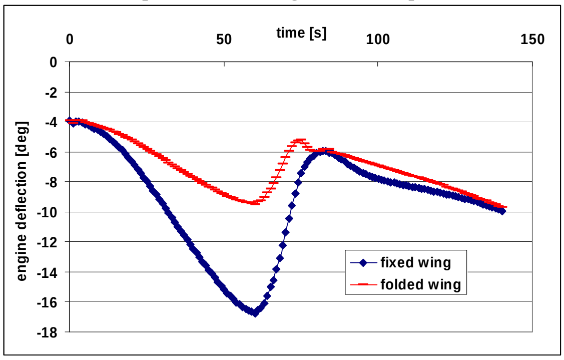

Figure 11: Required TVC angle of asymmetric RFS launcher with different wing configurations during ascent flight

A technical solution proposed here is a variable wing which is able to avoid or reduce negative impacts caused by aerodynamic forces encountered during ascent. Technical design of such a wing is still in a very embryonic stage. For configurational reasons, such a wing will be also required for the SHLL and TSTO applications described below. In a first approach, the wing is folded upward like for carrier aircraft. Preliminary aerodynamic analysis[5] of the adapted RFS configuration and succeeding flight dynamics simulation show an acceptable ascent trajectory control (Figure 11), if the RFS engines are pre-inclined by about 6 degrees.

3.2 Booster for Super Heavy Lift Launcher (SHLL)

As space exploration and exploitation advances, space transportation vehicles need to provide improved capability to enable more complex missions to be accomplished. A super heavy-lift launcher (SHLL) might be required, approaching the payload capability of the well-known Saturn V and the Energia boosters. Possible space-flight applications include manned Moon and Mars exploration, as well as large solar power satellites. This section addresses the question how reusable boosters are able to support these ambitious programs.

The SHLL consists of a central core stage, five circumferentially attached LFBB, and a small re-ingitable injection stage. Separate LOX and LH2 tanks of the large core stage are feeding three advanced Vulcain 3 engines with high expansion ratio similar to those assumed for the future EPC of paragraph 2. An ascent propellant mass of 600 Mg is carried, for which no sub-cooling is envisaged. The central core has a diameter of 10 m, similar to the Saturn V second stage S-II. The circumference is slightly above 62 m, allowing the integration of five LFBB boosters of chapter 2, if some kind of variable and retractable wing is attached. The small rendering in the lower part of Figure 10 illustrates one of number of possible foldable-wing configurations.

The SHLL injection stage is a derivative of Ariane5's ESC-B with strengthening to take care for the loads of the large payload. The 180 kN Vinci proofed to be sufficiently powerful for the injection task. Payloads of huge size are protected by a fairing of 8 m x 29 m. Table 4 summarises the approximate SHLL vehicle sizes while Table 5 exposes the masses for the proposed configuration.

Core stage length	28.65	m
Core stage diameter	10	m
Upper stage length	8.98	m
Upper stage diameter	5.6	m
Fairing length	29.5	m
Fairing diameter	8	m
Vehicle total length	69	m

Table 4: Dimensions of the SHLL configuration

GLOW LFBB mass, each	**222.3**	**Mg**
GLOW launcher mass	**1900**	**Mg**
LEO payload mass	**67280**	**kg**

Table 5: Masses of the SHLL configuration

As a reference mission a low-earth transfer orbit of 200 km x 600 km is selected. After a total burn time of approximately 1340 s the orbital conditions are reached. Figure 12 shows the evolution of altitude vs. velocity during simulated ascent flight. In this plot the separation of the five LFBB is easily identified. The boosters detach from the main vehicle, flying at a velocity of 1.55 km/s, at an altitude of 51 km. As these separation conditions are well under those examined for the nominal Ariane 5 simulation in Section 2, the fly-back loads are far from being critical.

Fly-back propellant, required by each booster for the return flight, amounts to 3250 kg, where this amount is inclusive of 30% reserve propellant. Flight loads remain within preset boundaries during the entire launch phase. Acceleration values touch a maximum of approximately 3.4 g and the dynamic pressure reaches a maximum of roughly 22 kPa,.

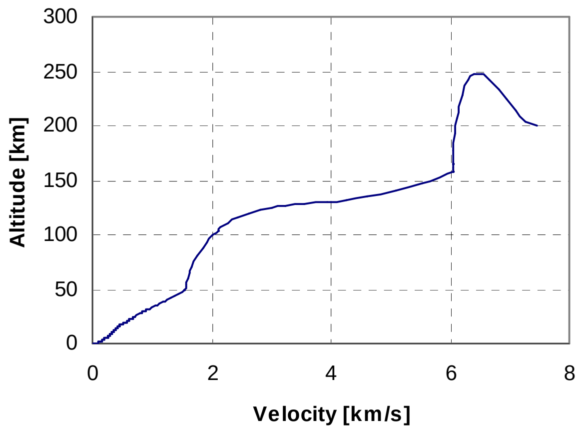

Figure 12: Altitude vs. velocity for LEO ascent flight of the SHLL configuration

3.3 Booster for Reusable TSTO

A widespread intention in the definition of future space transportation strategies is to increase the degree of reusability of a launcher. Therefore, as the next incremental step, a system with a reusable upper stage and evolved LFBB is investigated. A fully reusable TSTO system leads inevitably to large and heavy stages, if conventional rocket technology is used. A design with expendable external tank (ET) and external payload fairing is therefore the baseline for this preliminary study of a reusable TSTO to keep stage sizes and gross lift-off mass low.

Reuse of components and commonality with existing hardware are the driving parameters in the design of the TSTO system. The configuration consists of two LFBB boosters with foldable wing and an orbiter with fixed wings, evenly grouped around an EPC derived external tank. A small, expendable upper stage is used for GTO missions while it is intended to inject LEO-payloads directly by the orbiter. Both the upper stage and the payload sit on top of the orbiter beneath a fairing. Fairing separation will only occur after external tank separation due to geometric constraints.

The launcher missions are assumed to be in line with the predecessor model Ariane 5 with LFBB: A standard GTO mission as defined in paragraph 2.5 and a secondary mission to a LEO orbit in compliance with e.g. space station re-supply needs.

Additional constraints on stage sizing are due to stage return requirements. LFBB separation has to occur at conditions comparable to the Ariane 5 with LFBB design case in order to maintain structural integrity at reentry and to limit the return fuel mass. The orbiter shall reach the destination orbit for payload delivery in the LEO case and shall perform a once-around-earth trajectory in the GTO case to avoid a heavy air-breathing propulsion subsystem for return flight or the necessity of down-range landing sites.

A full flow staged combustion engine of RD-0120 class is assumed to be available in Europe beyond 2030; the time such a TSTO might become operational. Each booster is powered by three engines while the orbiter is equipped with one. The Vinci engine is used to propel the expendable upper stage. The use of subcooled propellant as specified in chapter 2 is assumed for all stages besides the expendable upper stage.

A mass breakdown and the global dimensions of the TSTO system are given in Table 6 and Table 7 respectively.

The GTO mission is a branched optimization problem, as two final conditions have to be considered: Delivery of the payload to the destination orbit and return of the orbiter to the launch site. The LEO mission is a classical problem in contrast. The orbiter reaches a stable orbit. A return to the launch site is easily achieved through favorable timing of the deorbit impulse.

Mg	GTO	LEO
Booster dry mass	47.2	
Booster propellant	167.5	
ET dry mass	13.3	
ET propellant	185.0	
Orbiter dry mass	28.8	
Orbiter propellant	50.0	
EUS dry mass	3.1	
EUS propellant	8.0	
GLOW	746.8	739.4
Payload mass	8.5	12.8

Table 6: Mass break-down of TSTO configuration

ET length	30.5 m
ET diameter	5.4 m
Orbiter length	28.8 m
Orbiter fuselage diameter	3.6 m
Fairing diameter	5.4 m
Fairing length	20.5 m
Vehicle total length	57.3 m

Table 7: Dimensions of the TSTO configuration

The payload performance of the current configuration is 8.5 Mg into GTO orbit and 12.8 Mg into a 400 km LEO orbit. The ascent trajectory of the GTO mission is shown in Figure 13. Re-entry and fly-back of the reusable boosters is not critical.

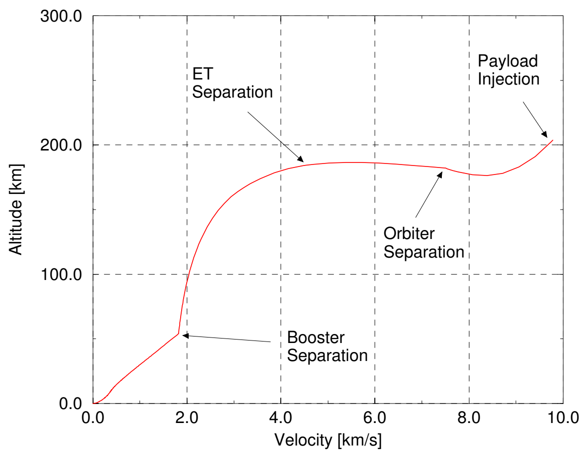

Figure 13: Altitude vs. velocity for GTO ascent flight

The achieved performance to LEO and GTO – though currently a result of very preliminary analyses - are considerably below the values of the predecessor configuration of expendable Ariane 5 core with LFBB. This fact raises the question, if the relatively complex launch configuration with up to four separate stages and an external tank will be able to significantly reduce specific launch cost. A more exhaustive trade study is necessary to find an optimal solution with augmented performance, before an evolution to the TSTO concept seems to be attractive.

4 CONCLUSION

Technical investigations on a partially reusable space transportation system with reusable booster stages, attached to an advanced future derivative of the expen-dable Ariane 5 core stage, demonstrate the feasibility of several promising design features. The fully cryogenic launcher is able to deliver almost 12500 kg of payload into GTO.

The reusable boosters are designed with the same external diameter as Ariane5's EPC, the large integral tank is of similar architecture, and the basic lay-out of Ariane 5's forward skirt JAVE is reused for the LFBB's attachment ring. Therefore, existing manufacturing infrastructure might be continuously operated for the RLV assembly.

A first wind tunnel test campaign of the LFBB has been successfully concluded. The aerodynamic vehicle configuration with two large canards has been refined and the wing has been adapted to a supercritical airfoil. The previously detected stability problem in the subsonic fly-back cruise regime has been considerably eased. Additional results indicate a potential for a further reduction in canard size which may lead to a LFBB configuration which is stable along the complete return flight and which has a very robust trim behaviour. A return trajectory flight simulation further demonstrates that under realistic canard actuator conditions the LFBB is fully controllable by active means despite potential longitudinal instability.

Several options to evolve the proposed partially reusable launch system have been technically assessed. At least three space transportation systems performing different operational tasks from the lower end to the very high upper end of payload capability can be identified for the LFBB.

The reusable booster is able to extend its application as a reusable first stage (RFS) in the class of small and medium size launchers with different upper stage options. In combination with small expendable stages it is found most critical to achieve acceptable re-entry loads for the reusable vehicle. To avoid excessive overloads the separation conditions must be restricted, hence limiting payload performance. In a parallel burn, asymmetric configuration, the aerodynamic moments of the wing are critical for ascent control of the launcher. Flight dynamic simulations prove that retractable airfoils significantly improve the situation.

Five LFBBs are able to accelerate a super heavy-lift launcher (SHLL) with a payload capability close to 70 Mg in LEO. No showstoppers could be found for this large launcher, but the boosters require variable wings for integration reasons.

Eventually, the partially reusable system with Ariane 5 core might evolve into an RLV TSTO still relying on the (upgraded) LFBB as the first stage element. A configuration design with two LFBB boosters with retractable wings and an orbiter with fixed wing, evenly grouped around an external tank is selected for this preliminary study. Although a technically workable configuration for GTO and LEO missions has been defined, some cost optimization is necessary, to show an advantage compared to its semi-reusable predecessor.

All applied technologies of the LFBB-RLV are well within reach for Europe in the next 10 years. The reusable stage can be used to support the transportation to orbit of a very broad range of payload masses. As the LFBB is able to replace a whole pallet of boosters and first stages with virtually the same type of vehicle, production can be surged to numbers otherwise not realistically achievable by a reusable stage. In combination with further operational synergies considerable cost reductions can be envisioned. Therefore, reusable booster stages represent an interesting and serious option in the future European launcher architecture.

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