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First-Stage Design Variations of Partially Reusable Launch Vehicles

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Different types of reusable first stages designed for a near-term application with heavy lift launchers are investigated. The attached reference expendable space transportation system is a future Ariane 5 with cryogenic core and upper stage but skipped solid rocket boosters. The design of the so-called liquid flyback boosters is restricted to the incorporation of powerful hydrogen or hydrocarbon rocket motors already under development or in operation. The analyzed layout variants of the reusable vehicle include single- as well as dual-booster configurations. Catamaran-type double fuselage stages are investigated to evaluate the potential in reducing the unsymmetrical thrust load of one-side-mounted booster. Along with their primary use to boost heavy lift geostationary transfer-orbit missions, a second task may be covered by the same vehicle to accelerate the upper stages of small and medium launchers. The additional design requirements in such a dual-use reusable launch vehicle are studied. The investigation includes trajectory simulations and optimizations for ascent, as well as an assessment of propellant requirements and vehicle loads during return flight to the launch site. Critical flight stability aspects are evaluated by static and dynamic simulations. A comparison of size and mass is included, as well as performance data of the different liquid flyback booster configurations. The relevant rocket engine figures of performance, mass, reusability, and throttling capability are presented.

Nomenclature

D = drag, N
M = Mach number
m = mass, kg
Q = heat flux, W/m^2
q = dynamic pressure, Pa
T = thrust, N
v = velocity, m/s
W = weight, N
γ = flight-path angle
ε = nozzle expansion ratio

Introduction

RECENT proposals concerning the introduction of reusable components in space transportation regard the first or booster stages. Such systems are usually called a winged flyback booster or a reusable first stage. Previous studies at the German Aerospace Center (DLR)[1,2] have shown that an Ariane 5 ECB version, with a replacement of its powerful solid rocket motors by reusable existing liquid propellant engines, is able to deliver almost the same payload into geostationary transfer orbit (GTO). The abolition of solid propellant stages offers a potential reduction in operation cost, if replaced by a reusable booster, and increases mission flexibility. Therefore, a similar design will be investigated more deeply within the German future launcher technology research program ASTRA.

Certain critical aspects have been detected during the early study. The unsymmetrical thrust load introduces some angle of attack. The Ariane 5 core stage (EPC and ESC-B) is designed for considerably lower normal forces. Another point of concern is the requirement to be able to achieve a balance of thrust and aerodynamic moments at each instant of the trajectory. Therefore, it is of high interest to analyze fully symmetrical twin boosters and a solo booster in single-body as well as dual-fuselage catamaran-type configurations.

Description of Examined Semireusable Variants of a Future Space Transportation System

The partially reusable space transportation system under study consists either of a single- or a dual-booster stage, which is attached to the expendable Ariane 5 core stage (EPC) at an upgraded future technology level. This stage is powered by a single, advanced derivative of the Vulcain engine with increased vacuum thrust and contains about 185,000 kg of subcooled propellants. A new cryogenic upper stage (ESC-B) is already in the predevelopment phase. It should include a new advanced expander cycle motor of 180-kN class (Vinci) by 2006. This study assumes a consumable propellant load of this stage of around 27,000 kg.

The usual mission of commercial Ariane 5 flights will continue to be operated from Kourou to a 180 × 35,786 km GTO with an inclination of 7 deg. These orbit data and a double satellite launch using the satellite support structure (SPELTRA) are assumed as a basis for this research analysis.

A continuous increase in geostationary satellite mass is projected. Therefore, the aim of the current study is to achieve maximum payload of a semireusable heavy lift launcher. This mass should be in the same class as for a future upgraded, fully expendable system using solid rocket motors. The design constraints of the flyback boosters are the attachment requirements with the Ariane 5 core stage, the need to stay within acceptable vehicle dimensions, and the determination of a suitable number of rocket engines. Therefore, liftoff thrust-to-weight is not individually optimized for each configuration. (The resulting T/W range is 1.2/1.29.) However, the ascent trajectory is slightly adapted to obtain the optimum trajectory always.

An overview of the investigated configurations is shown in Fig. 1. These include four, single liquid flyback boosters (LFBBs): two in single- and two in double- (catamaran-type) fuselage layout and two in a symmetrical twin booster attachment. The booster designation (X-11, X-12, etc.) facilitates identification in the subsequent comparisons. Three existing (two of them highly advanced) Russian

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Table 1 Engine characteristics as used in the study

Characteristic	NK-33	Vulcain 3	RD-0120	RD-180	RS-76
Propellant combination	LOX–RP1	LOX–LH2	LOX–LH2	LOX–RP1	LOX–RP1
Nominal thrust (SL), kN	1510	1351	1650	3826.3	4000
Nominal thrust (vacuum), kN	1680	1650	1936	4152	4448
Specific impulse (SL), s	297	351.3	383	311	307.9
Specific impulse (vacuum), s	331	429.2	449	338	342.2
Chamber pressure, MPa	14.5	13.9	21.5	25.7	18.2
Engine mixture ratio	2.6	5.9	6	2.7	2.7
Nozzle area ratio	27	50	60	36.9	34.3
Length, mm	3700	3335	4540	3560	4400
Diameter, mm	1500	1943	2200	3000	2367
Dry weight, kg	1435	2520	3449	5393	4187
T/W (SL)	107.26	54.7	42.88	72.32	97.38
T/W (vacuum)	119.34	66.8	57.96	78.48	108.29

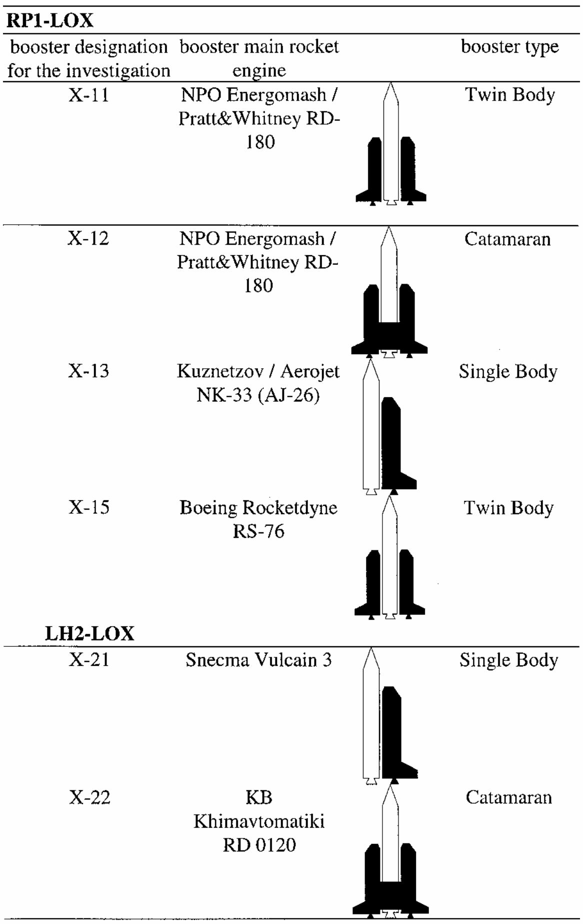

Fig. 1 LFBB configurations (black) with selected rocket engines.

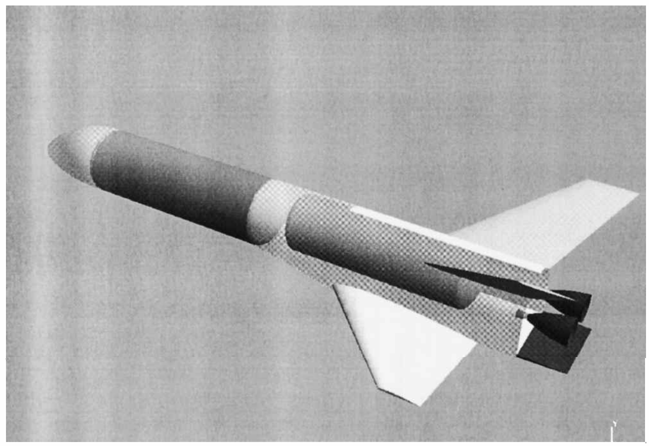

Fig. 2 Basic design of the LFBB configuration with semitransparent fuselage to show tank position.

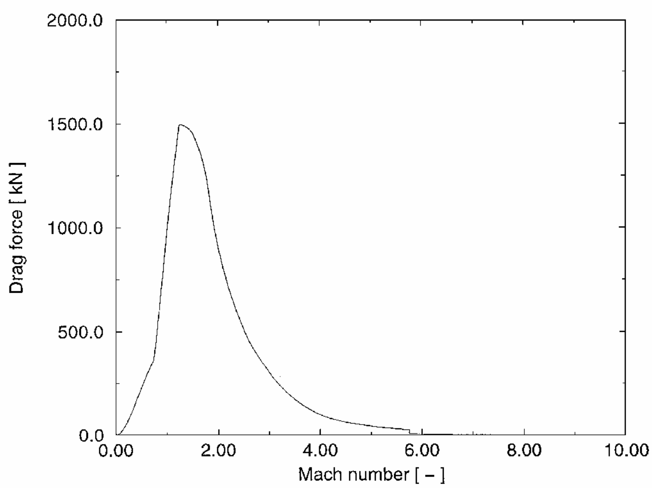

Fig. 3 Drag force of the X-11 launch configuration during ascent.

rocket engines, one proposed European, and one proposed U.S. engine are selected. All are in the high-thrust booster class. Three of them are hydrocarbon–kerosene rocket propellant (RP1)–liquid oxygen (LOX), whereas the other two are liquid hydrogen (LH2)–LOX designs. Major engine design characteristics are listed in Table 1.

For all investigated liquid flyback boosters, this study assumes a similar basic preliminary vehicle design: A cylindrical fuselage contains two separate tanks (one fuel, one oxidizer), a trapezoidal shaped wing, two vertical stabilizers on top of the fuselage in V configuration, and the rocket engines at the aft protected on their lower side by a body-flap (Fig. 2). The first tank containing LOX is always of integral structure and the other one a separate fabrication mounted on top of the wing carry through. The complete layout uses near-term technology and avoids comprehensive development programs. The simple geometry is chosen to enhance the feasibility of this comparative study. Also some aerodynamic efficiency will be favorably sacrificed to increased structural strength of a simplified layout and, hence, weight reduction. The overall dimensions are mostly determined by the engine dimensions, the total propellant volume, and the required wing area.

Aerodynamic drag during ascent is calculated for each configuration individually by fast, empirically based algorithms. The maximum drag forces considerably increase compared to the generic Ariane 5 vehicle due to the increased cross section of the LFBB configuration including additional stage attachment. Figure 3 shows the launcher's drag force during an ascent simulation for the X-11 configuration. Note the effect of booster separation close to Mach 6.

Table 2 Dimensions and estimated masses of the regarded LFBB configurations for GTO design mission

Parameter	X-11	X-12	X-13	X-15	X-21	X-22
Overall length, m	35.3	35.62	43	36	58.4	44.6
Fuselage diameter, m	3.8	3.8	5.4	3.8	6	4.5
Wing span, m	15.3	26.5	21.3	15.5	23.5	27.9
Stage mass empty (including margins), kg	31,415	57,805	58,285	32,856	85,812	76,092
Ascent propellant, kg	200,000	389,980	414,214.4	210,000	294,075	277,489.8
GLOW[a] stage mass, kg	234,615	474,185	496,200	256,000	397,587	372,982
Structural index	0.148	0.1388	0.1331	0.1472	0.2752	0.2563

[a]Gross liftoff mass.

Single LFBB, Single Fuselage

DLR started an analysis of the most simple configuration, similar to one that had already been regarded in Europe within the previous Future European Space Transportation Investigation Program (FESTIP) study (FSSC-16sr type). Some of the investigated designs of similar type vehicles lead to increased system weight and size, which, in some cases, using LH2 fuel, surpassed the length of the core stage.[3]

Such a bizarre configuration can be avoided using higher density RP1 as the propellant. One of the promising configurations in Ref. 2, with five NK-33 rocket engines, is redesigned with regard to updated requirements and increased mass margins of the German research program ASTRA.

The NK-33 is the oldest of all rocket engines under study. Originally developed in the 1960s for the unsuccessful Soviet crewed lunar program, this motor has some qualities especially interesting for this investigation. A chamber pressure of 14.5 MPa is considerably high and offers high-performance sea-level (SL) operation. The most remarkable feature is, however, the very high thrust-to-weight ratio of more than 100 (Table 1), which is unequalled by all other engines in this propulsion class. Recent applications of this LOX/RP1 engine have been proposed.[1] A throttling range between 77 and 114% has been proved in test firings.[4]

To fulfill an acceptable system thrust-to-weight ratio at liftoff, five NK-33 engines are selected for the LFBB configuration X-13 (Table 2). The LOX tank and fuselage diameter is 5.4 m, exactly the same as for the Ariane core stage. In a dense arrangement, all five of the engines can be integrated in the fuselage's base area. Two of the four turbojet engines for flyback are attached in a vertical position (like FESTIP FSSC-16) and the other two in conventional horizontal position below the rocket engines. The vertical arrangement offers vehicle packaging advantages, but requires a deflection of the engine's gas flow in the inlet and nozzle sections by around 90 deg, leading to increased thrust losses.

The second single-body configuration investigated that utilizes cryogenic propellants and that is powered by a proposed future version of the Vulcain engine. Up to now, the Vulcain is the largest French/European engine designed for the cryogenic core stage of the Ariane 5. An advanced, more puissant version 2 is starting its operational use in 2002. An even more powerful Vulcain 3 is currently in definition studies. It might include increased mass flow, higher chamber pressure, and a larger expansion ratio. Although no technical data are fixed as yet, the presented results of this paper and the ASTRA study are based on assumptions concerning the performance of this motor. A single engine with expansion ratio of about 100 is assumed to power the cryogenic core stage. The question of interest is whether the same engine is also suited for the LFBB, which might reduce the logistical effort at the launch site. A similar approach in Refs. 1–3, using the Vulcain 2, showed poor results in comparison with other engines. The basic explanation is the relatively high expansion ratio, not well suited for booster applications. Therefore, in this study, an adaptation of the LFBB engine's nozzle is favored. Engine data of the variant with a reduced expansion ratio of 50 are given in Table 1. It might be beneficial to reuse the booster engines at the end of their nominal lifetime in the expendable EPC stage for one final flight. This requires at least an exchange of the nozzle's supersonic part. Some doubts exist as to whether such a modification can be easily performed. This question should be more deeply analyzed in the thrust chamber design. Current throttling range of the Vulcain is quite small. Reusability has not been addressed yet because it is not required for the current application on the expendable Ariane 5.

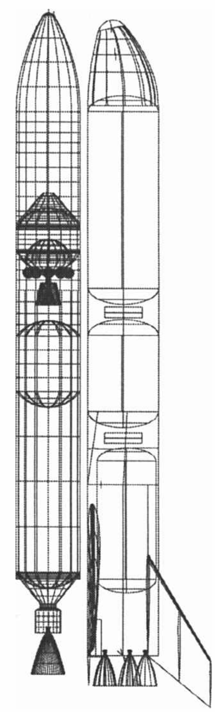

Fig. 4 Single X-21 LFBB (LOX–LH2) with single fuselage (at right) attached to Ariane 5 expendable stage.

Five Vulcain 3 engines with reduced expansion ratio are arranged in the fuselage's base, which has a diameter of 6 m. The booster follows the basic design, but this time the large hydrogen tank is subdivided into one forward integral tank, followed by the integral oxidizer tank, and a smaller nonintegral hydrogen tank above the wing. (See wire-frame drawing with internal arrangement in Fig. 4.) The total vehicle length can be reduced by this approach. The intermediate placement of the LOX is due to attachment constraints with the EPC core stage. Six turbofans are integrated, four of them in vertical position in intertank structures and the remaining two aft, below the engines. Although much effort is made in reducing the length, an overall dimension of 58 m is reached. This extent is slightly above the size of the expendable core stages, including the complete payload section.

Single LFBB, Double Fuselage, Catamaran Type

All single-booster stages experience a considerable c.g. movement normal to their flight direction, requiring a considerable thrust vector change during ascent, closely related to a critical aerodynamic angle of attack of the complete configuration. An alternative LFBB design in a double-fuselage configuration is able to reduce notably the aforementioned problems without sacrificing the operational advantages of a single flyback booster. A very compact layout can be realized if RP1 fuel is used.

The LFBB configuration X-12 powered by kerosene, burnt by two RD-180 engines, is shown in Fig. 5. The RD-180 belongs to the family of the most powerful and most advanced rocket engines

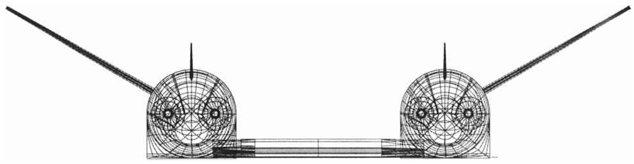

Fig. 5 Single X-12 LFBB (LOX–RP1) in double-fuselage (catamaran-type) design with two RD-180 engines (expendable core stage to be placed between fuselages).

(RD 170/172). A chamber pressure of up to 25.7 MPa is the highest known of any realized engine (Table 1). This staged combustion cycle engine uses an oxygen rich preburner. The range of throttling is between 50 and 100% (Ref. 5). Development started in the Union of Soviet Socialist Republics in 1976 with a first flight in 1985. It has been used in the Energia liquid strapon boosters and the Zenit (also Sea Launch) first stage. The two-chamber derivative RD 180 is in operation in the Atlas III and has also been selected for the future Atlas V. Its design for at least 20 reuses[5] and its relative compactness make the RD 180 an interesting candidate for a liquid flyback booster.

The basic fuselage design is used again, but the X-12's wing shape and arrangement is notably different. The two-body structure is bridged by a rectangular wing with small strakes attached at the fuselages. The fins are lowered to 30-deg inclination to serve as vertical stabilizer as well as additional lift-providing wings. Their size is large in comparison with the other vehicles. Because of a deficiency in lateral stability, two small nose fins are attached to provide the possibility of active control. The stage attachment, delivering the booster thrust to the expendable core stage, is larger in size, resulting in a heavier layout, because an additional safety distance is considered. This is because the staging maneuver is seen by DLR as a bit more challenging than for configurations not embracing the core stage as closely. A lot of interesting effects of the different aerodynamic contours and aerothermal behavior of this unusual design should be regarded in a future study. Dimensions and estimated mass of the Catamaran LFBB with RD-180 engines are provided in Table 2.

The same unusual configuration is also applied to one of the few large cryogenic engines developed for ground to orbit operation. The single chamber RD 0120 (also designated 11D122) is the first Soviet cryogenic engine. Because of its design for the Energia core stage at SL operation, many of the features are comparable to the space shuttle main engine (SSME). Combustion chamber and turbopump discharge pressure are at the same level as those of the SSME. Important differences are a single RD 0120 preburner instead of two, and a different pump arrangement. The throttling range is considerably large, between 25 and 114% (Ref. 6). As is not unusual for a high-pressure, cryogenic, staged-combustion engine, the thrust-to-weight ratio is notably reduced. It marks the lower boundary across all investigated types. In contrast SL and vacuum specific impulse represent the maximum values (Table 1).

Other than the former use in the Energia core stage, there exists no recent space flight application for this engine yet. It is proposed for future reusable single-stage-to-orbit and expendable vehicles. Notable is The Boeing Company investigation on heavy lift launchers.[7] Because this LFBB variation regards the application as a booster engine, a reduction in expansion ratio by introducing a new nozzle improves system performance. A moderate reduction to $\varepsilon = 60$ is assumed. Technical data as listed in Table 1 are calculated by a DLR cycle analysis program. The engine mass reduction due to the slightly reduced expansion ratio is assumed to be marginal and not considered in the data set.

Overall design of the RD 0120 LFBB (configuration X-22) is very similar to the RD-180 catamaran type (X-12), other than an increase in fuselage diameter and a growth in overall length due to the hydrogen fuel (Table 2). Six turbofans are to be integrated, three in each fuselage.

Dual LFBB, Single Fuselage

A conventional design using flyback boosters is found by replacing the two solid motors with two reusable LFBBs. This configuration seems to be the most promising for heavy launchers in the near future (Fig. 6). Some recent studies by The Boeing Company and Lockheed Martin of a possible space shuttle solid rocket booster (SRB) replacement are also based on this principle. The technical challenges of unsymmetrical loads can be eliminated by trading increased inert booster mass as well as additional operational and logistical cost.

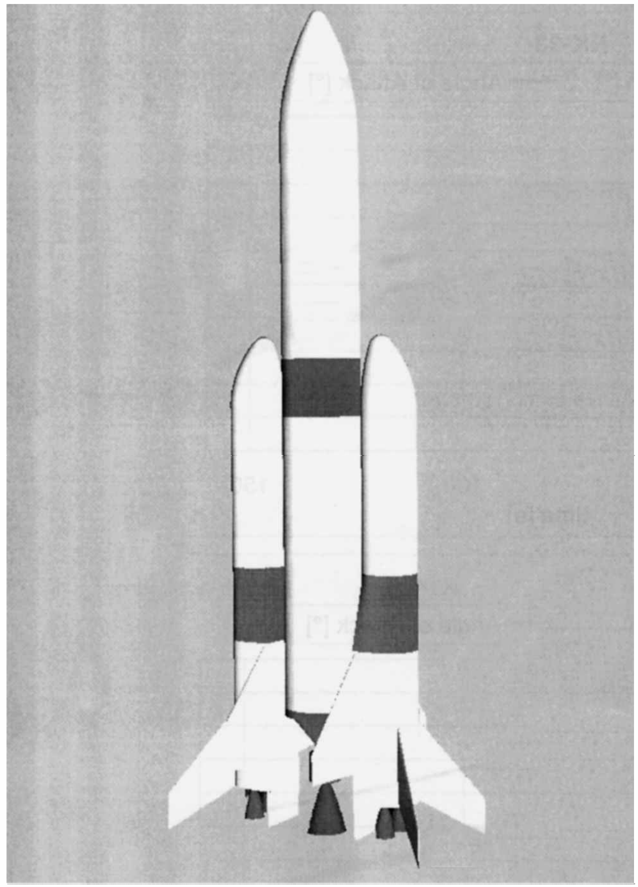

Fig. 6 Dual-LFBB configuration X-11 with LOX–RP1 (RD-180) engines attached to Ariane 5 core stage.

The first such concept (X-11) is again based on the RD-180 engine, where one motor is powerful enough to accelerate a booster and the attached core stage. The LFBB fuselage layout is similar to the catamaran-type X-12, but an additional annular strengthening is incorporated between the nose section and the integral tank. This part is added to attach a conical interstage carrying a single upper stage. (See Second Mission Suitability section.) The wing and vertical stabilizers are appropriately sized, with regard to the general layout shown in Fig. 2. Two airbreathing engines are installed in the vehicle's back. Dimensions and estimated component masses of one twin LFBB X-11 are provided in Table 2.

The second variant of a dual-LFBB configuration is also powered by an advanced LOX–RP1 engine. The RS-76 has recently been proposed by Boeing Rocketdyne to power heavy lift boosters, such as the reusable first stage, as a possible future replacement of the shuttle SRBs. If realized, the engine will incorporate a LOX-rich preburner, analogous to the Russian RD-170/180. The staged combustion design should be relatively simple with a medium chamber pressure of 18 MPa, which is considerably below the RD-180. According to The Boeing Company, a 100-mission life should be possible.[8] The engine thrust-to-weight ratio of around 100 is ambitious but still slightly below that of the NK-33.

One single RS-76 engine is sufficient to accelerate a single LFBB in X-15 configuration. Because of the increased thrust level as compared to the RD-180 propelled X-11, it is possible to slightly augment the booster's propellant loading. This results in a marginally increased vehicle length and an adapted wing area to balance a small growth in return flight weight (Table 2). Other than these small changes, the overall layout is nearly identical to the X-11 configuration powered by a Russian engine.

Comparison of Ascent Flight and GTO Performance

The overall ascent trajectory of all Ariane 5 with LFBB is similar to the generic GTO flight path of Ariane 5 with a solid rocket motor. After vertical liftoff, 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.

The separation conditions of the booster are not explicitly defined. The only criterion is to achieve maximum payload to GTO within the design constraints of the booster and core stage. The total impulse of the booster stages arrive at quite similar values because the core and upper stages are kept constant. Throttling of the LFBBs is not performed because the Ariane 5 acceleration limit is not reached. Flight performance is highly sensitive to the angle-of-attack history during booster operation. In the performed ascent trajectory optimization, it is restricted to remain below 2 deg and is further reduced in the region of elevated dynamic pressure to stay below 0.2 deg to meet structural requirements. These values are a little bit above the generic Ariane 5 values but advantageous for the lower thrust LFBBs to achieve sufficient climb. Although these path constraints are easily fulfilled by the symmetrical configurations X-11 and X-15, note that the required trim analyses of the single, side-mounted booster variants need further attention.

The unsymmetrical thrust loads and the c.g. movement perpendicular to the flight direction of the side-mounted LFBB lead imperatively to some angle of attack. The maximum change in c.g. in normal direction z is exceeding 2 m during LFBB operation. Most important is to achieve a static moment balance at each instant of the trajectory. This can only be realized by deflecting the main engines by several degrees.

It has been demonstrated by static and dynamic simulations that the moment balance is achievable for single-body as well as catamaran-type flyback boosters.[9] Nevertheless, the highly unsymmetrical loads pose a challenging problem to the mechanical outline. It might come along with an acceleration performance loss and introduces considerable structural loads on the expendable stage.

Therefore, the ascent trajectory of all unsymmetrical booster configurations is controlled so that the aerodynamic angle of attack is minimized. With regard to the single-body vehicles X-13 and X-21, it can be seen (Fig. 7) that AOA in the most critical part of the trajectory at maximum dynamic pressure cannot be brought below 1.5 deg. At the separation condition with maximum imbalance between the location of mass and thrust, AOA is around 5 deg. Booster engine throttling near main engine cutoff (MECO) is able to reduce the imbalance but at the expense of considerably reduced payload. At liftoff, an angle of more than 10 deg is unavoidable, but it is only of concern to launch tower clearance, not to normal load factor. Necessary engine deflection angle drifts from −4 to −12 deg, which is close to the mechanical actuation limit of most engines.

The catamaran-type double-fuselage LFBB variants X-12 and X-22 reduce the c.g. movement because the Ariane core stage is placed between the booster's tanks. Although a huge thrust imbalance exists between LFBB and the expendable vehicle, the mutual distance of the bodies is notably reduced. The engine deflection never exceeds 5 deg, and the AOA during the part of the trajectory with maximum dynamic pressure is held below 0.5 deg (Fig. 8). Note the different direction of deflection angles for single-fuselage and catamaran type, which is due to the selected orientation of the core stage attachment. It is equivalent to have negative or positive figures regarding the actuation requirements.

Because of the volume and, hence, propellant mass restrictions, the Vulcain-3-powered LFBB experiences the shortest acceleration time (Table 3). Separation velocity of all reusable boosters is close to 2 km/s at an altitude about 60 km. This is similar to the Ariane SRBs. It is of some interest to compare the MECO masses (dry mass complemented by propellant residuals and reserves and flyback fuel) of the different boosters. The two highest values are reached by the two LOX–LH2 configurations. A single LFBB offers some

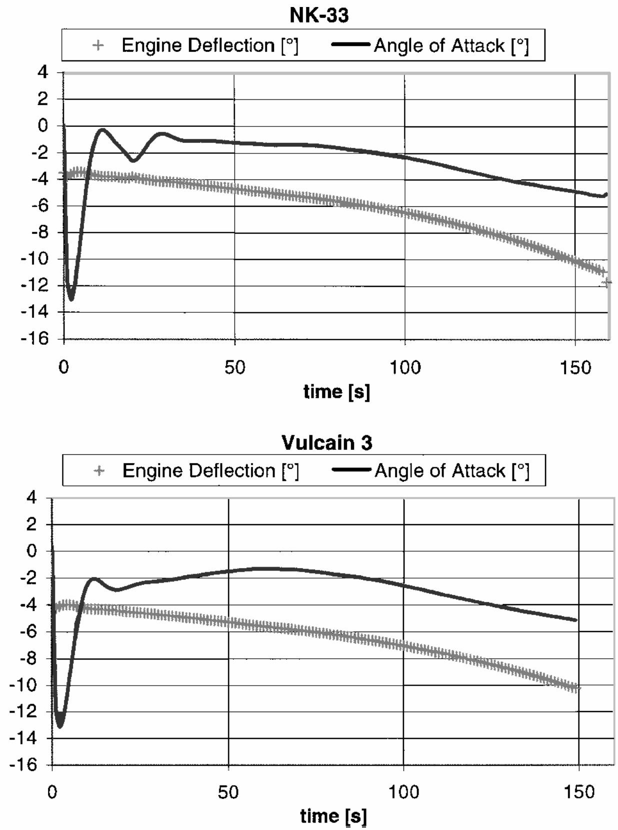

Fig. 7 Engine deflection angle required to reach static moment balance and resulting AOA of single-body LFBBs X-13 and X-21 along flight path.

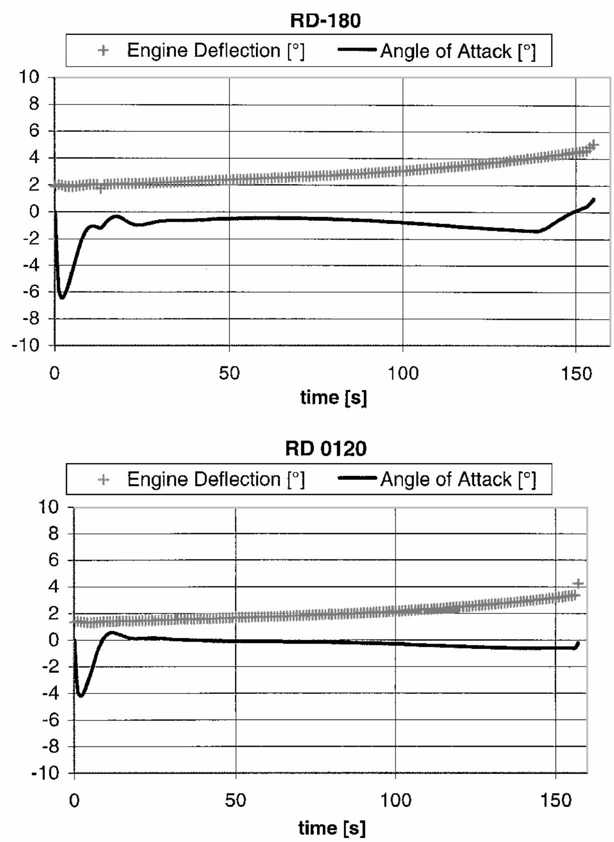

Fig. 8 Engine deflection angle required to reach static moment balance and resulting AOA of catamaran-type LFBBs X-12 and X-22 along flight path.

Table 3 Separation data of the investigated LFBB configurations

	LFBB designation					
Parameter	X-11	X-12	X-13	X-15	X-21	X-22
Time since liftoff, s	159.6	155.6	159.84	158.5	150	157.8
Altitude, km	57.99	57	59.16	57.12	59.6	64.9
Velocity, km/s	1.86	1.895	1.87	1.96	1.72	1.84
Mach number	5.75	5.86	5.81	6.05	5.38	5.9
Flight-path angle, deg	27	25.93	28.57	24.67	34.37	31.7
MECO mass, kg	87,430[a]	84,400	82,000	91,915.3[a]	103,512	95,517
Dynamic pressure, Pa	710.98	839.75	625.51	882.71	505.48	294.76

[a]Combined separation mass of two boosters.

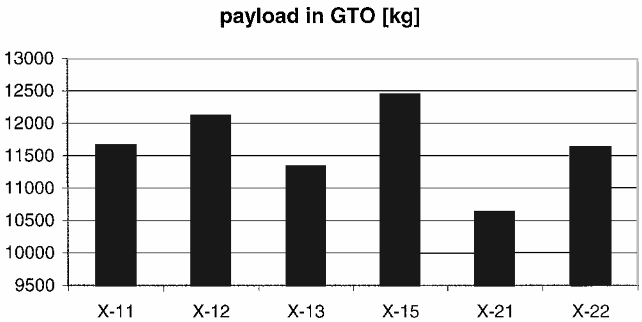

Fig. 9 GTO payload performance of regarded LFBB configurations.

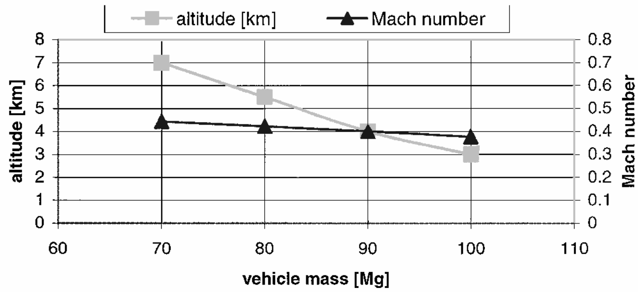

Fig. 10 Optimum altitude and Mach number of powered return flight as function of vehicle mass.

mass advantage in comparison with a symmetrical dual-vehicle arrangement. This conclusion can be drawn by comparison of X-11 and X-12, with the same type and number of RD-180 engines used.

The double-launch payload in GTO, achieved in all cases with the same Ariane core stage, is shown in Fig. 9. A relationship with the booster separation velocity can be stated. All reusable boost stages are able to deliver an impressive payload mass to GTO, considerably above today's Ariane 5 of around 6 Mg. Introducing the Ariane 5 ECB with a large cryogenic upper stage should augment the payload capacity to above 11,000 kg starting in 2006. The results obtained by this analysis of a partially reusable space transportation system with LFBB are best compared with an advanced version with improved core stage and proposed future solid motor upgrades. This improved, still fully expendable system would outperform the flyback booster configurations' payload between 2600 and 4300 kg. This result is obviously due to the considerably lower inert mass of the expendable boost stage.

Flyback Simulation and Return Fuel Requirements

The data of Table 3 describe the initial conditions of the LFBB return flight. These are quite similar for all configurations, other than a considerable mass difference between the RP- and the LH2-powered systems. Return flight mass is below the MECO value because the stage attachment is jettisoned and the solid propellant of the separation motors is already burned. Depending on the size and arrangement of a vehicle, this amounts to as much as 2500 kg in mass reduction.

Aerodynamic data sets of the return flight configuration are generated, using results produced within the ASTRA study and extensive NASA wind-tunnel tests.[10,11] The wing reference area is adapted to the modified geometry. The hypersonic maximum lift-to-drag ratio is 2.5. In the low subsonic regime, trimmed L/D reaches 5.2. Hypersonic trimming is performed by all aerodynamic flaps, including the bodyflap. A stable condition is achievable at least up to AOA of 35 deg. In this study, 35 deg is used as the upper limit during return flight.

Because of the remaining flight-path angle of about 30 deg, all LFBBs, climb in a ballistic trajectory above 100 km. When they fall back, the boosters still reach a velocity close to the separation conditions of 1.9 km/s (about Mach 6) at 50 km because the atmospheric drag is low. At this altitude and speed, the vehicles are not able to produce significant dynamic pressure and, as a result, no considerable lift force. Although the AOA is held at the 35-deg limit, a steep trajectory is performed, with a path angle γ diving as low as -30 deg (Refs. 1 and 2). During this period, no aerodynamic turnaround is possible, and a propulsive maneuver is prohibitively expensive. As a result, the LFBB continues to escape from its launch site at more than 6000 km/h.

When entering the denser layers of the atmosphere, the aerodynamic forces rapidly increase, finally stabilizing the LFBB altitude and achieving maximum deceleration at an altitude of around 20 km. In this segment of the trajectory, certain constraints have to be respected. The maximum normal acceleration must not exceed $3.5g$, and dynamic pressure should stay below 60 kPa. The simulation is performed under a closed control loop, which regulates the trajectory within load boundaries. An 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 the specified restrictions. The banking is automatically controlled to a flight direction with minimum distance to the launch site. After turning the vehicle, the gliding flight is continued to an altitude of optimum cruise condition.

During atmospheric reentry, the stagnation point heat flow reaches a maximum (about 110 kW/m^2), and its mechanical loads define the most severe structural dimensioning criteria of the LFBB. The thermal environmental situation is not critical and can be addressed by adequately choosing material and thermal protection. The maximum loads experienced show a high sensitivity to a change in separation conditions. Flight-path angle γ and the velocity are of the strongest influence.

The previous DLR studies concluded the flight simulation at the beginning of the powered return flight to the launch site.[1–3,12] The required fuel mass of the turbojet was estimated by remaining flight distance and assuming a constant specific fuel consumption.

A more elaborate method is introduced in this study. The complete powered return flight is controlled along an optimized flight profile. Aerodynamic data, vehicle mass, and engine performance (available thrust and specific fuel consumption) are analyzed to determine the stable cruise condition with the lowest possible fuel consumption per range (grams per kilometer). This is not a trivial task because 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

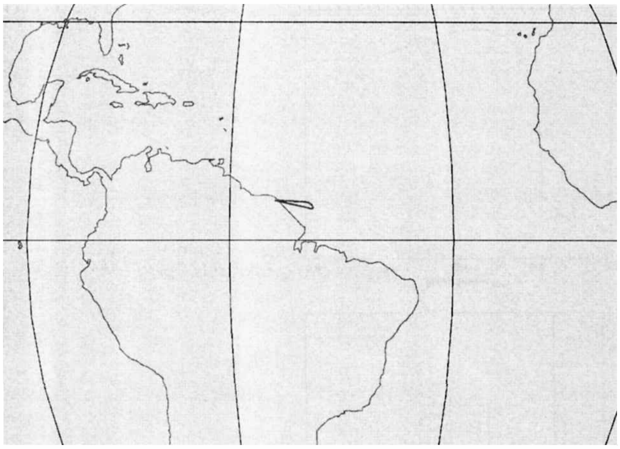

Fig. 11 Reusable stage ascent and flyback ground track of GTO mission.

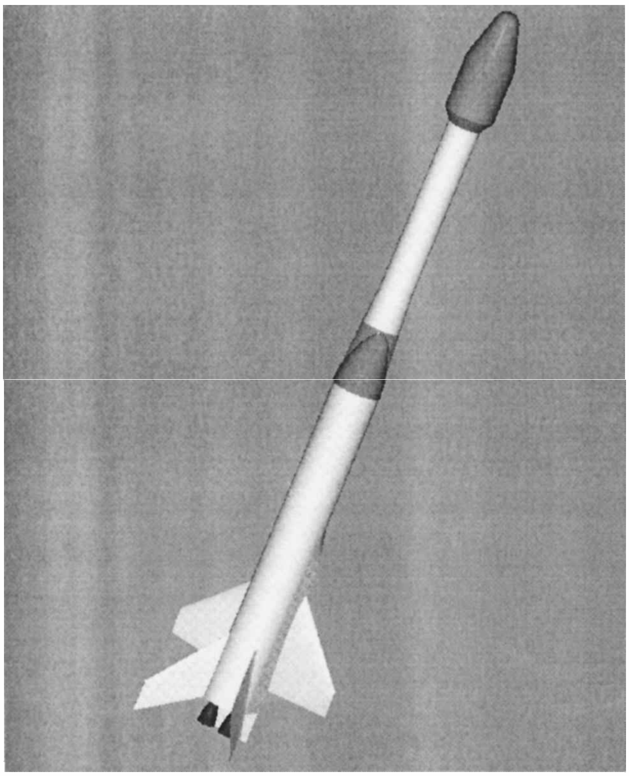

Fig. 12 LFBB (X-11) in dual role carrying one expendable upper stage at its nose. (Lower part of the interstage is semitransparent to show the booster's forward fuselage.)

to fuel consumption and a minimum necessary acceleration performance also have to be taken into account. Optimum flight profiles of each individual booster configuration can be calculated, which consider the vehicle's specific aerodynamics and engine performance as a function of weight. One such example data set is shown in Fig. 10.

The powered return trajectory is automatically controlled to follow the optimum flight condition, always directly heading to the launch site. Fuel flow is integrated to get its exact amount. Figure 11 shows the corresponding ground track above the Atlantic ocean.

In the case of RP1 rocket engines, kerosene fuel is used for the turbofan; in the case of LH2, they are powered by hydrogen. European fighter engines such as M-88 and EJ-200 are assumed to provide propulsion in dry mode. The calculated performance data adequately consider losses in the intake and nozzle, especially in the case of the vertically mounted engines. The turbofans are to be air started, requiring sufficient power of the auxiliary power unit. In this study, 20% flyback fuel reserves have to be included to take into account adverse conditions such as head winds. This results in 7–10-Mg hydrogen for flyback boosters with Vulcain 3 and RD 0120 engines. The kerosene mass of the other boosters ranges from 7.5 (small dual configuration) to 17 Mg (RD-180 catamaran type). The latter had to be redesigned in ascent propellant mass because of its larger than expected amount of flyback fuel. The main reason for this is found in the poor aerodynamic quality.

Second Mission Suitability

This section draws attention to the question of how far the liquid flyback boosters, sized for heavy GTO payloads, will be able to fulfill different space transportation tasks. The basic idea is to create a family of launchers, all based on a similar LFBB during the boost phase. Besides accelerating the EPC and ESC-B in the described dual configuration, the same single vehicle should be able to accelerate upper stages of small and medium launchers.

With regard to acceleration performance, the reusable booster is considerably oversized, which releases comfortable security margins. It also offers the opportunity to adapt the fuel mass and engine thrust level to a dedicated mission profile. Early DLR calculations[12] showed that a considerable payload can be delivered to low Earth orbit and sun synchronous orbit (SSO) making use of only one powerful cryogenic upper stage. This expendable second stage is assumed to be an upgraded version of the H10 of Ariane 4. It is attached to the flyback booster at its forward fuselage section covering the nose by a large interstage structure of about 8 m in length (computer rendering in Fig. 12). The interstage will be expended right after separation.

A single RD-180 vehicle of the dual booster X-11 configuration is more deeply investigated. Although stage separation conditions above 2.5 km/s are easily achieved by the powerful vehicle, the most severe limitation arises from the conditions during the return flight. Marginally increased velocity or flight-path angle γ will deliver considerably increased mechanical and thermal loads. If they exceed those of the vehicle's main role, the separation conditions have to be reduced. Numerical trajectory simulations performed for an SSO ascent and flyback show that separation must be accomplished below 2 km/s, to not violate the LFBB return flight design limits of $n_z = 3.5g$ and a maximum dynamic pressure below 60 kPa. Consequently the Δv requirement of the expendable stage increases to more than 6 km/s. To reach sufficient acceleration performance at this low staging condition, a thrust increased Vinci expander-cycle engine of 200 kN is selected. In a configuration as given in Table 4, a payload of about 1500 kg can be injected into a circular SSO.

Some technical data of the ascent trajectory into a 160×800 km transfer orbit are shown in Fig. 13. RD-180 thrust is continuously throttled by around 16% to stay within dynamic pressure limits and the maximum tolerable acceleration of $4.5g$. The second stage ignites after an 8-s phase of reorientation and engine preparation. This quite long duration causes some performance losses, but is linked to the Vinci nozzle extension process and a safe withdrawal maneuver of the reusable booster stage. The return flight propellant is found to be slightly above that of the GTO mission, but sufficient tank volume is available because the booster stage ascent propellants are 40% below their design values.

Active deceleration of the LFBB after separation by propulsive power might have a potential to enhance payload performance,

Table 4 Dimensions and vehicle masses of the X-11 LFBB with RD-180 engine and expendable upper stage

Parameter	SSO mission
Overall length including second stage, m	60.7
Maximum fuselage diameter, m	3.8
Wing span, m	15
Dry mass of the vehicle (including margins), kg	38,070
Propellant mass of LFBB (including margins), kg	136,000
Propellant mass of the expendable stage (including margins), kg	25,440
Payload mass, kg	1,500
GLOW vehicle mass	201,550

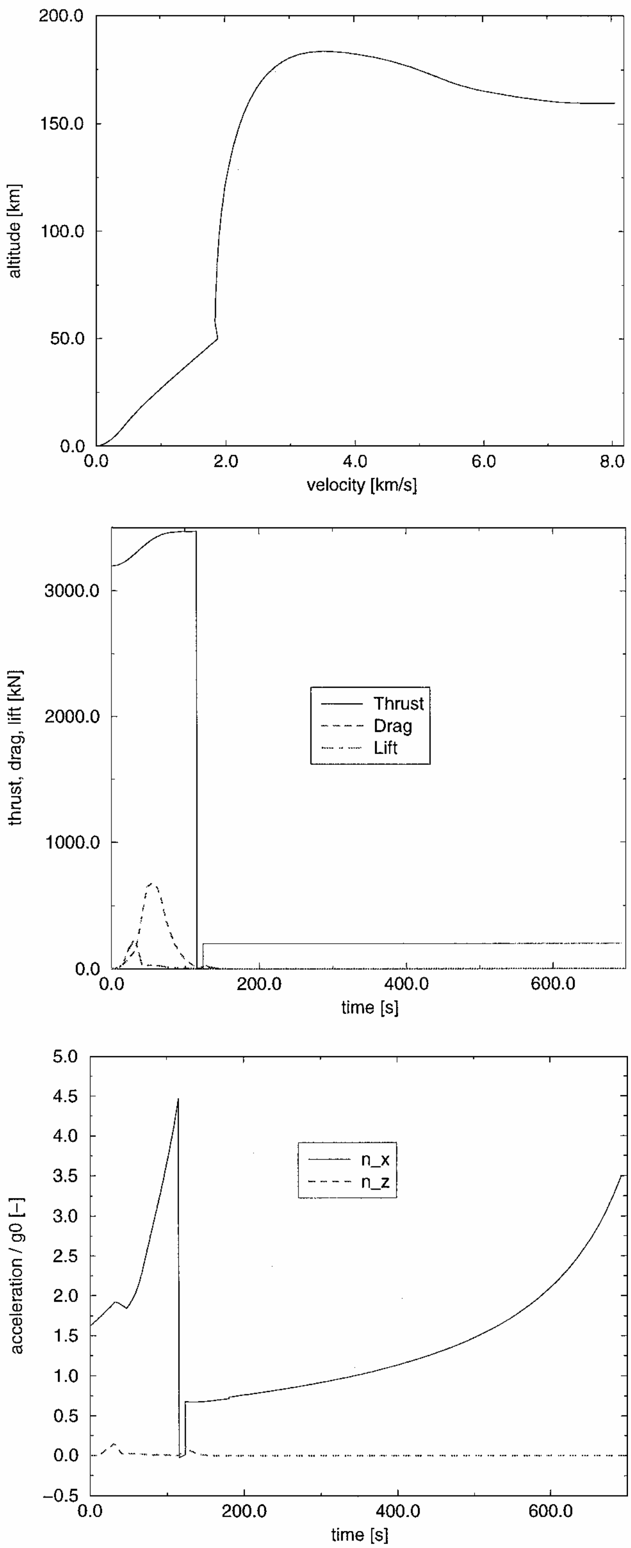

Fig. 13 Trajectory data of LFBB (X-11) in polar orbit mission.

without violating the return flight restrictions. This topic will be addressed in a future study.

Conclusions

The investigated partially reusable space transportation systems consist of different kinds of booster stages, which are attached to the expendable, advanced future derivative of the Ariane 5 core stage and a cryogenic upper stage (ESC-B). The LFBB sizing criterion is to achieve maximum payload performance, while staying within acceptable dimensions of the booster and its number of engines. One-body LFBBs in single-fuselage and double-fuselage (catamaran-type) configurations are examined, as well as symmetrical dual-booster arrangements.

All of the selected configurations and engines reach a large lift capacity (10.6–12.4 Mg in double launch to GTO) in a convergent design within this preanalysis. However, the resulting dimensions of the reusable boosters are quite different. The LFBB layout is mainly influenced by the fuel density and engine size. The low-density hydrogen requires very large tanks. The dimensions of a single booster using this fuel exceed those of the Ariane 5 core stage.

The structural index of LH2 boosters is becoming remarkably high due to the low density of this propellant. Therefore the empty masses of the LFBBs with hydrogen propellant are considerably larger than the empty masses of the LFBBs burning kerosene. However, the total liftoff masses of the completely cryogenic configurations are still around 20% lower than that of the combinations with LOX–RP1. This result is due to the higher average specific impulse of their engines.

The unsymmetrical thrust load and c.g. movement perpendicular to the flight direction of one-side-mounted boosters, as well as the requirement to achieve a static trim during the ascent trajectory, demand an analysis of trimming requirements. The remarkable differences between single- and double-fuselage configurations are demonstrated. The decreased distance between EPC and LFBB of the double-fuselage type ease the thrust vector angle and, hence, loads. Whereas single bodies experience critical conditions concerning the configuration's AOA and the engine's mechanical actuation constraints, a catamaran type is able to perform nearly like a conventional symmetrical launcher.

Such a conventional design, by replacing the two solid motors with two reusable LFBBs, seems to be the most promising variant to be realized in the near future for heavy launchers. The major drawbacks are surging operational costs and a slightly increased booster mass, but the regarded LOX-RP1 configurations both show good payload performance.

The differences in separation conditions between the regarded vehicles are found to be quite small. For that reason, the return flight trajectories are mainly similar. The simulation is performed under a closed control loop with parametric variation to find the optimized conditions. The loads during this phase implement the most severe requirements on the design of the LFBBs. The maximum experienced loads show a high sensitivity to a change in separation conditions. The powered return trajectory to the launch and landing site is integrated along the optimum engine consumption performance. The resulting amount of fuel is considered to include 20% margin.

LFBBs sized for heavy GTO payloads are investigated, fulfilling different space transportation tasks. A single vehicle of an originally symmetrical dual configuration is able to accelerate upper stages of small or medium launchers. If additional structural load cases of the booster are included in the primary design from the beginning, such configurations can be operated. At an acceptable penalty to the original mission, the benefit of reusable first stages might be enhanced.

The study shows that LFBBs in a symmetrical dual arrangement are the most promising configuration for near-term applications. If they are designed utilizing kerosene propellant, a compact booster layout can be realized, still be able to deliver a heavy payload to orbit. If a powerful, reusable rocket engine is assumed to be available, such configurations might challenge today's solid rocket motors.

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