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Semireusable Launch Vehicle: A Next-Generation Launch Vehicle?

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Advanced launch systems studies are ongoing at MAN Technologie AG, Karlsfeld, Germany, contributing to a broader European effort that is examining options for the next space transportation system to be developed there. One promising candidate that uses medium-term technologies is a vertical takeoff semireusable launch vehicle featuring a reusable booster and an expendable core stage. The dedicated design of fully cryogenic stages enables the launch vehicle concept to bring up to geostationary transfer orbit a payload mass of up to 10 Mg and a low-Earth-orbit mass of 20 Mg. The total liftoff mass is about 520 Mg. This launch vehicle concept proposal could culminate in a fully reusable launch vehicle, a booster and an orbiter stage, for Europe in the long term. The status of the studied launch vehicle concept is summarized. The design features and trade topics leading to the semireusable launch vehicle concept are shown. The selected semireusable launch vehicle is presented as a viable interim step between existing expendable launch vehicles and fully reusable launch vehicles.

Nomenclature

a	=	acceleration, m/s^2
g	=	Earth gravitation, 9.81 m/s^2
H	=	altitude, km
Hx	=	cryogenic propellant mass, Mg
$H10.3$	=	Ariane 4 upper stage
R	=	range, km
T, t	=	time, s
v	=	velocity, m/s
x, y, z	=	x, y, z direction
γ	=	flight-path angle, deg
Δv	=	velocity increment, m/s

Subscripts

dyn	=	dynamic
max	=	maximum
r	=	relative

Introduction

EUROPE is about to implement its newest launch workhorse, the Ariane 5, into operation. The launch vehicle was initiated, designed, and produced in the competition tradition of Ariane 1, Ariane 2/3, and Ariane 4. Further specific cost-saving measures are on the way to improve Ariane 5's future competitiveness. As part of the European Space Agency (ESA) has run the Future European Space Transportation Investigation Programme (FESTIP) and initiated the Future Launcher Technology Programme (FLTP).[1] Both programs are driven by one key question: Which is the most promising launch system for Europe after Ariane 5? In this sense, activities are focused on further reducing specific launch cost of space transportation to be competitive in the future commercial market.

As part of these efforts, MAN Technologie AG, Karlsfeld, Germany, initiated an in-house study, "Liquid Fly-Back Booster for Post-Ariane 5 Era." For more than a decade, MAN Technologie AG has investigated expendable and reusable launch vehicles and dedicated technology areas. "The European Advanced Rocket Launcher Study 2," which refers back to the "Future Launcher Study," is only one example of these efforts.[2,3]

This paper is concerned with an always-present question: Could a semireusable launch vehicle (SRLV) be the next step for Europe? The paper has the following objectives: 1) establishment of a reference concept for detailed system analyses; 2) system design and operational analyses; 3) identification of relevant technologies with respect to availability, schedule, cost, and other alternatives; 4) estimation of program cost; and 5) detailing a development program schedule.

Requirements, Constraints, and Design Rules

The governing study item was to substitute the existing solid rocket booster of Ariane 5 by a liquid fly-back booster (LFB) stage and to analyze its impact on the core stage, as well as its design and performance capabilities. This leads to the application of the expected Ariane 5 mission scenario in 2005 and beyond for geostationary transfer orbit (GTO). The major system requirement is therefore to transport a 10-Mg payload in a double launch mode into a GTO with 7-deg inclination. Further important items are as follows: 1) launch and landing site: Kourou, French Guiana; 2) use of proposed or existing components and stages of Ariane; 3) application of Ariane design rules; 4) use of proposed or developed rocket engine performance; 5) use of European rocket hardware production; 6) launch rate: 24 launches per year; and 7) launch cost reduction by reusability of the LFB.

As numerous space transportation system (STS) studies have shown, a well-stated, dry mass margin; propellant residual; and reserve approaches are key items for a successful vehicle design. In the case of the LFB, dry mass margin of about 15% is applied, emphasizing a conservative design approach. The propellant residuals were used between 1 and 2% of the propellant mass. The propellant reserve is usually 1.3%. For the LFB fly-back only, kerosene (24% or 2.5 Mg) is included to cover uncertainties in engine performance, vehicle aerodynamics, headwinds, landing procedures, and emergency approach.

This paper study follows a double-design-loop approach. First, study loops produce a convergent vehicle design according to layout, mass properties, propulsion, aerothermodynamics, performance, and stability. This interim design will be further detailed with respect to operations, demonstration, development, and cost in the second loop. Afterward, a final design leads to the proposed Ariane LFB STS.

Conceptual Vehicle Analyses and Design

STS System Trades and Sensitivities

The overall launch vehicle trades were driven by variable core stage mass Hx and the reusable LFB mass. Trades were performed with respect to propellant, engine performance inclusive nozzle

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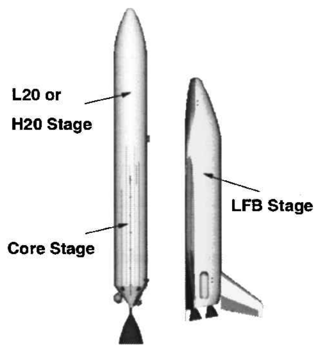

Fig. 1 Optimized SRLV stages.

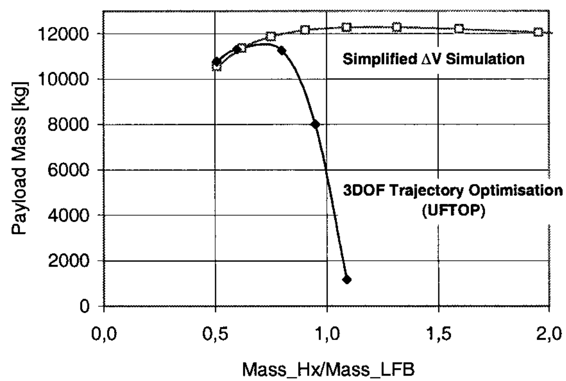

Fig. 2 Optimal staging between core stage and LFB mass with L20 upper stage (fixed liftoff mass of 520 Mg).

extraction for core stage, cross feeding, and structural mass models. In the case of the upper stage, only fixed versions of a storable L20 and a cryogenic H20 upper stage were considered (Fig. 1). Within an initial staging analysis, the optimal stage fraction between the core stage mass and the LFB mass were determined to 0.77.

Only a detailed trajectory analysis leads to this result, as shown in Fig. 2. A simplified Δv optimization does not include thrust or trim effects and is not adequate. Based on this vehicle model, the cross feeding between the LFB stage and the core stage leads to no significant performance advantage and is therefore not recommended.

At the end of these trade analyses, an LFB stage with a 210-Mg propellant mass and 65 Mg of inert mass and a core stage with 190 Mg of propellant mass and 22 Mg of inert mass were selected as key data to start further iterations.

A sensitivity analysis gave very important system trends. The upper-stage substitution of L20 with H20 leads to an additional 3.4-Mg payload. The nonconsideration of the high-performance engine (HPE) nozzle extraction design reduces the payload mass by about 1 Mg. Taking all of this into account, a total payload mass of 11.2 Mg can be used. In the case of a lower specific vacuum impulse of 10 s for all HPE engines, a payload reduction of 2.6 Mg has to be accepted. An additional 5-Mg inert mass of the LFB reduces the payload mass of 250 kg (5%), and a 1-Mg inert mass increase of the core stage would lead to a further 330-kg (33%) payload reduction. This is summarized as follows:

1) The use of the Ariane 5 core stage with upper stages looks very promising. The Δv potential of the present Ariane 5 core cryogenic stage is too low. Increasing the Δv of this core stage would enable reduction of the separation altitude and fly-back propellant, resulting in one medium-size LFB that fits in the core stage interface points, the front skirt, and the aft thrust skirt points.

2) The higher core stage Δv results in more propellant and/or higher engine specific impulse. For more propellant, a higher engine thrust is required. Viable thrust value is about 1700 kN and therefore a new rocket engine class without nozzle extraction is required.

3) Use of the HPE for both the LFB and the core stage simplifies the overall STS design, including development cost, and so one propellant combination, the cryogenic LO_2/LH_2, for both stages is proposed.

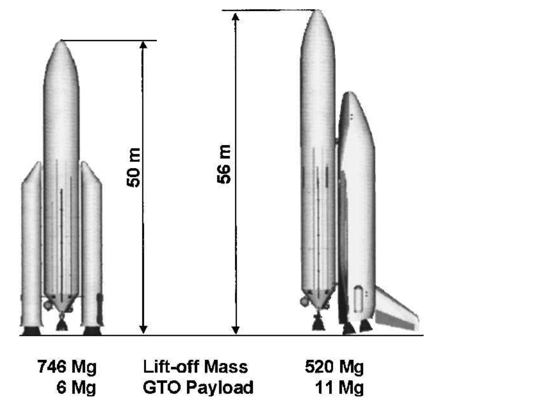

Fig. 3 Comparison of Ariane 5 (left) with Ariane LFB (right).

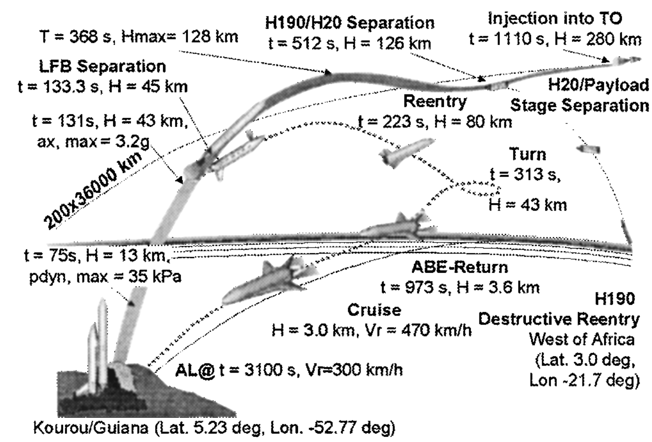

Fig. 4 Overall GTO mission profile.

4) An advanced cryogenic upper stage such as ESC-B brings additional performance delta, and so a new cryogenic upper stage with a 150-kN-thrust rocket engine is mandatory for high payload performance.

SRLV Reference Design

The Ariane LFB STS is an SRLV with a fully reusable LFB, an expendable core stage, and a cryogenic upper stage (Fig. 3). The core stage and the LFB are mated in parallel.

Five high-performance engines, one in the core stage and four in the LFB, lift the STS with 522 Mg gross liftoff mass. The liftoff acceleration is 1.35 g.

After stage separation, the LFB flies back to the Kourou landing site, and the core stage and the upper stage bring the 11-Mg payload into GTO. Compared to an improved Ariane 5 with a 54-m height, the overall STS height will increase to about 56 m.

Overall Mission Profile and Performance

The overall mission profile of the Ariane LFB consists of five major sections: mated ascent-inclusive separation, H190 ascent, H20 ascent-inclusive insertion, LFB flight, and H190 reentry-inclusive destructive impact. The major trajectory states are shown in Fig. 4. Overall analysis of all these phases, performed with UFTOP (Universal Flight Trajectory Optimisation Program) in three- and six-degree-of-freedom (DOF) mode, leads to a convergent profile.

As shown in Fig. 5, the maximum axial acceleration can be limited to 3.2 g with 0.5 g normal acceleration along the whole ascent trajectory. At $t = 130$ s, the design case for the stage attachment and stage interfaces structures is reached.

The main focus of the mission profile is the stage-separation interface. It dominates not only the following ascent core-stage ascent trajectory and its impact area, but also the fly-back trajectory and therefore the whole LFB design. In the present case, the stage separation takes place at an altitude of 45 km, dynamic pressure of 2580 N/m^2, relative velocity of 1530 m/s, and $M4.6$.

Table 1 LFB geometrical data

Parameter	Value
Fuselage length	38.0 m
Maximum fuselage width	5.4 m
Maximum fuselage height	5.8 m
Wing span	21.0 m
Aerodynamic reference area	342.0 m^2

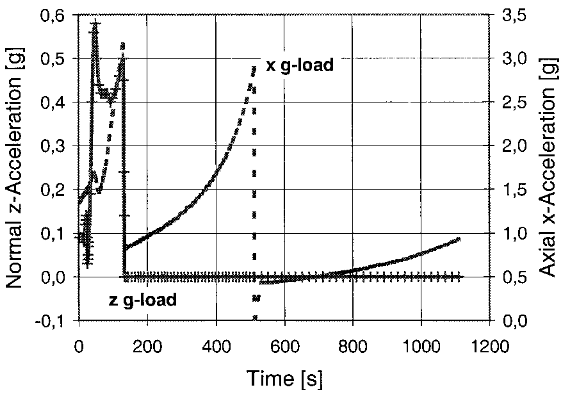

Fig. 5 Nominal ascent accelerations.

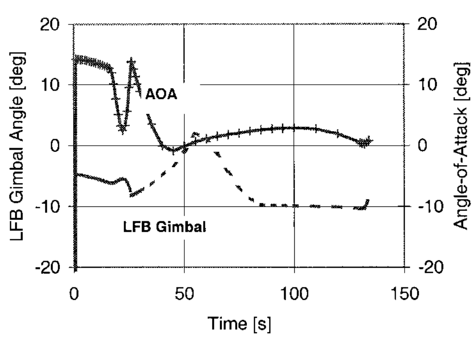

Fig. 6 Nominal ascent AOA and gimbal angle.

This dedicated, low separation altitude significantly reduces the design challenges for the LFB. One consequence is the maximum cruise distance: 270 km to Kourou. The maximum reentry altitude is about 80 km and represents the design driver for the attitude control system (ACS). The maximum reentry heat flux will not exceed 62 kW/m^2 in the stagnation point.

One specific performance and flight control issue is the vehicle trim via (TVC) of the LFB engines in the mated ascent phase. Figure 6 shows the gimbal angle histogram, which is between 3 and −10 deg. As a result of expected high aerodynamic loads, the angle-of-attack (AOA) constraint is between ±5 deg in a high-pressure regime. These curves show very comfortable flight states during the whole mated ascent.

Another important aspect is the abort capability of the LFB in case of malfunction of the core-stage HPE. Results indicate that the nominal separation conditions, such as maximum altitude and dynamic pressure, can be reached. The analyzed AOA and gimbal angle are comparable with the nominal ascent constraints. These conditions make safe separation and recovery of the LFB in case of a core-stage engine abort more feasible.

LFB Design

Figure 7 shows the configuration of inclusive subsystems of the reusable LFB. As a result of sensitivity analyses, no propellant cross-feeding devices are considered in the proposed design. Choice of vehicle shape is influenced by the need to use simplified surfaces to reduce manufacturing costs. The aerodynamic configuration was developed using design guidelines derived from the space shuttle and similar vehicle design data.

The LFB configuration (described in Table 1) is a double-delta wing–body design that uses a control-configured design approach.

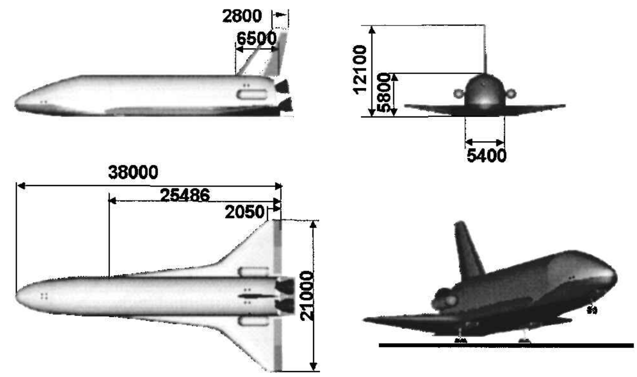

Fig. 7 LFB configuration data; millimeters.

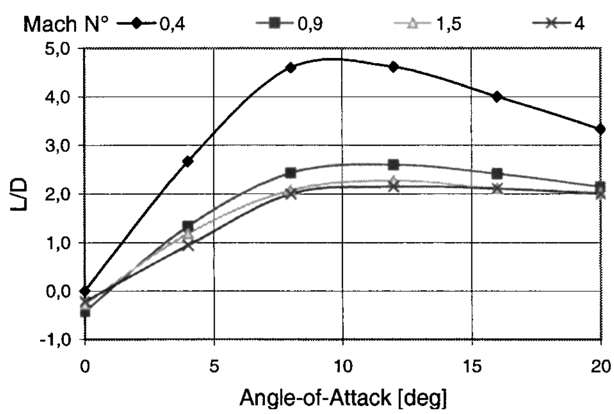

Fig. 8 LFB trimmed lift-to-drag vs AOA.

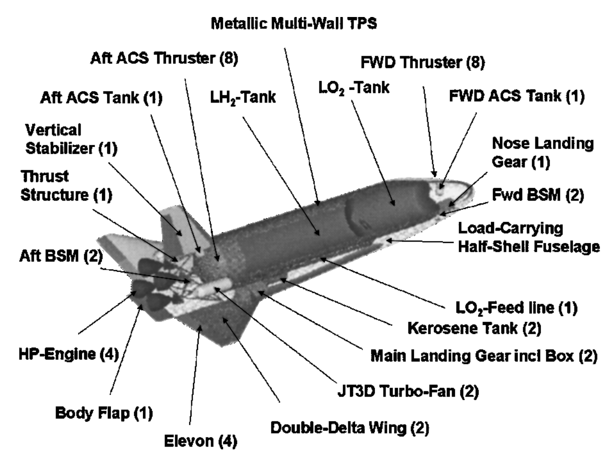

Fig. 9 LFB major subsystems.

The wing was sized for landing. The corresponding wing loading is 165 kg/m^2, with 300 km/h landing speed. The planform area was selected for hypersonic trim and to provide sufficient span to achieve the desired subsonic lift-to-drag ratio of 4.5 for fly-back and landing (Fig. 8).

A very significant design parameter is the base drag, which is about 0.5 at M 0.4 for the LFB configuration. This design parameter is mainly dictated by the truncated aftbody cross section and the turbofan engines.[4] It dramatically influences the turbofan engine design and the fly-back propellant, which are significant design criticalities.

A first subsystem design analysis was performed on the parts shown in Fig. 9. The major objective of this activity was to determine the design and location of the center of gravity (COG) in the different flight regimes. Based on the subsystem location in Fig. 9, a COG of about 68% of the vehicle length can be confirmed and fulfills the aerodynamic stability requirement.

The propellant tank design, like the 5.4-m-diam core stage, is a common manufacturing feature. Because of the low thermal loads, the LFB can be designed as a heat-sink metallic structure (metallic

Table 2 Key data of the high-performance engine[5]

Parameter	Value
Maximum vacuum thrust	1720 kN
Specific vacuum impulse	451 s
Mixture ratio	6.6
Chamber pressure	245 bar
Diameter	1.987 m
Length	3.294 m
TVC angle	±10 deg
Mass	2530 kg

Table 3 Key data of JT3D-3B air-breathing jet engine (ABE)

Parameter	Value
Maximum static thrust	80.1 kN
Specific fuel consumption	15.14 kg/(s · N)
Mass flow	1.21 kg/s
Length	4.2 m
Diameter	1.4 m
Mass	1950 kg

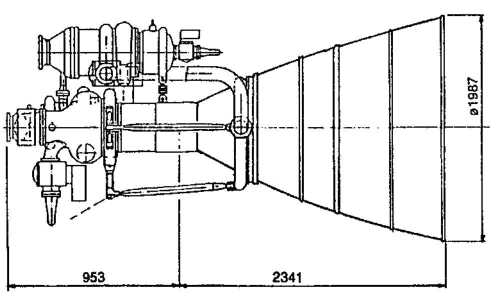

Fig. 10 HPE for the LFB.[5]

multiwall). This avoids the need for a tile thermal protection system (TPS), which reduces maintenance costs. Except for the wing leading edges, nose cap, elevons, and aft bulkhead, the LFB is an all-aluminum structure. Titanium is used on the wing leading edges, elevons, and nose cap. Carbon-silicon-carbon composite (CSiC) material is used for the body flap and aft bulkhead because of the plume-recircularization heating environment.

The rocket engine design is based on a progressive engine development outlook in Europe toward HPE technology (Fig. 10). The staged combustion cycle approach uses LO_2 and LH_2 with a mixture ratio of 6.6. This design was proposed in the FESTIP study[5] and is used here as baseline. The key data are summarized in Table 2.

A realized comparable rocket engine of this technology class is the Russian RD-0120 for Energia.[6] With a vacuum-specific impulse of 455 s, a thrust of 1990 kN, and a chamber pressure of 218 bar, it is a model for staged-combustion-cycle engine development in Europe. Recent work discussed in Ref. 6 considered the reusability aspects and foresees a potential of 100 missions of mean time between overhauls. According to the drag profile at $M0.45$, two Pratt and Whitney Aircraft JT3D-3B turbofans[7] (United Technologies Corporation) (Table 3), as used in Boeing C, KC-135E airplanes, cover the fly-back requirements of 150-kN engine thrust. The required 7.5 Mg of kerosene is loaded in two cylindrical tanks near the fuselage bottom section and the expected 68% COG location to realize a neutral trim position.

On the basis of the presented design and analyses, the LFB mass budget described in Table 4.

H190: Core Stage

The core stage design is derived from the present Ariane 5 EPC design experience. Nevertheless, essential design changes have to be realized to come up with the improved H190 stage. Major issues are 1) additional 20 Mg of ascent propellant, which leads to an additional 2 m of stage length; 2) asymmetry of the load path LFB/H190; and 3) change of the main load path from the front skirt to the aft thrust

Table 4 Mass budget for the LFB stage

Parameter	Mass, kg
Aerodynamic surfaces	5,795
Body structure	13,414
Launch and recovery systems	2,424
Induced environment protection	2,434
Rocket engines	11,994
ABEs	4,713
ACS	1,665
Power supply	1,976
Avionics	860
Design reserve	6,791
Dry mass	52,048
Residual propellant	2,443
ABE fuel, reserve and residual	1,900
Reserve AOCS	117
Landing mass	56,508
ACS propellant	1,155
ABE fuel	5,578
Reentry mass	63,241
In-flight losses	945
Reserves, main propellant	0[a]
Main ascent propellant	207,000
Total liftoff mass	271,186
Launch pad propellant	3,078

[a]Considered in the core stage budget (see Table 5).

Table 5 Mass budget for the core stage H190

Parameter	Mass, kg
Structures	13,170
Rocket engine (HPE)	2,530
Avionics	439
Design reserve	787
Propellant, residual, reserve, and losses	5,028
Main ascent propellant	190,000
Total liftoff mass	211,954

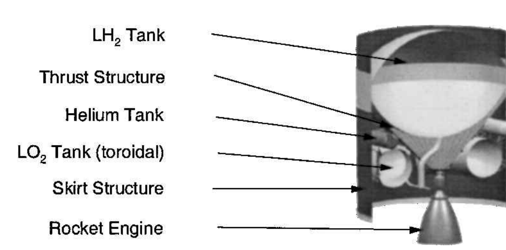

Fig. 11 Cryogenic upper stage (ESC) design.[8]

skirt of the H190. The two latter will lead to a further 1.5 Mg in structure mass.

The new stage design comprises the mass budget described in Table 5. This mass estimate is based mainly on the use of aluminum and in some areas of CFRP materials.

H20: Cryogenic Upper Stage

The LFB study started with an improved L20 upper stage with storable propellants derived from the Ariane 5, the L9 stage. But in-house activities[8] and present design work on a European cryogenic upper stage (ESC) encouraged the study team to go along with the cryogenic approach. A design option with a toroidal LO_2 tank is shown in Fig. 11.

The assumed cryogenic engine thrust is 150 kN and 460 s specific vacuum impulse, which are in line with the proposed Ariane 5 upper-stage engine (Vinci).

A first design analysis of the upper stage leads to the mass budget shown in Table 6. Compared with other realized ESCs, the H20 design is between the Titan III mass data and the newly proposed European cryogenic upper-stage ESC version A (ESC-A) (Fig. 12). The present mass discrepancy between ESC-A and H20 of about 1.5 Mg is within the performance overshoot of the LFB system and

Table 6 Mass budget for the upper stage H20

Parameter	Mass, kg
Structures	2,750
Rocket engine and system	500
Avionics	100
Propellant, residual, and reserve	450
Design reserve	380
Mass	4,180
Vehicle equipment bay	1,150
Main ascent propellant	20,000
Liftoff mass	25,330

Table 7 Ariane 5 launch vehicle cost elements

Element	Cost, %
System	3
Fairing	4
Speltra	3
Storable propellant stage	5
Vehicle equipment bay	8
Core cryogenic stage	31
Solid rocket stage	42
Diverse	4
Total	100

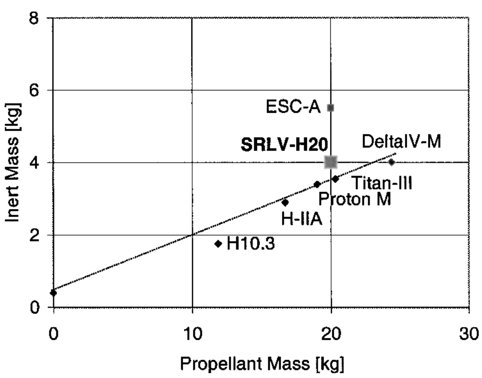

Fig. 12 ESC mass in comparison.

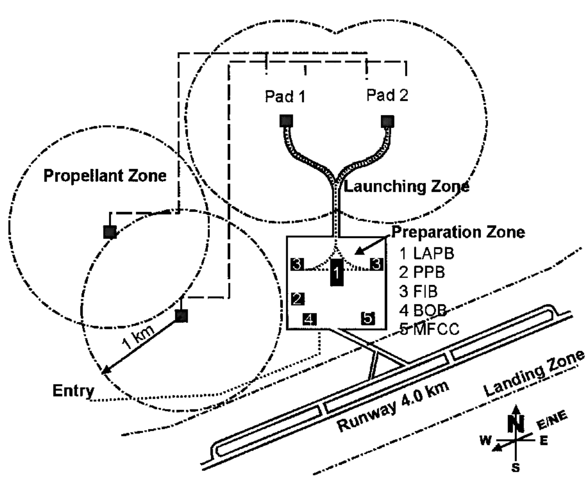

Fig. 13 General zone arrangement at Kourou, French Guiana.

therefore represents an additional design margin. On top of the upper stage is the fairing structure with 2014 kg mass, which protects the payload against aerodynamic, acoustic, and thermal loads. It will be jettisoned at an altitude of 110 km.

Ground Facilities and Operations

The principal ground facility scenario is based on four zones: preparation zone, propellant zone, launch assembly, and landing zone. Their locations are shown in Fig. 13, and they are influenced by the 1-km safety distance requirement.

The central building of the preparation zone is the launcher assembly and preparation building (LAPB). Here the Ariane core stage is assembled and prepared for mating. In parallel mode, the LFB is maintained, erected, and mated with the expendable core stage. The SRLV composite is then transferred to the launch table in the final integration building (FIB). The payloads are prepared in the payload preparation building (PPB) and, after transfer to the FIB in a cleanroom container, they are integrated onto the launcher. After final checkout, the launcher is transferred to the launch pad and fueled from a stationary umbilical building and then is launched.

The LFB landing on the 4-km runway is under mission flight control center (MFCC) authority. Afterward the LFB is brought to

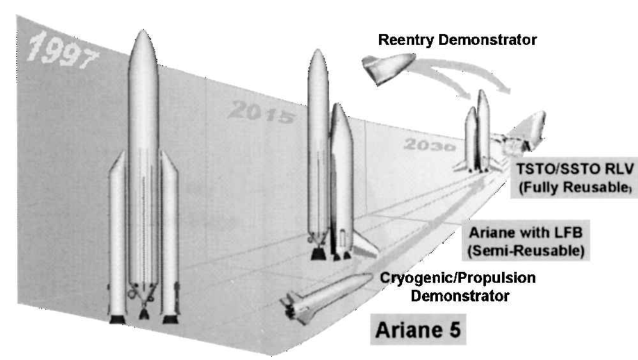

Fig. 14 Programmatic outlook for the Ariane LFB.

either the LAPB for on-line refurbishment and maintenance or the booster overhaul building (BOB) for off-line refurbishment. All proposed facilities can be established with state-of-the-art means, and they can ensure high mission flexibility with this parallel turnaround approach.

Technology, Development, and Cost Views

The Ariane LFB STS is based on several key technological areas: 1) a reusable cryogenic tank with CFRP cold structures, 2) reusable external and internal cryogenic tank insulation, 3) a LO_2/LH_2 HPE with 250 bar chamber pressure in stage combustion cycle design, 4) nondestructive inspection technology (health monitoring), and 5) fully autonomous reentry, turn, cruise, and landing capability.

An option, how to realize such an development effort via demonstrators, is shown in Fig. 14. The dedicated LFB demonstrator can be designed to demonstrate the key technological areas. The demonstrated in-flight reusability aspects are the most important features. At the end of a demonstration phase, in about 2007, semireusable two-stage-to-orbit (TSTO) development should be well defined. A dedicated reentry demonstrator for hot reentry will not be necessary for the semireusable TSTO but is mandatory for the development of a fully reusable STS.

The launch cost potential of the Ariane LFB concept, which is typical for an SRLV, can partially be derived from the present Ariane 5 cost structure. The main cost elements are shown in Table 7. About 60% of the launch cost comes from the launch vehicle itself.

The other 40% of the cost is due to risk reserves, ground operations, and the launch vehicle operator. A breakdown the launch vehicle cost shows that about 60% belongs to core stage, upper stage, and other payload-related cost items. These costs can be compared to a derived H190 inclusive the upper stage. The other 40% is the maximum cost-saving corridor for a reusable LFB.

Taking into account the overall launch cost structure, the maximum cost-saving potential will be only 25% compared with an Ariane 5 launch. First cost analyses showed the LFB maintenance and refurbishment cost will optimistically reduce the 25% savings to 15%, if aircraftlike operations are assumed. These SRLV launch cost items will add up to an overall launch cost minimum of 85% of today's Ariane 5 launch.

Conclusions

The study results for the SRLV showed a highly promising space transportation concept with a significant performance potential.

With a gross liftoff mass of 522 Mg, the LFB system delivers about 11 Mg of payload into a GTO of 200 × 36,000 km with 7-deg inclination. Taking into account the described launch cost saving of maximum 15% compared with today Ariane 5 launch, the answer with respect to the next STS step for Europe is yes. This step also Europe's broadens outlook for high-performance rocket engine development and reusability structures and operations. Compared with development of a fully reusable TSTO launch vehicle or single-stage-to-orbit vehicle, this SRLV represents only a moderate risk for STS development.

Confronting the SRLV concept with a specific launch cost reduction requirement by a factor of 10, this launch vehicle type cannot be recommended as a next STS step for Europe. The nonreusable cost items dominate in the final cost tables. Only further study with respect to operations, technology, development, and cost can improve the final recommendations. This can be a driving task in Europe's Future Launcher Technology Programme.

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