Propulsion Systems Definition for a Liquid Fly-back Booster

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Abstract

This paper describes the final design status of a partially reusable space transportation system which has been under study for more than five years within the German future launcher technology research program ASTRA. It consists of dual booster stages, which are attached to an advanced expendable core. The design of the reference liquid fly-back boosters (LFBB) is based on LOX/LH2 propellant and a future advanced gas-generator cycle rocket motor. In focus are the four different propulsion systems and the main propellant feed and pressurization system.

Subscripts, Abbreviations

D	Drag	N
L	Lift	N
M	Mach-number	-
$\dot{Q}$	Heat flux	W/m^2
T	Thrust	N
W	weight	N
l	body length	m
m	mass	kg
p	pressure	Pa
sfc	specific fuel consumption	g/kNs
q	dynamic pressure	Pa
v	velocity	m/s
Π	Pressure ratio	-
α	angle of attack	-
γ	flight path angle	-
δ	deflection angle	-
ε	expansion ratio	-

CAD	computer aided design
CFRP	Carbon Fiber Reinforced Polymer
EAP	Etage d'Accélération à Poudre (Solid booster stage of Ariane 5)
EPC	Etage Principal Cryotechnique (Main cryogenic stage of Ariane 5)
ESC-B	Etage Supérieur Cryotechnique (Cryogenic upper stage of Ariane 5)
FEM	finite element method
FLPP	Future Launcher Preparatory Program
GLOW	Gross Lift-Off Mass
GTO	Geostationary Transfer Orbit
HPC	High Pressure Compressor
JAVE	Jupe AVant Equipée (forward skirt of Ariane 5)
LEO	Low Earth Orbit
LFBB	Liquid Fly-Back Booster
LPC	Low Pressure Compressor
MECO	Main Engine Cut Off
NPSP	Net Positive Suction Pressure
OPR	Overall Pressure Ratio
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
SRM	Solid Rocket Motor
SSO	Solar Synchronous Orbit
TET	Turbine Entry Temperature
TSTO	Two Stage to Orbit
TVC	Thrust Vector Control
cog	center of gravity
sep	separation
s/l	sea-level
0,0	sea-level, static

1 Introduction

A reusable booster stage dedicated for near term application with an existing expendable core has been under investigation within the system studies of the German future launcher technology research program ASTRA and research is continued in the ESA FLPP. 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. (e.g. ref. [1] and [2]) 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.

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

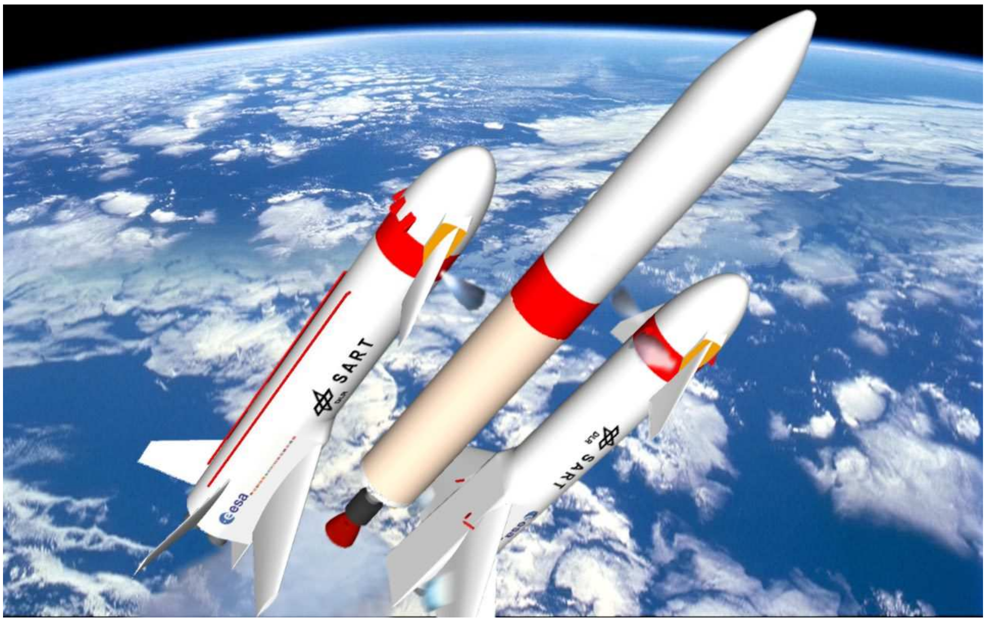

Figure 1: Artists impression of the separation of two attached reusable fly-back boosters from the Ariane 5 core stage

2.1 LFBB Geometry Data and Lay-Out

Three rocket engines are installed in a circular arrangement at the aft of each vehicle. The total length of the latest LFBB variant “Y-9” is almost 41 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 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 has the same diameter as the EPC core stage as well as similar lay-out but is shorter in length. LOX is stored in the upper portion of the tank and is separated by a common bulkhead from the main LH2 tank. The ascent propellant mass of the latest Y-9 LFBB-configuration is 168500 kg. 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 to feed the engines through this second tank.

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. The first phase of the aerodynamic design studies, summarized in references [7] and [8], showed the essential need of canards to increase the static margin and to enable the trim of the vehicle. The succeeding work defined a refined aerodynamic configuration of the LFBB. This latest design has a canard with a leading edge sweep of 65° and a trailing edge sweep of 22°. An asymmetric NACA 3408 airfoil is used for the canards. The main wing lay-out is based on the transonic RAE 2822 airfoil. The wing spans about 21 m and its exposed area is about 115 m^2.
More information on the LFBB's aerodynamic design and performance has been published in references [7] to [10].

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, with an option to be also implemented 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.

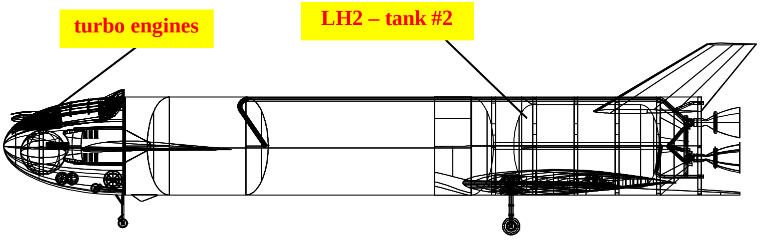

Figure 2: LFBB (Y-9) projection in the x-z-plane

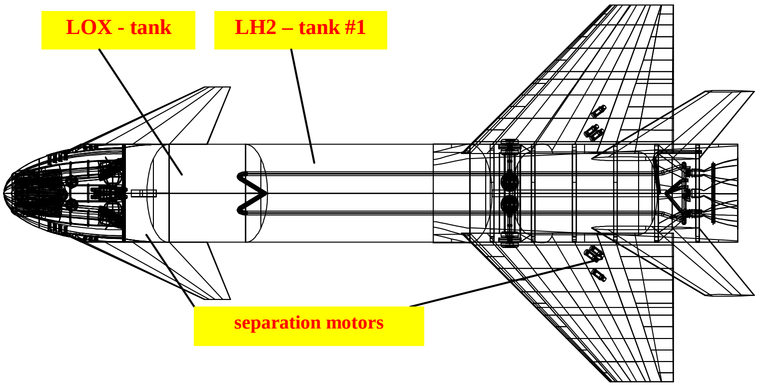

Figure 3: LFBB (Y-9) projection in the x-y-plane

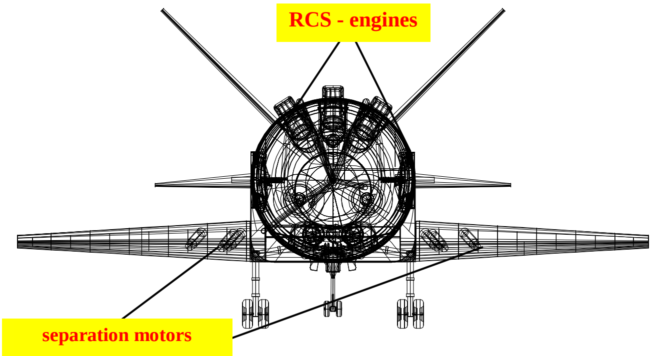

Figure 4: LFBB (Y-9) projection in the y-z-plane

2.2 Mechanical lay-out of vehicle structure

A preliminary mechanical design of major structural elements has been performed. 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 houses a large number of different subsystems (see Figure 5, left). The turbofans, their secondary LH2 feed tank, the RCS and tanks, the nose landing gear and some avionic subsystems are located inside the nose assembly and are to be supported by the structure.

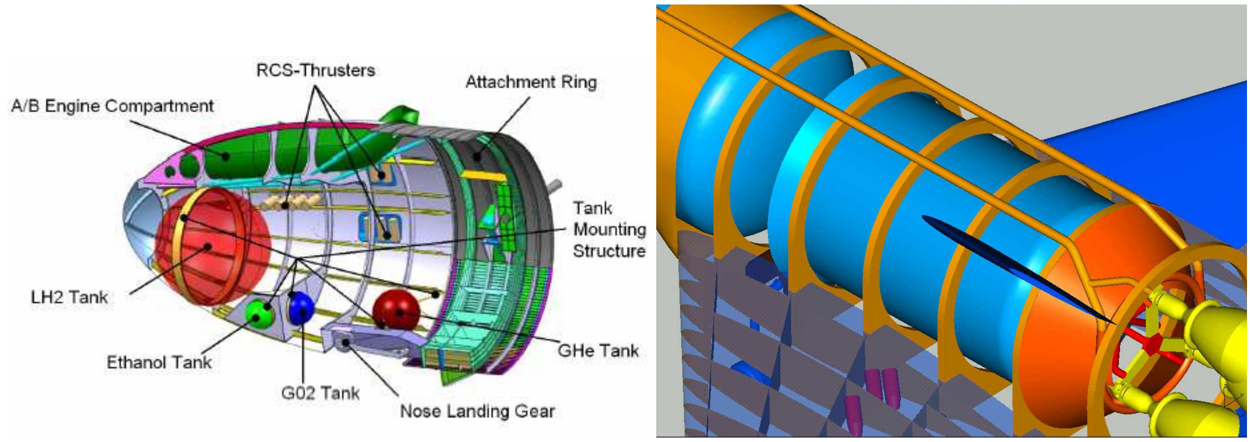

Figure 5: Preliminary design of the LFBB nose and attachment ring (left) and rear fuselage structure including the second hydrogen tank as CAD model (right) showing internal lay-out and some subsystems

The forward fuselage consists of an integral, load carrying LH2 and LOX tank and the attachment ring structure. The cylindrical tank parts are integrally stiffened with the stiffeners place on the outer tank surface. The reference configuration's tanks are to be fabricated from aluminum lithium alloy Al 2195. The rear fuselage is proposed to be made of CFRP, locally reinforced against buckling. 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. The thrust frame is designed as a conical shell structure, also made of CFRP. (see Figure 5, right)

3 Propulsion System

Four different and independent propulsion systems have to be included in the reusable booster stage:

- Main rocket propulsion
- Fly-back turbofan engines
- Reaction Control System (RCS), and
- Solid separation motors

3.1 Main rocket propulsion

The reusable booster stage propulsion is based on the same advanced gas generator cycle engine also assumed for the EPC, but employs an adapted nozzle with reduced expansion ratio. This new type might include an increased mass flow and a higher chamber pressure than the operational European Vulcain 2 engine. Although such an engine is not yet under development, in the ASTRA-study it has been called "Vulcain 3". The nominal engine performance data of the variant to be used in the LFBB configuration is given in Table 1.

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

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	-

Throttling demand on the reusable engine is relatively benign. In order to evaluate the throttling capabilities of the "Vulcain 3" engine, different off-design calculations have been performed with the DLR code LRP2 in the throttling range 95% to 105% of nominal thrust.

The underlying assumptions are:

- constant chamber throat diameter and expansion ratio
- constant gas generator throat diameter
- constant turbine pressure ratios
- efficiency of the turbo machinery is varied according to efficiency estimates by the code
- pressure loss and heat transfer in the cooling channels varies according to chamber pressure changes ($\dot{Q} \sim p_c^{0.8}$)

The engine mixture ratio has been varied in order to generate a certain thrust level or a certain chamber mixture ratio respectively. Variations have been made with respectively the LOX or the LH2 mass flow held constant. The mixture ratio variation leads to different chamber pressures. Thus different pump powers are needed to establish the changing mass flows. The results show that a variation in oxidizer mass flow (constant LH2 mass flow) is more suitable for throttling than the inverse case (cf. Figure 6). The related power adaptation on the LOX turbopump is approximately +/- 15 %.

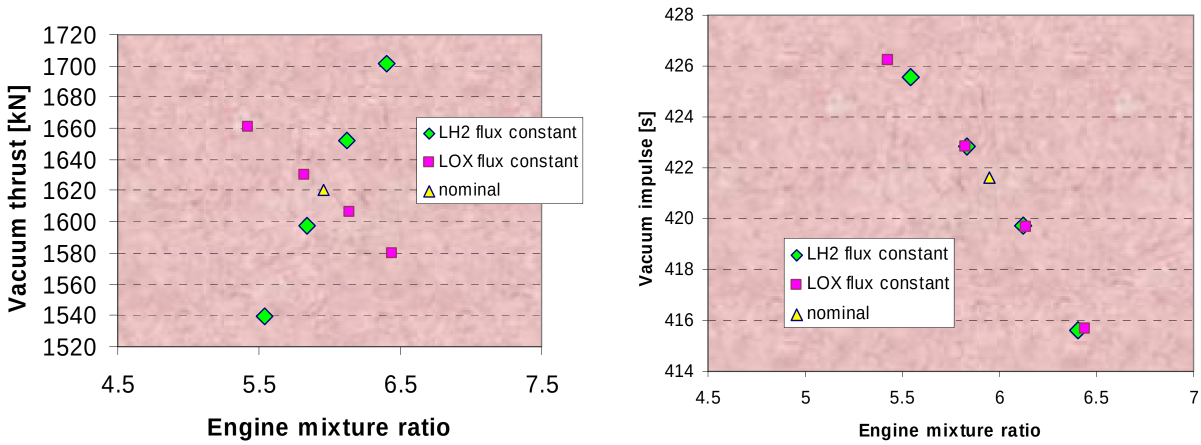

Figure 6: Vulcain 3 off-design thrust (left) and vacuum specific impulse (right) vs. engine mixture ratio

3.2 Fly-back turbofan engines

Three turbo engines without afterburner which use hydrogen are currently foreseen for fly-back to reduce the fuel mass. The feasibility of replacing kerosene by hydrogen in an existing military turbofan (EJ-200) investigated within the ASTRA-study, shows promising results and no show-stoppers. According to the manufacturer MTU Aero Engines, the installation of the EJ200 *DRY Hydrogen* into the LFBB can be readily achieved by low risk modifications. To limit the costs related to the development programme it is assumed that the majority of existing EJ200 components can be used without modifications and new validation [11]. The EJ200 DRY Hydrogen is based on the EJ200 production configuration. Main technical data at sea-level are given in Table 2.

Table 2: EJ-200 technical specification data at Kourou sea-level static conditions and hydrogen propellant according to *abp* [12] calculation

OPR	-	26
$\Pi_{FAN/LPC}$	-	4.35 (3 Stages)
Π_{HPC}	-	5.98 (5 Stages)
HP-Turbine	-	1 Stage
LP-Turbine	-	1 Stage
Bypass ratio λ	-	0.4
air mass flow	kg/s	77
TET	K	1800
$T_{0,0}$, dry	N	54000
$sfc_{0,0}$, dry	g/kNs	8.1

The engine is capable of continuous operation with hydrogen fuel under all LFBB attitudes and manoeuvre loads. Some special attention has to be given to the engine conditions after re-entry of the LFBB from space flight and the

conditions for assisted wind milling and lighting the engine. Engine mountings are the same as EJ200 baseline. The LFBB will have mounts and supporting structure to accommodate the EJ200 mounts.
These assumptions lead to the following EJ200 DRY Hydrogen modifications required to the engine for the hydrogen application in the LFBB (compare Figure 7):

- The Front Jet Pipe will be changed / modified for DRY version installation for the LFBB programme.
- The existing engine LP- and HP customer bleed system will be blocked; the HP5 Cooler will be removed.
- Minimum change to the Accessory Gear box.
- The Variable Inlet Guide Vane system will be changed from hydraulically driven to electrically driven Actuators.
- The Main Engine Fuel Pump, Afterburner Fuel Control Unit and Main Engine Fuel Metering Unit will be removed
- A new Main Fuel Metering Unit and fuel piping reconfigured for gaseous hydrogen fuel usage is required.
- Adapted dressing hardware is required
- Control System: DECMU software modification to adopt for hydrogen fuel and optimised performance for thrust requirements
- Dedicated combined engine starter/generator mounted for engine and LFBB power supply.
- Ram Air Cooled engine Oil Cooler (ACOC)

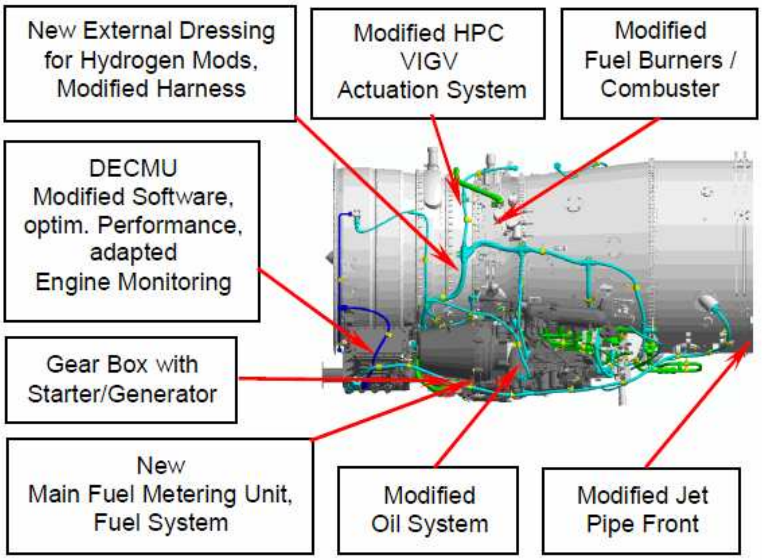

Figure 7: Modifications required for the EJ200 DRY Hydrogen compared to the production version [11]

EJ200 DRY engines will have the same cleared life as the series production engines installed in the current military fighter application. This lifetime is fully sufficient for the LFBB which might not need more than a few hundred hours of fly-back operation. It is assumed that the hydrogen will have no detrimental effect on the hot gas path parts.

3.3 Reaction Control System

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 [6]. For the LFBB configuration this requirement leads to 10 thrusters on each side of the vehicle (4 yaw, 3 up/down pitch and roll) with a thrust level of 2 kN per engine. Different propellant combinations have been looked at. Besides the classical but toxic N_2O_4 / MMH, the environmentally friendly GO_2 / Ethanol and GO_2 / GH_2 are being studied.

The functional diagram of the RCS is presented in Figure 8. Ten thrusters are installed on each side of the LFBB. Four of them on either side control the yaw movement and three each are operating upward and downward for pitch- and roll control. The current number of thrusters enables a slight redundancy.

The dry mass of the complete GO_2 / Ethanol RCS (I_{sp} 3189 m/s) is estimated at about 370 kg with about 225 kg propellants. If the challengingly high ignition reliability should not be met for the new fuels, a classic N_2O_4 / MMH system could be selected as a back-up, which would even save about 50 kg total mass.

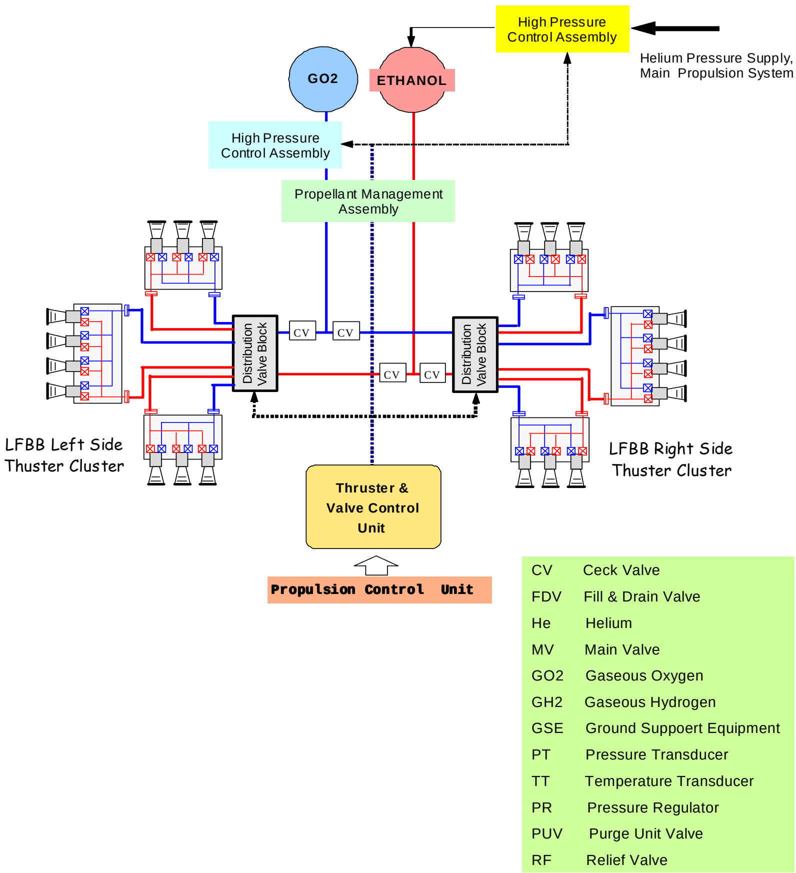

Figure 8: GO2/Ethanol RCS Schematic Diagram

3.4 Separation motors

The solid separation motors are located in the attachment ring and inside the main wing structure (see Figure 3, Figure 4, and Figure 5, right). The design of the motors is derived from the motor lay-out used on the Ariane 5 EAPs but with increased thrust to account for the higher separation mass of the LFBB. Therefore, the propellant grain is elongated by about 64% and the throat diameter is increased by 28%. Table 3 lists characteristic data of the motor.

Table 3: Characteristic data of LFBB separation motor

Maximum Thrust [kN]	120
Burn time [s]	0.5
MEOP [bar]	130
Propellant Mass [kg]	31.9
Length [m]	0.9
Diameter [m]	0.345
Mass [kg]	58.3

3.5 Propellant Feed and Pressurization System

The propellant supply system shall deliver the propellants within specification limits of all liquid engines in their operational modes. Most critical due to the high flow-rate and tight constraints of the turbopump inlet conditions is the main propulsion system. The propellant feed and tank pressurization system is preliminarily designed with the specialized DLR code pmp assessing different options for the pressurizing gases.

A minimum engine entry NPSP of 40 kPa on the hydrogen side and 190 kPa on the oxygen side has been assumed. Due to the convex shape of the common bulkhead of the oxygen and Hydrogen tanks, the oxygen tank has to maintain always a higher pressure than the hydrogen tank. This is made to prevent buckling of the bulkhead at all times. Figure 9 shows the required tank pressures over time for the oxygen and the two hydrogen tanks of the LFBB. The pressure in the second non-integral hydrogen tank has no specified nominal value before its operation starting around 116 s after lift-off. However, its pressure has to be controlled within tight constraints for structural reasons and to ensure the safe operation of the interconnected hydrogen feed system.

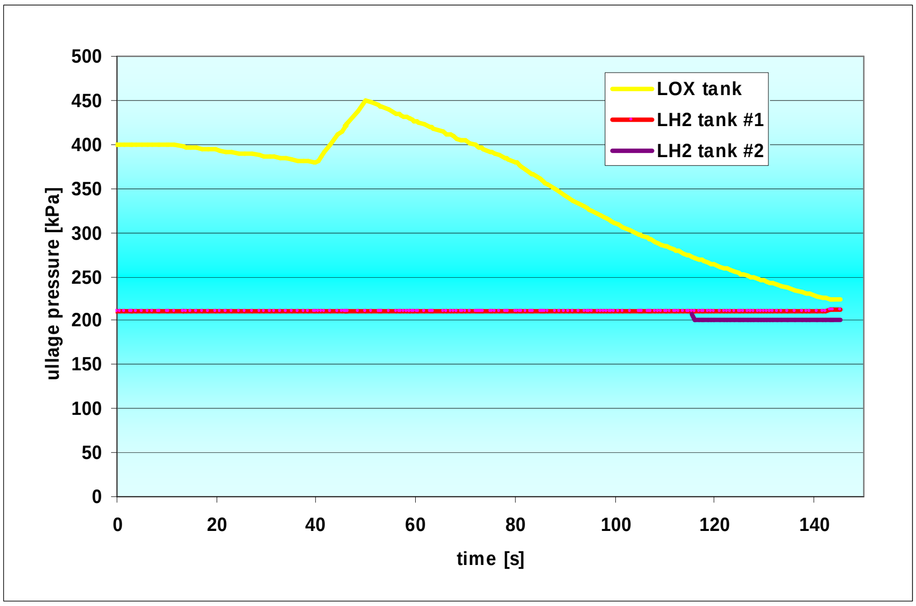

Figure 9: Required tank pressures for the nominal LFBB ascent trajectory

The main rocket propellants are stored at subcooled conditions to increase the propellant loading within the available tank volume and to reach favorable NPSP values due to reduced vapor pressure.

While the hydrogen tanks are pressurized with GH2, two options exist for the LOX-tank: Helium or gaseous oxygen (GO2). Although He seems to be more attractive at first, due to its lower molecular mass, its considerably more complicated pressurization system in comparison with O2 justifies a detailed analysis. A complete simulation of the tank ullage conditions during the ascent flight has been performed.

It turns out that the required gas mass of Helium (and vaporized oxygen!) is no more than 43.5 % of the required pure gaseous oxygen mass. However, unavoidable reserves and residuals in the high pressure supercritical helium storage tanks are already reducing the mass edge to less than 40%. Additional masses for two He-tanks, piping and control equipment result in only 45 kg advantage for a Helium-pressurization system compared to an oxygen-pressurization system (Figure 10). Taking into account cost considerations, GO2 is currently selected as the preferred pressurant of the LOX-tank because its payload drawback is miniscule. However, potential safety requirements for inerting the tanks during reentry and atmospheric fly-back might alter the decision.

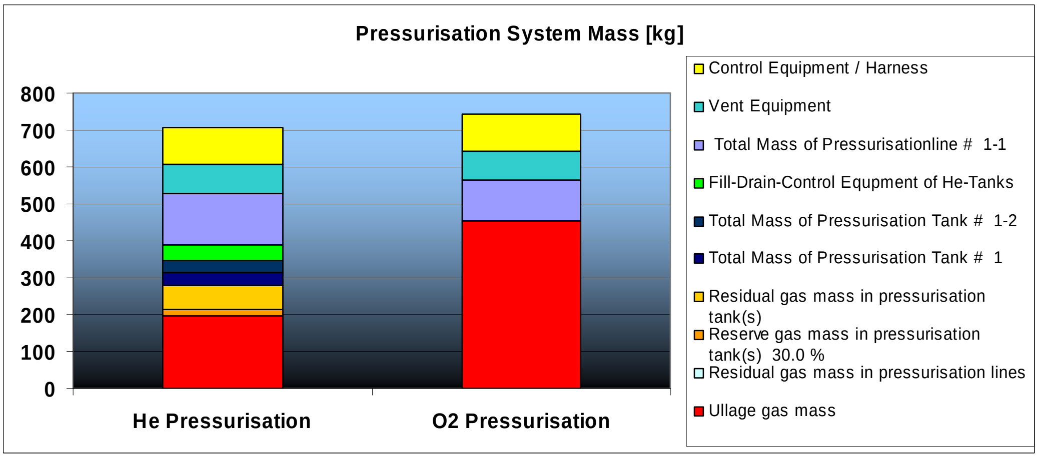

Figure 10: Mass budgets of the two considered LOX tank pressurization systems

The usage of the remaining hydrogen including the residuals and potential reserves from the separate aft tank to propel the turbofan engines looks as a promising and elegant technical solution. However, sloshing of the fly-back LH2 and its vaporization at hot walls during reentry maneuvering might be of serious concern. An engineering analysis based on energy balance and ideal gas relations is performed using pmp to assess the criticality under the following conditions:

- ullage pressure at MECO: 200 kPa
- ullage volume of the LH2 tank #2 at MECO: 59.5 m^3
- Assumption that the tank wall in contact with the ullage gas has exactly ullage temperature and that this stored heat can be potentially released to the fluid. Then the maximum heat stored in the Al2219 tank wall @ 93 K resp. 15 K fluid temperature is 39.6 MJ.
- variation of heat amount transferred to fluid in thermodynamic simulations as percentage of wetted surface and duration of heat-release
- No venting options are considered in this analysis although venting might considerably counter the pressure build-up.

The blue line in Figure 11 represents the theoretical case of reentry flight in which the liquid hydrogen remains "frozen" in its cold aft position. Then only outside reentry heat is transferred into the tank (approximately 15 MJ) but no heat is released from the hot wall itself. The ullage pressure increases to about 245 kPa in approximately 400 s.

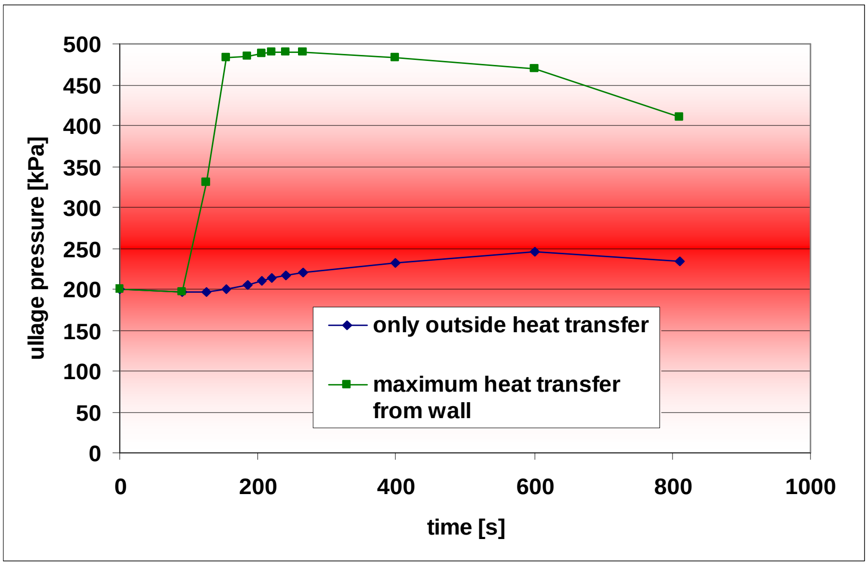

Figure 11: Ullage pressure for different amounts of heat transfer wall to fluid (aft LH2 tank#2)

If in the simulation the total heat-transfer to the LH2 fluid is sharply increased by 37.2 MJ in no more than 30s, the maximum ullage pressure rises by 120 % to 482 kPa (represented by the green line in Figure 11). This simulation is assumed as a worst case because almost the full amount of stored heat is discharged in a short time. The two lines in Figure 11 might be interpreted as the lower and upper bounds of the uncontrolled pressure rise inside the aft tank during reentry. The actual heat release should generate a pressure profile between these lines.
In the worst case the total vaporized LH2 up to the turbofan ignition might rise by 92 % (compared to no heated wall effect) to a total of 92.8 kg. Although this number is well below the available fly-back reserves it is important to carefully take into account these potential losses.

4 Launcher System Considerations and Payload 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. This trajectory has to respect certain constraints, which are close to those of today's Ariane 5 ECA 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 are listed in Table 4. The dry mass incorporates the results of the detailed structural and subcomponent analyses. The separated satellite payload mass in double launch configuration exceeds 12.3 Mg. The fully cryogenic launcher (boosters, core, and upper stage) is able to deliver almost 2 % of its gross lift-off mass into GTO.

Table 4: Characteristic mass data of the Y-9 LFBB launcher with Ariane 5 core stage in GTO mission

	kg
LFBB dry mass:	**46200**
LFBB inert (MECO) mass:	**54000**
GLOW LFBB mass:	**222500**
GLOW launcher mass:	**698850**
GTO payload mass (multiple launch):	**12330**
GTO payload mass (single launch):	**13140**

All presented data result from an iterative design loop, reflecting the DLR-SART design principles. The ascent trajectory data sets are fully consistent with the corresponding descent and fly-back trajectories. A quasi-optimal return trajectory is found by parametric variation of the initial banking maneuver [13]. 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 [13] 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.

Including 30% fly-back fuel reserves to take into account possible adverse conditions like head winds, the booster needs about 3.65 Mg hydrogen for its more than one hour return leg. The trimmed hypersonic maximum lift-to-drag ratio reaches a value of about 1.6. In the low subsonic and cruise flight regime trimmed L/D is around 5.5 as has been verified by windtunnel tests.

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. Such a roadmap is proposed in references [4], [5].

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 [4]. 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 [4].

Five LFBBs are able to accelerate a super heavy-lift launcher 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 [4]. 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.

5 Conclusion

Technical investigations on a partially reusable space transportation system with reusable booster stages, attached to an advanced future derivative of the expendable Ariane 5 core stage, demonstrate the feasibility of several promising design features. The fully cryogenic launcher is able to deliver between 12300 and 13100 kg of payload into GTO depending on the choice of a multiple or single launch configuration.

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 exploited for the RLV assembly. A preliminary design of the structures, major subsystems, and all propulsion systems has been carried out.

The four different propulsion systems have been extensively investigated with the following results: A high thrust gas-generator cycle engine with small throttling range seems to be sufficient for the partial-RLV-application. An existing military turbofan for fly-back can be adapted by low risk modifications to hydrogen fuel, enabling a significant MECO mass advantage. Storage of this hydrogen in partially filled tanks during reentry could become a challenge, but engineering analysis shows manageable conditions. Taking into account cost considerations, oxygen gas is currently selected as the preferred pressurant of the LOX-tank because its payload drawback is miniscule. The environmentally friendly combination of oxygen and ethanol is the RCS propellant baseline.

The ASTRA investigation gives evidence that a semi-reusable launcher is a robust and flexible space transportation system. All applied technologies of the LFBB-RLV are well within reach in the next 10 years. Cost analyses show the specific transportation costs of this launcher to be attractive and the development expenses to be the most affordable of all proposed future reusable launch vehicles in its class. The reusable booster stage can be further 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.

Acknowledgements

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