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A liquid reusable strap-on booster system discussion for future European launch vehicles

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Abstract
A liquid reusable strap-on booster for a future launch-vehicle concept is discussed and benchmarked against an equivalent solid strap-on booster launch vehicle system design. Therefore, a reference vehicle, equipped with solid strap-on boosters, is established to fulfil certain aspects of current European space transportation needs. Those solid boosters are subsequently replaced by a liquid LOX/LCH4 reusable alternative. Both launch vehicle concepts are compared and evaluated from perspective of current R&D activities, environmental impacts and future needs.

1. Introduction

The European independent access to space is currently guaranteed by the Ariane and Vega program. European launch vehicle start-ups have emerged for some time, however not yet demonstrated spaceflight capabilities. Global competition of the to-space transportation market has intensified with further new and established player and with strong focus on reusability. Additionally, the importance of sustainability demands the reduction of spaceflight's environmental impact.

A major driver to ensure competitiveness and independency is continuously improvement. Improvement of materials, technologies and how to approach challenges. Regarding European launch vehicle systems, these topics are currently promoted mainly by several ESA, EU and private funded projects and programs. For future European heavy lift of launch vehicles first studies, concepts and research-program results have already been published by various suppliers, space agencies and system primes indicating a technology focus toward liquid oxygen (LOX) / liquid methane (LCH4) propulsion systems and reusable stages. [1]

MT Aerospace AG (MTA), as a leading European supplier for aerospace technology and hardware, is always aspired to contribute towards the European space transportation´s future. Therefore, MTA continuously pursues a better understanding of potential future launch vehicle system and system prime needs. Hence, a potential prospective and coherent application case shall be identified to investigate and study.

One focal point of the above-mentioned published studies for future European launch vehicle systems are liquid reusable strap-on boosters (LRB). Considering existing company heritage and recent research activities, potential design concepts and use cases of those LRBs shall be elaborated and discussed.

A reference launch vehicle, equipped with solid strap-on boosters, is established to fulfil certain aspects of current European space transportation needs. Those solid boosters are subsequently replaced by a liquid LOX/LCH4 reusable alternative. Both launch vehicle concepts are compared and evaluated from perspective of current R&D activities, environmental impacts and future needs.

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2. Solid Rocket Motor - Reference Vehicle

The reference vehicle is based on available European launch vehicle technology. The core-stages propulsion system relays on LOX/LH2 technology with aluminium structures and structural tanks. No vehicle optimization is done, as the focus is on exchanging the strap-on booster stage. Fundamental propulsion parameters of the reference vehicle are presented in the table of Figure 1 below.

SRB Configuration		
Upper Stage: LOX/LH2		
	F_{max}=	180kN (vac)
	I_{SP}=	450s (vac)
Main Stage: LOX/LH2		
	F_{max}=	1370kN (vac)
	I_{SP}=	430s (vac)
SRB		
	F_{mean}=	3000kN (vac)
	I_{SP}=	280s (vac)

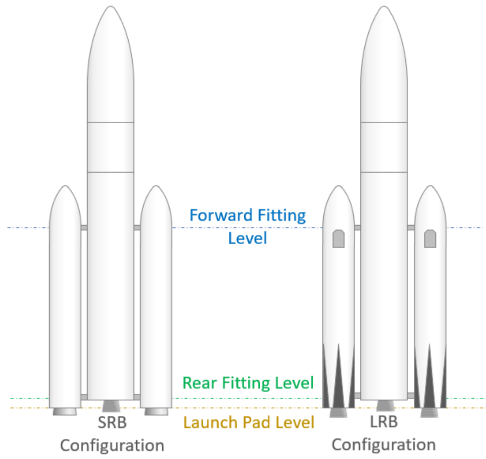

Figure 1: Reference SRB launch vehicle with major stage propulsion parameter (table left) and main interface level shared between each configuration (level indicator right)

Main function of the reference SRB vehicle configuration is to provide a comparable baseline payload performance and main interface levels between the main-core and strap-on booster as well as main-core and launch-pad. Figure 1 above displays those levels which are applicable for both configurations.

3. Liquid Reusable Booster

Besides fulfilling the two major topics of eco-friendly propellants and system reusability, the design of a liquid reusable strap-on booster for future European launch vehicles has to fulfil several high-level requirements to cope to the needs of the European and global space market. The defined requirements set a first baseline for the further development of the individual systems located within the booster to guarantee the applicability of the design with European launcher vehicles and attractiveness to customers. For each of the systems located within the whole booster system various options exist and system trade-offs have to be performed in order to determine the best solutions. Within this paper only exemplary trade-offs are presented, but a similar process is performed for each individual subsystem contributing to the booster's flight.

3.1 High-Level Requirements

As basis for the LRB system design, a set of high-level requirements is defined to enable an application of the booster with the reference vehicle configuration. These requirements are provided in Table 1.

Table 1: High-Level Requirements of Liquid Reusable Booster

#	Title	Detail
HLR-01	Provide adequate performance based on SRB configuration	The LRBs performance shall be comparable to the SRB mission envelopes regarding payload mass and target orbits

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HLR-02	Utilize the same mechanical connections as for SRB configuration	The LRB shall be able to use the existing hardware I/F on the main stages to avoid large impact on general vehicle design
HLR-03	Utilize PROMETHEUS rocket engine	The usage of PROMETHEUS engine (LOX/LCH4) (under development) for all main engine/thrust needs is mandatory
HLR-04	Reuse flight hardware	The LRB shall be reusable under consideration of specific and limited refurbishment activities for a minimum of TBD flights.
HLR-05	Launch from same launch pad as SRB configuration	The LRB version shall be launched from same modified launch pad as the SRB configuration. Modifications allowed.
HLR-06	Safe Landing	The LRB shall land controlled, precisely and safe with legs

3.2 Concept of Operations

As part of the initial development process, the system's concept of operations (ConOps) is elaborated. It considers the operational aspects of integration, test, launch and disposal or reuse [2]. Development and production of hardware details, including logistic operations during assembly, integration and test (AIT), will be investigated in a subsequent study loop. The phases of the potential LRB ConOps are shown in Figure 2 below. It begins with the AIT activities required for the nominal operation of the LRB. Within this step, newly manufactured parts are joined to subassemblies prior to the integration in the complete system together with the refurbished booster subassemblies and tested to guarantee the correct functioning of the booster. These steps are followed by the launchpad operations to prepare the liftoff and the mission of the booster until the landing is completed. The flight of the booster after separation is not detailed because it depends on the selected landing site. Within the Post-Launch activities, the required steps for a refurbishment are detailed beginning directly after the touchdown at the landing site without further detailing the level of inspection and refurbishment activities because the extend of refurbishment required for re-using the booster is not detailed at the moment. After successful refurbishment, the refurbished subassemblies are reused for the integration in the LRB.

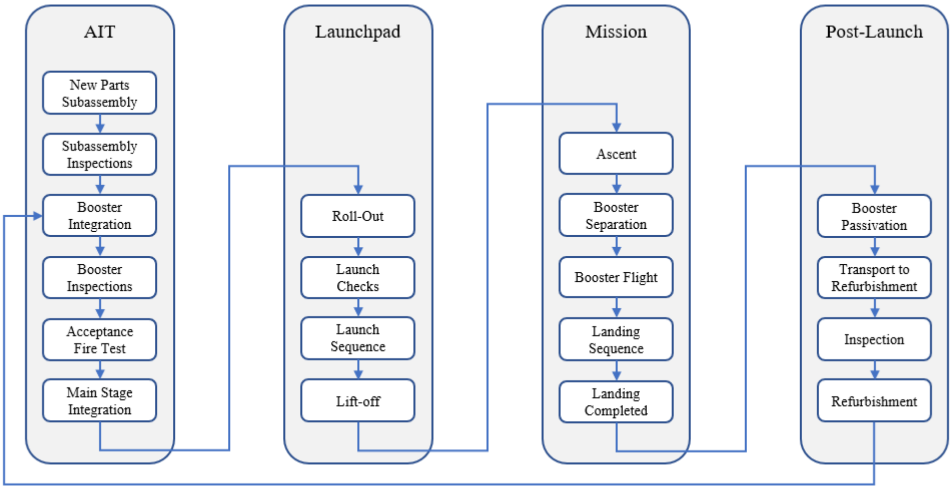

Figure 2: Potential ConOps of Liquid Reusable Booster.

3.3 System Breakdown

In comparison to a single use booster, additional systems have to be included for a LRB to control the flight after separation and provide a controlled landing. As a first step for the further detailed development, a system breakdown is created. This top-level breakdown in Figure 3 shows the relevant subsystems and their

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interactions without details such as sensors or actuators. The Prometheus engine itself is included as a separated subsystem except for the propellant feed due to the delivery as a complete system.

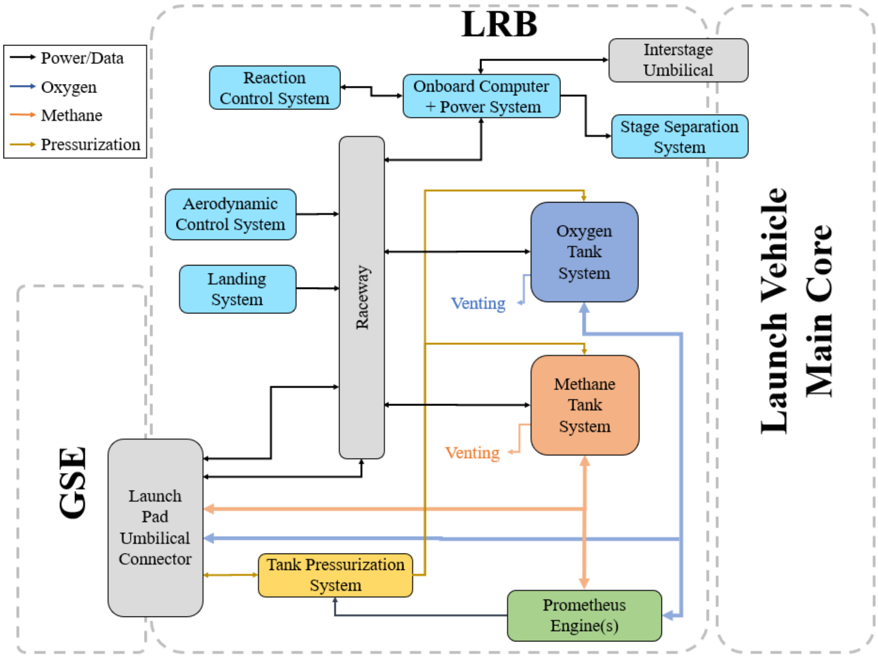

Figure 3: Liquid Reusable Booster System Breakdown

3.4 System Trade-Offs

The LRB design definition process compiles of various engineering loops to elaborate promising trade-offs to fit the above-mentioned requirements. Main target is not to identify the one most auspicious solution, but to discuss and evaluate different potential results toward various application capabilities. A future launch vehicle system is driven by a wide range of boundary conditions and therefore an adequate toolbox of feasible design-solutions is mandatory.

3.4.1 General LRB Vehicle Design

To reduce the mentioned wide range of boundary conditions within this investigation, preliminary design limitations for the LRB are made. Main focus here is on the general propellant tank concept, the multi-engine-bay (MEB) design concept and the main mechanical interfaces on the strap-on booster.

A) General Propellant Tank Concept

To store the maximized amount of propellent within the restricted envelope volume, a common-bulkhead tank design with internal feed lines is chosen as baseline. The vehicles forward dome is part of the main mechanical interface discussion below, the rear dome is outlined in the following MEB paragraph.

B) Multi-Engine-Bay

Respecting the SRB average thrust and available PROMETHEUS engine performance values [3][4][5] a rear-skirt section design to house three liquid engines (multi-engine-bay) is selected. The considered engine performances are shown as part of Figure 4 below.

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LRB Propulsion System	
Prometheus	
F_{mean}=	1200kN (vac)
F_{max}=	1440kN (vac)
F_{min}=	360kN (vac)
I_{SP}=	360s (vac)

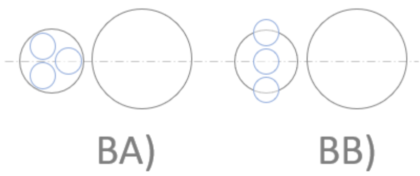

Figure 4: PROMETHEUS Engine Performance and Arrangement considerations

Based on the estimated geometrical size of PROMETHEUS and the restricted LRBs diameter of 3.5 m the engines arrangement presented in Figure 4 are discussed as following:

BA) Circular Positioning:

This positioning allows a more symmetrical load introduction towards the vehicles structure. Due to the arrangement potentially all three engines need to be fired during landing approach for sufficient stability. Even considering the engines proposed throttle capability the thrust-level is high above the expected LRBs net weight. The circular positioning of engines within this vehicle weight to thrust ratio is expected to be challenging.

BB) Linear Positioning:

This positioning is considered perpendicular towards the main-stage / booster axis and requires bulged cavities on the MEB to house the engines. A single, central engine firing may during landing approach is considered sufficient to decelerate LRBs net weight.

Beside the planar engine arrangement, the flight-axial positioning is an additional topic of interest. Repeating, a maximum propellant volume is mandatory. Figure 5 below illustrates potential MEB axial positioning in comparison to a SRB configuration baseline. A discussion follows subsequently.

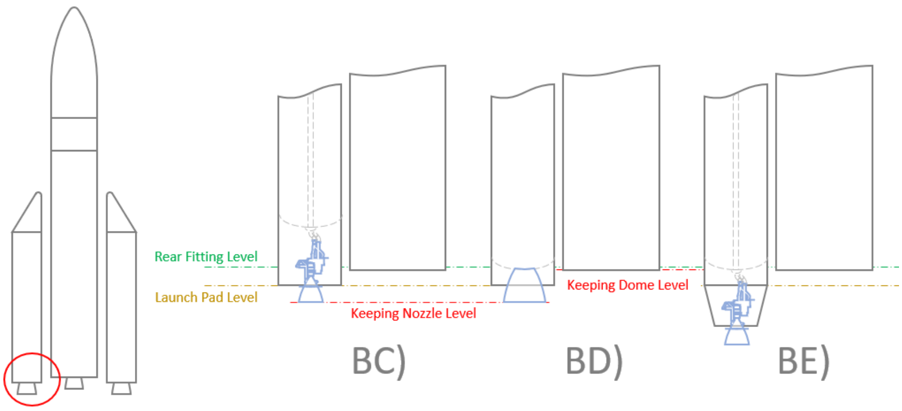

Figure 5: MEB flight-axial positioning

Taking the launch-pad level and HLR-5 (same launch-pad for SRB and LRB configuration) into account, two options are identified:

BC) Keeping Nozzle Level

Mechanical vehicle resting interface is identical for each configuration. Geometrical clearance below Pad-Level is also identical. Thrust force introduction point is similar, potentially shifted slightly upwards in flight direction. The envelope volume for propellant tanks is reduced, as the engine needs more space.

BD) SRB Configuration Baseline

Baseline for comparison.

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BE) Keeping Dome Level

Mechanical vehicle resting interface is identical for each configuration, potential design modifications are necessary on vehicle and pad side to allow sufficient bearing. Geometrical clearance below Pad-Level is reduced, therefore a cone shaped aft-skirt is considered to reduce impact. Thrust force introduction point shifted downwards opposing flight direction. The envelope volume for propellant tanks kept similar.

C) Mechanical Main Interface towards Main Core

The strap-on booster is considered to be mechanically connected to the main core via two interface points as shown in Figure 6. These are a forward fitting to introduce the major flight-axial loads towards the main stage and a rear fitting bearing mainly lateral loads. The rear fitting is considered to stay unchanged for both, SRB and LRB, configurations.

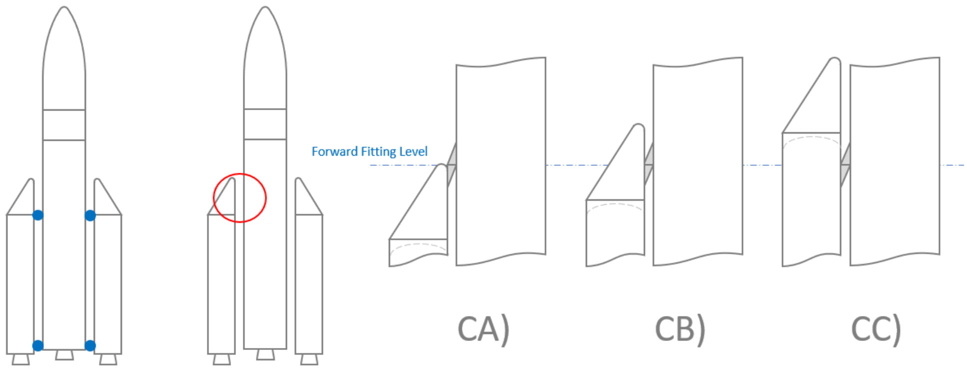

Figure 6: Strap-On Booster Mechanical Main Interfaces towards the Main-Stage

Potential forward fitting design variations are displayed in Figure 6 above. In all cases, the main interface position, the Forward Fitting Level, stays fixed on the main stages side. Three feasible solutions are discussed:

CA) Nose-Cone Cap

An interface position at the nose-cone cap level. Respecting cone shape and height, the smallest envelope volume for the propellant tank is given. Cone could allow a smooth transmission of general loads on the cylinder towards the cap without major local structural reinforcements.

CB) Intermediate / Elongated Forward Skirt

An interface position at an intermediate cone height or on an elongated forward skirt. Larger envelope volume for propellent tanks are given (in direct comparison with A) e.g.). Local structural reinforcements need to be considered, to transmit general loads from the cylinder towards the interface.

CC) Pressurized Tank

An interface position at pressurized tank level. Larges envelope volume for propellant tank possible. Flexible positioning in height. Complex local structural reinforcement within a pressurized, sealed tank is necessary. Depending on contained propellant component various design solutions possible, but challenging.

3.4.1 Tank System

Considering no main interfaces toward the main core within the pressurized and sealed tank compartment, the size of the tanks is limited by the required fitting positions, as introduced above. Within these constraints, the maximal amount of propellant shall be stored while simultaneously be capable to withstand the given load environment. To achieve this goal various design options are available. An overview of investigated design choices is shown in Table 2 providing a morphological box with potential combinations for selection.

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Table 2: Potential Design Options for the LRB Tank System

PARAMETER	**DESIGN OPTIONS**			
Material	Aluminium Alloys	Stainless Steel	Composites	
Tank Layout	Separated Tandem Tanks	Tandem Tank Common Bulkhead	Concentric Tanks	Multiple Tanks Parallel
Dome Geometry	Elliptical	Hemi-spherical	Cassini Curve Shape	Torispherical
Dome Segmentation	Single Panel	Multiple Panel		
Cylinder Panel Segmentation	Single Panel	Multiple Panel		
Structural Stiffening	Unstiffened	Stringer	Isogrid	Orthogrid
Propellant Line Positioning	Internal	External		
Tank Pressurization	Inert Gas Pressurization	Autogenous Pressurization	Self-Pressuri-zation	
Propellant Location	LOX Top	LOX Bottom		
	LCH4 Bottom	LCH4 Top		
Propellant Temperatures	No Gradient	Gradient		
Joining Method	Welding	Fasteners	Adhesives	

Beside others, the dome geometry is one of most impacting parameters, directly affecting the total tank systems mass. The following aspects are considered exemplarily:

- Primary Impacts
    - Total surface (best surface to volume ratio: hemispherical dome)
    - Discontinuities or high gradients in curvature (e.g. between constant radii and at the transition to the cylindrical section as for spherical cap geometries), which lead to an unfavourable stress distribution and / or negative hoop stresses
    - Thermal behaviour
- Secondary Impact
    - Dome height (directly determines the height and mass of potential adjacent structure)

Selecting non-hemispherical or non-elliptical dome shapes, the transient radius towards the cylinder shall always be respected. Some shapes may lead to a larger dome surface area, resulting into a larger dome mass, on the contrary allow weight reduction in the transient radius due to lower stress gradients within this transition regions.

Figure 7 displays a comparison of common dome shapes with an attached short cylinder section, standardized to a given height. A brief assessment addressing some key aspects are included in the figure.

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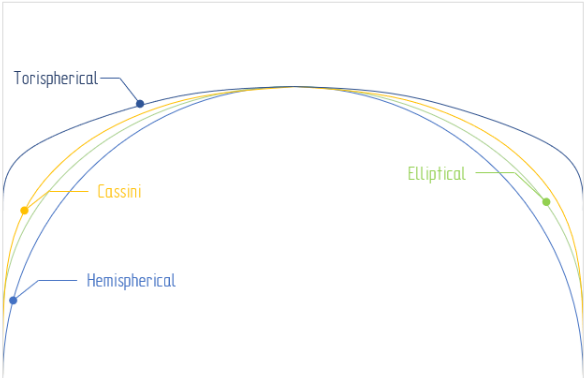

Dome Geometry	Elliptical	Hemi-Spherical	Cassini Curve Shape	Tori-spherical
Primary Mass Impact	Good	Very Good	Very Good	Medium
Secondary Mass Impact	Medium	Very Poor	Poor	Good
Stress Distribution	Medium	Good	Very Good	Medium
Length of Cylindrical Section	Medium	Short	Medium	Long
Total Length for eq. Volume	Medium	Long	Medium	Short

Figure 7: Dome-Shape Comparison

Tank materials are also in major focus during development. Mainly taking aluminium-alloys, stainless-steel or composites into account. Each material has advantages and disadvantages regarding e.g. raw-material costs, processability and material properties. Carefully chosen metallic materials increase their potential during low temperature applications such as cryogenic propellant storage. For reusable system, the life cycles load spectrum regarding damage tolerance analysis is from great importance. A short discussion about materials environmental impact is presented in 5.1.1 below.

3.4.2 Landing Leg System

The landing leg system respectively the landing leg (LL) consists of different components, which fulfil various tasks to guarantee a safe landing and the reusability of the launch vehicle. Various potential LL design configurations are investigated during several research activities. A selection of setup and deployment variations is shown in Figure 8. Verified by a kinematic assessment, the so called "tripod" configuration with one foldable or extendible primary and two rigid secondary struts shows most promising applicability. Additionally, a stability vs. mass analysis shows advantages of a four-leg system in comparison to a three-leg system. The three-leg system needs significant longer struts to ensure the same stability as a four-leg concept, resulting in a higher total mass.

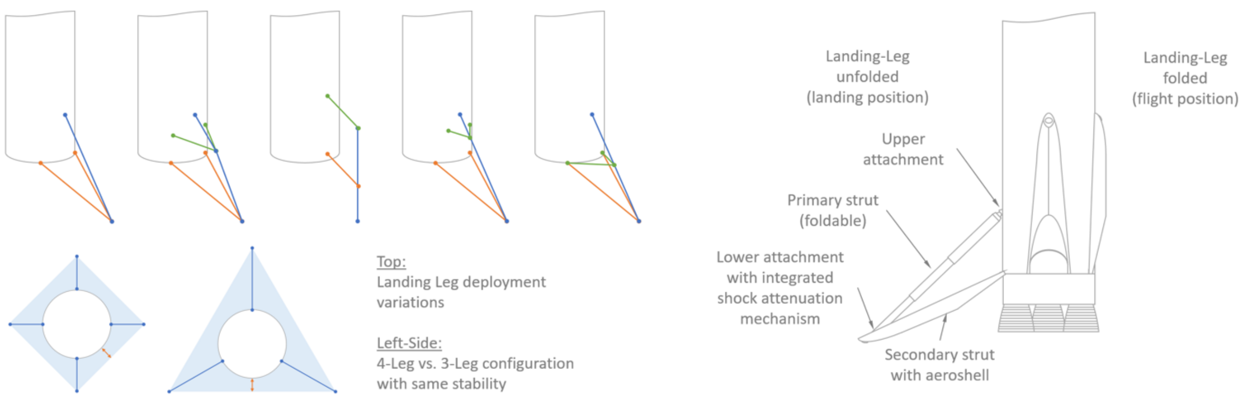

Figure 8: Investigated Landing-Leg configuration (left) and major components of a Landing leg (right)

The main components of the RETALT derived LL design configuration are the primary and the secondary strut made of CFRP, which sustain the loading during landing and flight. The lightweight struts are manufactured in automated fibre placement (AFP) technology and cured in an inhouse thermal vacuum chamber.

The shape of the secondary strut is designed by an optimized CFRP layup to carry the tension and torsion loading but also the integrated aerodynamic cover is designed to reduce the drag during ascend and to minimize the aerothermal loading during descend. Despite the optimal aerodynamic design of LL, a thermal protection system (TPS) is applied. For the low loaded regions, the TPS is not interchangeable but for high temperature areas a TPS patch system is installed, which can be changed in short duration and no cost intensive refurbishment is needed.

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To transfer the loading from the LL into the launcher vehicle, 3D printed additive manufacturing (AM) interfaces are installed. The deployment of the LL is realized by a semi-active pusher, which means the deployment is activated by an impulse and folds out under gravity until latching. [6]

3.4.3 Aerodynamic Control Surfaces

To control the booster´s return trajectory, aerodynamic control surfaces are considered. Various potential design solutions are already in focus of current research activities [7] or demonstrated in flight (see SpaceX Falcon 9). Derived from MTA´s RETALT contribution several concepts are investigated shown in Figure 9 below. For RETALT, the final configuration led to the planar-fin design, which was manufactured at MTA in 1:5 sub-scale with metallic and composite components including metallic AM manufactured parts. [6]

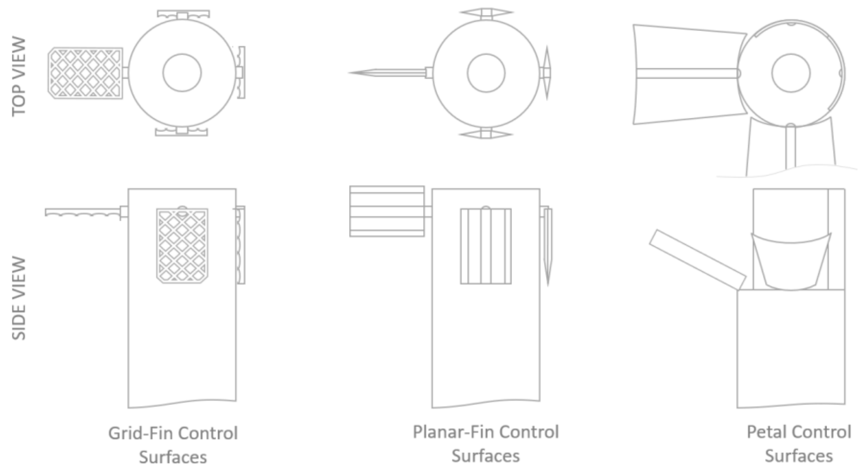
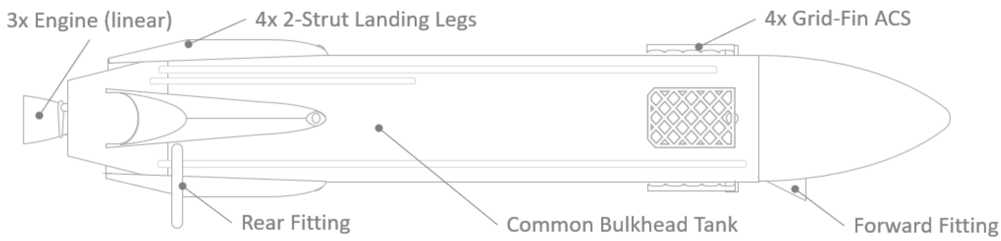


Figure 9: *Potential Aerodynamic Control Surface Designs*

3.5 Selected LRB Design for Comparison

For an exemplarily comparison of the SRB and a LRB vehicle configuration, a potential LRB concept is established and preliminarily dimensioned. The selected concept does not display the best solution nor an optimized design. It is only considered as paradigmatic concept. Figure 10 displays the chosen LRB configuration.



LRB Concept	
m_{LOX}=	113200 kg
m_{LCH4}=	32500 kg
$m_{Lift\text{-}Off}$=	162800 kg

Figure 10: Potential Aerodynamic Control Surface Designs

For preliminary and quick dimensioning of launch vehicle main tanks and structures, a MTA internally developed tool called ODIN (Optimal Design INvestigation) is used. The tool allows a fast estimation of preliminary dimensions, wall thickness and mass based on general thrust, aerodynamic loads and pressure loads. Stiffened and unstiffened design solutions, but also various parametric adopted dome shapes can be applied. ODIN results are used as baseline for deeper strength analysis investigations with e.g. finite-element-method (FEM) software applications.

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4. Performance Comparison of SRB and LRB

As described in section 3.1, one of the LRB´s HLR is a similar mission envelope regarding target orbit and payload capacity in comparison to SRBs. As first step in achieving this comparison, the change in velocity supplied by the two vehicle concepts is compared for a given payload as well as the change of payload for an identical change in velocity. Losses such as gravity, aerodynamical drag or steering are not considered on this level. For future detailed comparison, a simplified 2-DOF trajectory simulation based on numerical integration is currently being set up. This simulation shall enable a comparison between the two different types of boosters concerning achievable orbits for the same payload or payloads for comparable orbits. The calculation approach is described in more detail below and an exemplary trajectory of a launch vehicle is shown. Afterwards, the required return trajectory of a reusable booster is evaluated.

4.1 Performance Comparison

As basis for the calculation of the velocity change Δv supplied by the rocket, the Tsiolkovsky rocket equation is applied, see equation 1. Thus, the performance comparison is based on the exhaust velocity of the engines c_e, the initial mass m_0 and burnout mass m_f. The calculation of the total velocity change is divided into three flight phases, because of the structure of the chosen launch vehicle with two boosters, a main stage and an upper stage. These three phases are the flight with 1) the main stage and boosters, 2) the main stage and 3) the upper stage. This simplified calculation assumes a constant exhaust velocity c_e for each of these flight phases, which is calculated from the mean thrust and mass flow rate of the correspondent stage. The inputs for the determination of the two values are given in Figure 1 and Figure 4. By this approach, the increase of the specific impulse with increasing altitude is not considered. In addition, it neglects the gravity, drag, thrust and steering losses during the ascent and as such delivers a higher Δv than achieved in reality.

$$\boldsymbol{\Delta v = c_e \times ln\left(\frac{m_0}{mf}\right)} \qquad \textbf{(1)}$$

The resulting velocity changes for the calculation with a payload of 10000kg are shown in Table 3 as normed values with respect to the initial velocity change Δv of the reference vehicle with SRBs. The liquid (expendable) booster (LB) corresponds to the first LRB concept, but considers no fuel for the landing and has no mass for the landing and ACS system included. The LRB with a return to launch site (RTLS) reserves 20 % of the propellants for the return and landing in the vicinity of the launchpad.

Table 3: Results of calculation of velocity change $\boldsymbol{\Delta v}$.

Stage Configuration	$\boldsymbol{\Delta v/\Delta v_{SRB}}$	**Payload Mass**
SRB Launch Vehicle	1.00	1.00
LB Launch Vehicle	1.01	1.00
LRB RTLS Launch Vehicle	0.95	1.00
LRB RTLS Launch Vehicle	1.00	0.775

To gain a first estimation about the performance difference between the launch vehicle with SRBs and a liquid booster, the achieved Δv of the launch vehicle with SRBs is compared to the launch vehicle with LBs. Assuming the same payload of 10000kg, the two concepts deliver almost the same overall velocity change with a slightly higher value of 1% for the LB. As can be seen by these values, the LB delivers a similar performance, if the losses during the launch are of the same magnitude. However, different launch trajectories might occur because of variations in lift-off mass and thrust influencing the resulting losses.

For the RTLS of the LRB, the reserved propellant and the landing system add additional mass at burnout. Taking these two masses into account, the total velocity change, with unchanged payload, reduces to 95% of the SRB launch vehicle. To achieve the same velocity change as the other two concepts without changes to the LRB, a reduction of

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the payload mass is required. For the evaluated case, the payload mass has to be reduced by approximately 22.5%. Thus, the application of a LRB with RTLS reduces the performance of the overall launch vehicle.

4.2 Trajectory Simulation of Launch Vehicle

A trajectory simulation of the launch vehicle is currently established by a numerical integration simplified to two dimensions. Thus, the trajectory is calculated from the given values of the subsequent step and their calculated rate of change. As inputs for the calculation, the thrust, mass, drag and fuel flow of the launch vehicle at each time step are required. As basis for the launch trajectory, a vertical start from an equator-near launch pad in eastward direction and a subsequent gravity turn to transition from the vertical to the horizontal flight into a “parking” orbit are defined. From this orbit, subsequent orbital manoeuvres can be performed. The gravity turn requires no further impulse after setting an initial pitch angle, which causes the launch vehicle to automatically pitch over. To achieve orbital velocity, a further acceleration in comparison to the direct launch trajectory may be required. This further acceleration is often achieved by approaching and initial peak above the target altitude to gain further horizontal velocity while the launch vehicle decreases in altitude [8].

In general, the goal of the trajectory calculation is a more detailed performance estimation to compare the two concepts and not a final definition of the launch trajectory. Thus, the acceleration up to the orbital velocity is considered during a horizontal flight. During this flight period, a portion of the launch vehicle’ thrust is used to remain at the same altitude. After reaching orbital velocity, the remaining energy of the launch vehicle can be used to compare the configurations. A further trajectory optimization would lead to an increase of all launch vehicle performances, but exceeds the potential of the described trajectory simulation and should be performed using dedicated tools, such as OTIS or POST [8]. Furthermore, simplifications within the process are accepted for the comparison such as the neglection of steering losses, wave drag and a simplified atmosphere model, but a detailed trajectory design has to be performed using values of the real hardware.

4.2.1 Exemplary trajectory for Ascent

The exemplary, preliminary launch trajectory shown in Figure 11 follows the launch profile described above. For a configuration applying SRBs, the booster separation is performed when the boosters provide less thrust than required for a further acceleration of the booster. The main stage shutdown and LB separation are linked to the available amount of propellant within the tanks since no prior thrust decrease is expected.

Within the two plots, various details of the described launch profile can be observed. Considering the plot of altitude over time on the left side, the details of the assumed launch profile are visible. The first part of the trajectory shows an increase in altitude, whose gradient increases at first due to the increasing vehicle’s velocity until the gravity turn leads to a more horizontal orientation. After this point, only a horizontal acceleration up to the orbital velocity takes place. After the orbital velocity is reached, the centrifugal force exceeds the gravitational force and the launch vehicle’s altitude increases, as seen in the last part of the trajectory. Considering the plot of velocity over time on the right side, two main aspects are visible. The general increase in velocity shows two points with a sudden change of the velocity gradient. These are the points of stage separations, in this case the booster separation and separation of the main stage. After these points, the thrust and acceleration of the launch vehicle decrease because of the application of less powerful engines in the higher stages. Furthermore, a higher velocity increase occurs towards the end of each stage’s burn time because a comparable thrust is applied to a lighter vehicle, which leads to higher accelerations.

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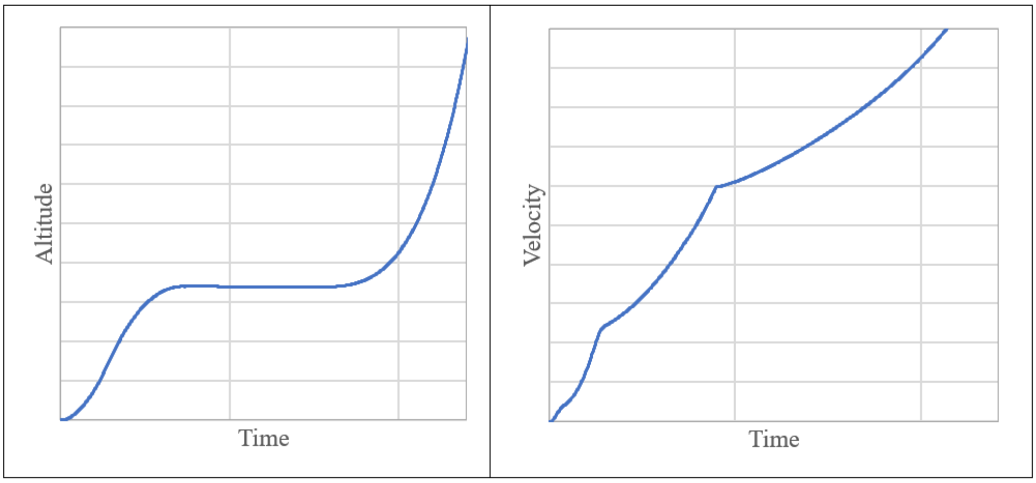

Figure 11: Exemplary launch profile of launch vehicle

4.3 Return Trajectory of Booster

For a reusable booster concept, a controlled landing of the booster is required. Commonly applied approaches for LL equipped vehicles are 1) landing on ship-based landing platforms in downrange direction (DRL) or 2) the return to a dedicated landing zone close to the launch pad (RTLS) [8]. At this point, the evaluation is limited to the influence on the trajectory of the booster for a RTLS. The resulting trajectory for such a return is shown on the left side of Figure 12 and includes the required loop within the trajectory to return to the vicinity of the launch pad. The return and landing require the performance of thrust manoeuvres to initiate the desired trajectory and guarantee a safe landing. At first a burn is performed to initiate a parabolic trajectory with impact at the desired landing zone. In the following, a landing burn to reduce the vertical velocity is required and possibly a re-entry burn to reduce the aerodynamic forces during the deceleration within the atmosphere. After separation, the booster's altitude further increases because of the remaining momentum of the booster until the gravitational force has decelerated it vertically and accelerates it towards the surface.

The general development of the velocity over time is shown for the RTLS on the right side of Figure 12. It shows the absolute value of total velocity and the vectoral vertical velocity. At first, the total velocity decreases because of the booster burn to return to the launch pad. This step would not be present for the ship-based landing. Afterwards, the gravitational force decelerates the booster, until the vertical velocity is zero leading to a first minimum in total velocity and the peak of the trajectory is reached. In the following, the total velocity increases because the booster is accelerated downwards leading to a negative vertical velocity. Upon entry into the denser atmosphere levels, the booster is decelerated by the drag acting onto the vehicle and further falls towards the earth, but with decreased velocity. In the shown example, the velocity does not reach zero towards the end because no landing boost is performed and the booster impacts on the ground.

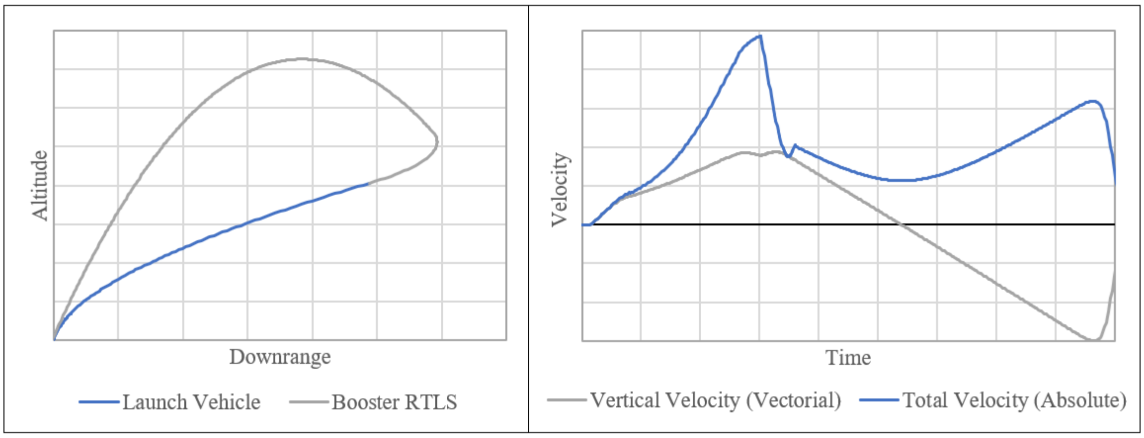

Figure 12: Exemplary return profile for LRB

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Applying the same simplified two-dimensional calculation approach as before, the trajectory of the booster after separation can be determined. Main results of the calculation are the required boost for the RTLS and the velocity at the impact on ground. In addition, the aerothermal loads acting on the booster during the entry without a re-entry burn can be estimated and show whether this manoeuvre is required. All these values enable the determination of the additional propellant required for the return and landing of the reusable liquid booster.

5. Additional Discussion

An additional discussion is stated respecting specific reusability topics, sustainability and environmental impact of the hardware as well as some operational aspects. Those topics have been identified as important, however are currently not investigated in depth but planned to be included in detail for subsequent activities.

5.1 Environmental Impact

Sustainability and environmental impact across the product's complete life cycle are important topics for current and future developments. Selected thoughts on structural material selection, propellant supply and thermal protection are presented below.

5.1.1 Material Selection

The environmental impact of the selected material is compared by considering the global warming potential of equivalent CO2 emissions for one ton of produced sheet material. This evaluation considers hot rolled stainless steel sheets, aluminium sheets and composite primary material carbon fibre as well as epoxy resin. For both stainless steel and aluminium, 70 % recycled and 30% new material within the manufacturing is considered. The resulting global warming potential is presented in Table 4. It should be noted, that the values are dependent on the manufacturing steps, logistics operations and the primary energy source. For example, the application of solar or hydroelectric power during the manufacturing reduces the global warming potential of all three materials. As can be seen, stainless steel has the lowest global warming potential for the same amount of material whereas the composite material has a significantly higher potential mainly caused by the production of the carbon fibres. The share of recycled material also has a large impact on the equivalent CO2 emissions, which also leads to a much higher value for composite because a recycling of this material is not common. Increasing the amount of recycled material within the metal-based products the global warming potential reduces further.

Table 4: Global Warming Potential of considered materials.

Material	**Global Warming Potential [kg CO2-Eq / 1000 kg]**	
Stainless Steel Sheet	approx.2 740	[9]
Aluminium Sheet	approx. 5 000	[10]
Composite Fibre +	up to 39 000	[11]
Resin Material	6 700	[12]

5.1.2 Propellant Supply

Liquid methane is used as fuel for the liquid reusable booster. This fuel choice is mandated by the HLR to use the Prometheus engine for the LRB. From an environmental point of view liquid methane splits into CO2 and water vapor during a stoichiometric combustion. For a combustion with fuel surplus additional intermediate products are formed and result in the emission of CO, HO, NOx and soot. These emissions however, at a launch rate equivalent to today's rocket launches, are negligible compared to the aviation industry and Earth's total production, but the influence of soot and cloud formation on Earth's radiation balance is not yet fully understood [14]. Nevertheless, the emitted CO2 from

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conventional methane production based on natural gas is of fossil origin. To minimize resource consumption, the production of methane should be changed from the conventional production using natural gas to a sustainable process. For example, a biogas production process could be used. Within this context, the French national space agency CNES presented a trade-off study, which proposed a space-grade biomethane production in French Guiana. It is suggested to use processes like anaerobic digestion and landfill gas to produce biomethane directly in French Guiana for the reasons of cost savings, positive environmental and social-economic impacts, instead of considering full fossil methane sourcing or transporting the fuel from Europe [14]. However, this concept is still within development and its applicability for a large-scale operation has to be demonstrated for a use for the LRB.

5.1.3 Thermal Protection

A thermal protection material based on renewable materials for external heat shields as well as the thermal insulation of hot structures is cork [15] [16]. Cork-based materials offer great thermal protection properties and at the same time are a sustainable resource. With its closed-cell structure, cork is lightweight, resistant to acids, fuels and oils, airtight and watertight and impervious to rot. Cork is the outer bark of the cork oak tree and hence can be sustainably harvested without damaging the tree. This means that cork is not only a natural raw material, but also renewable. Another advantage of cork is its process friendliness. It can be easily bonded to most substrate materials, using common adhesive systems. In addition, it can be trimmed and machined with regular tools and equipment without the need for any specific protection equipment and can be easily covered with specific coatings. [17]

The actual environmental impact comparing non-organic based thermal protection, such as ceramic heat-tiles e.g., and organic based protection, such as cork, need to include the product total lifetime. If a high replace rate is applicable for a reusable system, the evaluation may alter.

5.2 Launch Site and Ground Facilities

Reusable stages of launch vehicle systems have specific requirements regarding general ground facilities based on their ConOps. The introduced LRB configuration, for example, needs a launchpad with bi-fuel capabilities (LCH4 and LH2), erectors, landing sites for two boosters, de-erecting and ground-transportation means as well as refurbishment facilities for maintenance or replacement activities. Beside this, additional measures need to be considered for increased tracking and communication efforts for the returning stages.
MT Aerospace currently investigates within several research activities the full scope of ground means and operations regarding reusable systems. Including potential refurbishment activities on vehicle and infrastructure. For some key elements such as an automatic erector detailed concepts have been elaborated and demonstrated on subscale test hardware. [18]

6. Conclusion

For future applications, liquid reusable strap-on booster concepts are discussed and compared with a solid rocket motor strap-on booster on basis of a common, non-optimized reference core vehicle. A high value is set to incorporate current European research and development activities of related key technology field. Additionally, the sustainability and ecological impact of such concepts are considered. To improve the vehicle trade-off results, a 2-DOF trajectory simulation tool is currently established. Furthermore, general financial aspects are going to be in the point of focus to evaluate the economic viability of those concepts.
The lessons learned of this discussion helps to improve the understanding of potential future system and customer needs. Whereupon upcoming joint development activities will be more sustainable from ecological and economical point of view.

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