Outlook on the New Generation of European Reusable Launchers

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Abstract

The technical investigations described in this paper evaluate the two seemingly antipodal design approaches of either establishing a launcher family consisting of modular building blocks or choosing a full-size reusable launcher stage which serves all missions with adaptations limited to the upper- and kick-stage selection.

The paper summarizes major results of the preliminary technical design process iteratively performed at DLR-SART. The overall shape and aerodynamic configuration, the propulsion, the architectures of the stages are described and different technical solutions are compared. Payload performance is optimized for the different concepts in the GTO-mission, manned flight to ISS and to SSO. The winged configurations' controllability in hypersonic reentry and subsequent subsonic flight is assessed.

Keywords: RLV, LOX-LH2-propulsion, LOX-LCH4-propulsion, VTHL, VTVL, in-air-capturing

Abbreviations

3STO	Three-Stage-To-Orbit
AEDB	Aerodynamic Database
ALM	Additive Layer Manufacturing
AOA	Angle of Attack
BEO	Beyond Earth Orbit
CAD	Computer Aided Design
DOF	Degree of Freedom
DRL	Down-Range Landing site
ELV	Expendable Launch Vehicle
GLOW	Gross Lift-Off Mass
IAC	In-Air-Capturing
ISS	International Space Station
LAS	Launch Abort System
LCH4	Liquid Methane
LEO	Low Earth Orbit
LFBB	Liquid Fly-Back Booster
LH2	Liquid Hydrogen
LOX	Liquid Oxygen

MECO	Main Engine Cut Off
MR	Mixture Ratio
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
RTLS	Return To Launch Site
TPS	Thermal Protection System
TRL	Technology Readiness Level
TSTO	Two-Stage-To-Orbit
TVC	Thrust Vector Control
VTHL	Vertical Take-off and Horizontal Landing
VTVL	Vertical Take-off and Vertical Landing
CoG	center of gravity
cop	center of pressure

1 Introduction

The European sector of space launchers is currently quite fragmented into a wide variety of different stages and motors. Unfortunately, the situation is not much improving in the near future, as even more systems of much different sizes and technologies are planned to be commissioned soon. Diversity of ideas could be nice but is not necessarily the most efficient way.

At the same time, the geopolitical and technological landscape is rapidly changing. In recent years, the share of Europe of all launches worldwide is dramatically reduced compared to the glorious years of early Ariane operations. The private US-company SpaceX now has a dominant role in the number of launches using its partially reusable Falcon(9/H) rocket (share 2022: 34% of all successful flights worldwide vs. Europe's total share only 2.2%, see e.g. [1]). Definition and subsequent development of a new affordable and sustainable European space transportation system has become now urgent.

The two elements required of all advanced European launchers are:

- Reusability (offering cost advantages when applied to RLV first stages as demonstrated by the SpaceX Falcon example) and thus the successful mastering of return technologies, and,
- as far as possible, an environmentally friendly ("green") space transportation system.

One of the launcher concept options could be a family of launchers supporting a wide range of payload performance as proposed in ESA's 2021 program *New European Space Transportation Solutions* (NESTS) [2] where "all studies state that future needs shall be answered by modular, re-usable, agile, flexible, robust and affordable solutions". The idea bases upon using "building blocks" of common stages or main propulsion rocket engines and applying them in a modular way with up to four different launcher classes from micro, through intermediate, heavy and “super heavy” types.

SpaceX, at the same time, is following a somehow contrarious approach. A single TSTO launch vehicle should serve all kinds of missions and should be economical even for those which have payload requirements much below the design capacity. This is already the case today with small satellite missions transported on the Falcon9 but will become in the future even more explicit with the Starship&SuperHeavy combination. This vehicle is intended to become soon an operational ultra-heavy launcher well exceeding the size of all rockets ever built to date (see independent technical analyses in reference [3]!) and it is unlikely, SpaceX would withdraw itself from its current key-market with comparatively small payloads.

The question coming up in this landscape can be formulated: What is the best approach for Europe and its space transportation needs? Building human settlements on Mars requiring a powerful deep space missions’ capability is not in the top position of the agenda. However, huge and heavy single payloads are still required to be transported into orbit while constellation deployment, smaller Earth-observation satellites or even human space transportation [4] could be part of the portfolio mix.

2 Common Missions and Elements

2.1 Mission assumptions

All presented RLV-configurations in this paper are assuming similar key mission requirements:

- GTO: 250 km x 35786 km
- ISS crew, 200 km circ., 51.6°
- SSO: 500 km x 500 km, 97.4°
- Launch site: CSG, Kourou, French Guiana

The vehicles should be capable of performing secondary missions to LEO, MEO or BEO.

All upper stages are to be actively deorbited at the end of their mission into Earth orbits to reduce the buildup of additional space debris. A contingency of fuel mass is reserved for this final part of the mission.

2.2 Main propulsion systems

The different launcher systems studied make use of a portfolio of different liquid rocket engines, either in production, in development or in conceptual study level. All these engines make use of LOX as oxidizer and the fuel options hydrogen (LH2) and methane (LCH4).

Both, closed- and open-cycle rocket engines have been considered in the investigations. All engine performance data are based on cycle analyses run by DLR verified by comparison with similar existing engines. The key engine data are all listed in reference [8].

A staged combustion rocket engine has been proposed and defined as SpaceLiner Main Engine (SLME) having a moderate nominal chamber pressure of 16 MPa [5]. This engine is not only attractive for the DLR SpaceLiner but also for any kind of European LOX-LH2-RLV-stage. Thrust level is relatively large at 2200 kN but still with capabilities of existing test stands. The size of the SLME in the smaller booster type is a maximum diameter of 1800 mm and overall length of 2981 mm. The larger second stage SLME has a maximum diameter of 2370 mm and overall length of 3893 mm [5]. Both engine variants are shown with their Integrated Power Head architecture of turbo-machinery and two preburners as simplified CAD-models in Figure 1.

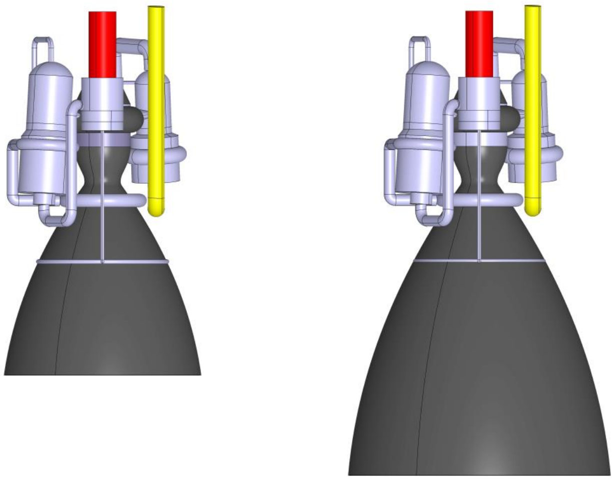

Figure 1: SLME simplified CAD geometry with nozzle expansion ratio 33 (left) and 59 (right) [5]

An advanced rocket engine already qualified today is the closed expander cycle Vinci which is to be used in the upper stage of Ariane 6 [7], [9]. Currently, Vinci is the most powerful engine of its type worldwide. The good performance data of this engine makes it attractive for powering smaller Building-Block stages or the upper or kick-stages of the 3STO- and Mini-TSTO-concepts described in sections 3.1.1 and 3.2.1.

The M10 *Mira* engine is a European methane rocket engine, conceived for use on upper stages of future Vega-E launchers. This type is a derivation of the Russian RD-

0146 engine of CADB as closed expander cycle for the LOX-LH2 propellant combination [10].

PROMETHEUS is the precursor of a new European large-scale (100-tons class) liquid rocket engine designed for low-cost, flexibility and reusability [11] and the abbreviation stands for "***P**recursor **R**eusable **O**xygen **Meth**ane cost **E**ffective prop**u**lsion **S**ystem*". This engine is planned to be operated in open gas generator cycle. Baseline propellant combination of the PROMETHEUS-engine is LOX-LCH4.

Currently, the precursor of PROMETHEUS is under development. The engine data of the presented RLV-study have been calculated by DLR to make realistic performance of a full-scale engine available for the launcher system design. The intention of this paper is *not* to provide an accurate prediction of the future PROMETHEUS for which technical characteristics are not yet all frozen.

An interest has been identified in using the advanced low-cost additive manufacturing processes to be implemented for PROMETHEUS but transferring them to an engine with the higher performing LOX-LH2 propellant combination. Such a hypothetical advanced Vulcain or PROMETHEUS “H” has also been calculated to be used in the European RLV-launcher study.

Note in Figure 2 and Figure 3 the significant difference in specific impulse performance depending on propellant combination and, less visible but relevant, between closed and open cycle. In case of the gas-generator PROMETHEUS the vacuum Isp of the LH2-engine is almost 90 s superior to the methane variant while sea-level improvement is restricted to 77 s due to the chosen nozzle design with higher exit pressure of the methane-version. The staged combustion-cycle SLME brings further improvement of more than 20 s.

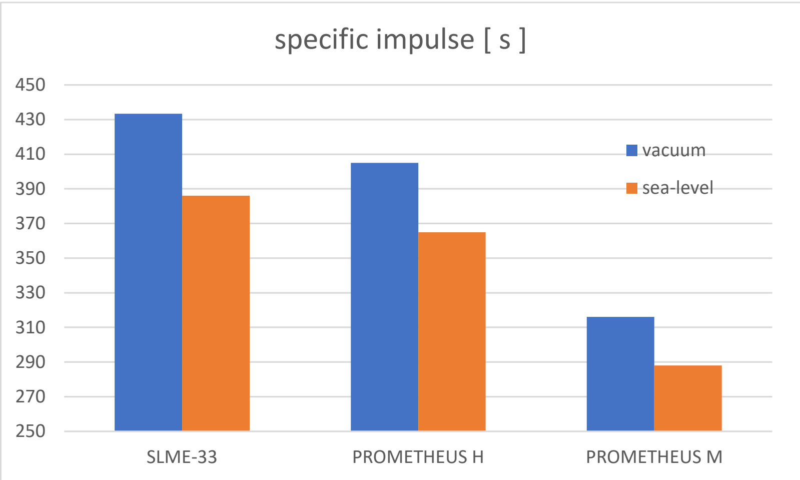

Figure 2: First or booster stage engine performances

The upper stage engine performances (Figure 3) are mainly driven by propellant choice and selected nozzle expansion and less by the cycle type. Methane-engines are slightly more than 90 s below hydrogen and the gain of closed cycles is roughly 20 s.

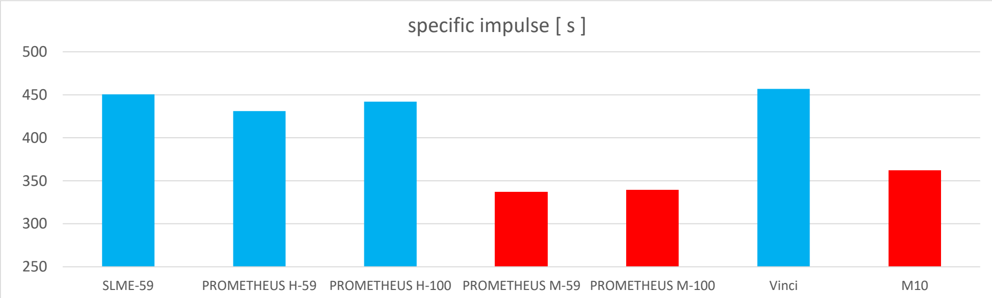

Figure 3: Upper stage engine performances in vacuum (light blue: LOX-LH2, red: LOX-LCH4)

2.3 RLV recovery methods considered

The question of the best recovery method for an RLV-stage is subject of intensive debate and also to systematic investigations [12], [13]. Criteria for selection are performance and cost as well as technology availability which is linked to development risk. Two recovery and return strategies offer attractive conditions for high performance missions. Both are related to a Down-Range "Landing" (DRL) and these are baseline for the first stage RLV investigated in this paper. Current European TRLs are roughly the same for both methods.

2.3.1 VTVL with down-range sea-landing

Vertical Landing downrange is a viable option for future RLV proposals which has also been considered for potential evolution option for Ariane 6 with liquid boosters described in [4]. Currently, SpaceX is using this method to land Falcon 9 and Falcon Heavy booster stages on the so-called autonomous spaceport droneships (ASDS), a barge positioned downrange of the launch site in the oceans.

VTVL require engine reignition capability to perform several maneuvers following MECO of the returning booster. First, the stage continues to travel on a ballistic trajectory up to its apogee, where it starts falling back to the earth's surface again. At a certain altitude, dependent on the mission profile and aerothermal loads experienced, one or more engines reignite to slow the stage down and thus limit re-entry loads. After shutting down the engines again the reusable stage is slowed-down aerodynamically to subsonics and an engine is reignited to gradually decrease the speed to a safe vertical landing coinciding with touchdown on the barge.

Compared to VTHL, vertical landing stages are not equipped with conventional wings or rudders and flaps. Instead, landing legs are required and some kind of aerodynamic controls, like grid fins for the Falcon 9, which usually are adding less dry mass as the VTHL recovery hardware. However, VTVL instead require a certain amount of non-negligible propellant to be kept for the return maneuvers, thus adding to the inert mass of the launcher ascent acceleration mission and hence reducing payload performance [21].

2.3.2 VTHL using “in-air-capturing” (IAC)

The patented “In-air-capturing” intends the winged reusable stages to be caught in the air, and towed back to their launch site without any necessity of an own propulsion system [15], [16]. The idea has certain similarities with the vertical Down-Range Landing (DRL)-mode (section 2.3.1), however, initially not landing on ground but “landing” in the air. Thus, additional infrastructure is required, a capturing aircraft of adequate size for the to be towed RLV. Used, refurbished and modified airliners should be sufficient for the task.

A schematic of the reusable stage's full operational circle when implementing IAC is shown in Figure 4. At the launcher's lift-off the capturing aircraft is waiting at a downrange rendezvous area. After its MECO the reusable winged stage is separated from the rest of the launch vehicle and after a ballistic trajectory is soon reaching denser atmospheric layers using aerodynamic lift and drag for deceleration without propulsion.

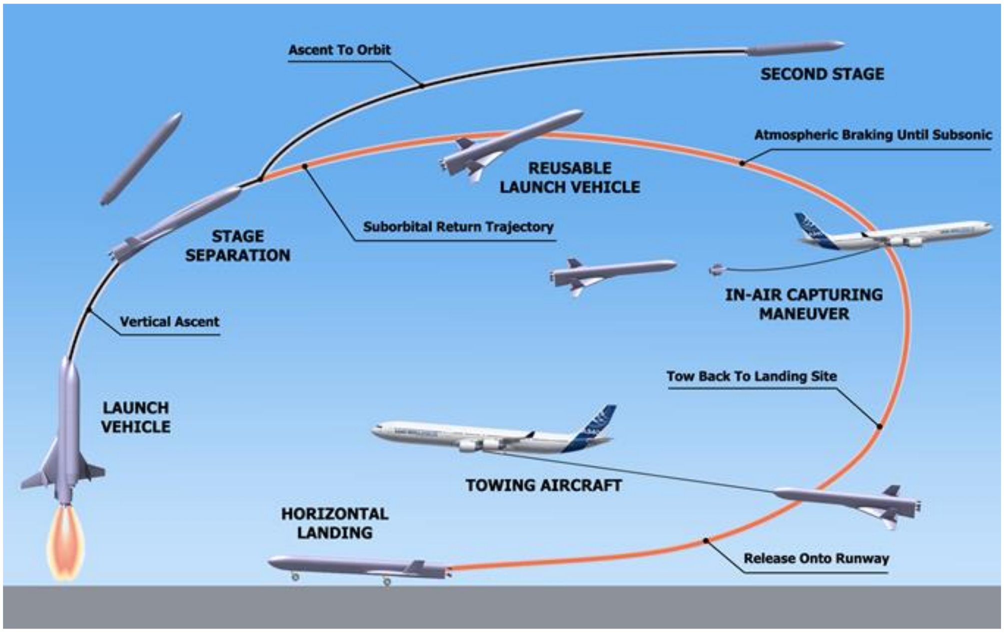

Figure 4: Schematic of the proposed in-air-capturing

In subsonic gliding flight at approximately 10 km altitude, a reusable returning stage usually has to initiate the final landing approach or has to ignite its secondary (e.g. turbofan) propulsion system. Differently, within the in-air-capturing method, the reusable stage is awaited by an adequately equipped capturing aircraft (most likely fully automatic and potentially unmanned), offering sufficient thrust capability to tow a winged launcher stage with restrained lift to drag ratio. The reusable unpowered stage is approaching the airliner from above with a higher initial velocity and a steeper flight path, actively controlled. The time window to successfully perform the capturing process is dependent on the performed flight strategy of both vehicles but can be extended for up to more than one minute. The entire maneuver is fully subsonic (around 160 m/s) in an altitude range from around 8000 m to 4000 m [15]. In order to keep the two large vehicles always in a safe distance to each other, the actual contact and towing rope connection is established by a small agile vehicle [15], [16]. After successfully connecting both vehicles, the winged RLV is towed by the large carrier aircraft back to the launch site. Close to the airfield, the stage is released, and autonomously glides like a sailplane to Earth.

From a performance perspective, the IAC mode is highly attractive. In a systematic comparison of different RLV-stage return modes [12], [13], [15] with all launchers generically sized for the same GTO mission, the IAC-mode constantly shows a performance advantage compared to alternate modes. Costs for recovery of RLV-stages have been estimated and are found to be very similar for the IAC and DRL modes without any significant edge for one of them [15]. The ascent propellant loading is between 15% and 32% less for the IAC-mode compared to VTVL in DRL-mode resulting in significantly smaller and lighter stages. Depending on the architecture and the operational scenario this improvement can allow cost reductions between 10% and 25% for IAC compared to the vertical landing method downrange on a ship as operated by SpaceX [15].

Accurate numbers on the cost-saving would require the selection of a specific launcher system and its mission and application scenario. A somehow similar approach including preliminary results is described for the launch vehicles of this paper in reference [26], however, here not in focus of the recovery methods.

In order to accelerate the development of "in-air-capturing"-technology, the Horizon 2020 project with the name FALCon (**F**ormation flight for in-**A**ir **L**auncher 1st stage **C**apturing dem**on**stration) has been kicked-off in March 2019 and was finished after 45 months in November 2022. With total funding of 2.6 M€, the FALCon project addressed three key areas [15]:

- "in-air-capturing"-Simulation (subscale and full-scale)
- "in-air-capturing"-Experimental Flight Demonstration
- "in-air-capturing"-Development Roadmap and economic benefit assessment

Significant progress was reached by performing sophisticated full-scale- and lab-scale-flight experiment simulations [15], [16], [17], [18]. The flight experiments were supported by refined simulations of the planned formation flight maneuver with subscale vehicles. The technical maturation plans of the in-air-capturing"-technology have been defined and discussed and allow the advanced RLV-recovery-technology to be implemented in a completely new, partially reusable European launch vehicle to be operational around 2035 [15].

3 New Generation of European Reusable Launchers

Europe's Ariane 6 developments in two different configurations, A62 with two solid strap-on boosters and A64 with four solid strap-on boosters, are ongoing [7]. Further performance enhancements by increasing the propellant loading of the solid boosters are in preparation for a Block 2 version. Nevertheless, activities on the next generation of completely new launch vehicle stages have to be further advanced as the rapid developments in the field of space transportation (mainly in the US and in China) make also in Europe a completely new generation of RLV necessary.

On the first look the potential future launcher options seem to follow an antipodal approach.

3.1 Families of "Building-Block" Launcher Systems

ArianeGroup's view of the future has been announced early last year [19]: A small, partially reusable Maïa rocket announced starting its operations already in 2026, followed by reusable versions of the medium-lift Vega and heavy-lift Ariane 6 rockets. Common "Building-Blocks" of similar size stages for different size launchers should become a family spanning a significant payload range. Figure 5 shows how such configurations could look like if based on LOX-Methane propulsion and the PROMETHEUS liquid rocket engine.

Figure 5: French industrial proposal of a future "Building-Block" launcher family [19]

Currently, no technical publication on the type of family as presented in Figure 5 is available. DLR initiated its own independent preliminary design study with the two propellant options LOX-LH2 and LOX-LCH4. High-level mission requirements might be somehow different to the launchers of Figure 5. This is not relevant as the comparison is made here between the “Building Block” Option 1 and the large size winged Option 2 (see section 3.2).

The optimum sizing of a “Building-Block” launcher family could be quite complicated. Minimization of life-cycle cost is a potential target, however, would require good knowledge of future launch scenarios. The latter is hard to reliably estimate, the more as projections are 30 to 50 years in the future.

Therefore, a pragmatic approach has been followed in reference [8] delivering a suitable selection of building block stages which can be used as the baseline of any launcher family. These stages might not be exactly at a theoretical optimum but with the uncertainty in several assumptions this is not relevant for the launcher designs.

Only open gas-generator type engines have been selected for the “building block” families. Data for these engines are all summarized in reference [8] and show sea-level thrust (at take-off) is in the range 1150 kN to 1200 kN. The preliminary launcher sizing is adapting take-off thrust levels only in discrete steps by adding or removing a full engine.

Another baseline requirement is the preference of TSTO configurations over alternative architectures in order to reduce costs. The DLR-defined families do not strictly limit their configurations to TSTO but allow also 3STO or “common core booster” architectures for high-performance missions as derivatives. Nevertheless, also in the stage sizing of DLR the TSTO concepts play the dominant role in the pre-definition of the common stages.

The search for suitable stage sizes has in all cases been based on the M and L categories. The more extreme configurations to the left of the range (S) and to the right (XL and XXL) are derivatives and should not impact the stage sizing. The M-variant is to target the SSO mission and is to be based on a large first stage and a small expendable upper stage. The L-variant’s design mission is GTO for single satellite deployment consisting of a large first stage with several liquid engines and a medium size second stage using the same engine in its vacuum variant.

Both M- and L-launcher variants are optimized for minimum GLOW individually. However, this optimization is under the constraints of the available engines and while the first stage includes several motors, the upper stage should have only a single engine with large nozzle expansion.

After individual stage pre-sizing the data are compared and the size of the “Building Block” stage elements are frozen. It turned out both for hydrogen and methane BB-concepts that the choice is rather straight-forward and that the M- and L-variants remain close to their optimum size when adopted to the common stages [8]. The three defined stages are transferred afterwards to the S-, the XL- and the XXL-variants.

3.1.1 Family of hydrogen "Building Block" launchers

Following the described design approach and choosing the hydrogen engines Vinci and PROMETHEUS "H" in two versions for RLV-Booster and 2nd stage with adapted expansion ratio a total of five different launchers (Figure 6) based on three building block elements has been defined:

- S-Type: H61 + H15
- M-Type: H240 + H15
- L-Type: H240 + H61
- XL-Type: H240 + H61 + H15
- XXL-Type: 2 H240 + H240 + H61

for which the numbers represent total nominal propellant loading in tons.

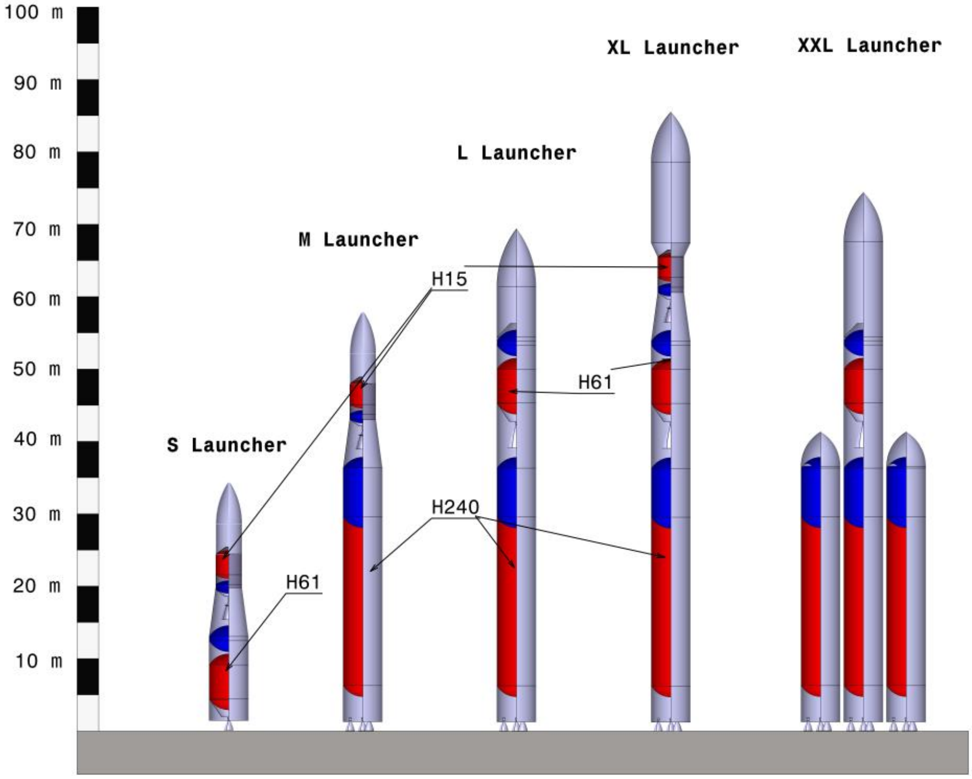

Figure 6: Building-Block launcher family LOX-LH2 combination

The L-launcher could deliver 2250 kg separated payload to GTO with the first stage performing a Down-Range Landing (DRL). The XL-configuration with two expendable upper stages more than triples this performance to around 7250 kg again using DRL. This capacity would already allow the transportation of super heavy satellites. The XL-variant shows impressive performance in reusable mode as GLOW is still below 400 Mg, however, at the expense of increased complexity of the three-stage launcher making use of all three BB-elements. The XXL-version with the three similar H240 stages has more than double GLOW compared to XL but in case of all its lower stages reused would exceed the XL-performance only by about 1 ton (+ 14%). In case the core stage becomes expendable, payload to GTO is strongly elevated and would allow to beat Ariane 6 in double launch assuming RTLS of the side boosters. If the boosters are performing a DRL-mode return, the payload in GTO could be up to 14800 kg.

It has been impossible to find an S-class BB-launcher with any meaningful payload assuming RLV first stages as VTVL. Further, T/W at the landing burn would exceed 3, even with the engine deeply throttled-down to 30% nominal thrust level. The safe vertical landing of the first stage by closed-loop control under these conditions is almost impossible. With the S-Launcher based on the defined BB elements as RLV hardly feasible and at best with minimal performance, this concept is obviously the least attractive of the whole family. Although SSO-payload performance as an ELV is at 1.5 tons and comparable to Vega, the S-type is unlikely to be kept in the hydrogen BB-family.

Beyond the reference SSO- and GTO-mission also the capabilities of the XXL-configuration in an ISS-transfer orbit for crewed missions have been assessed. Mission constraints are similar to the previously analyzed DLR - ArianeGroup study EURASTROS (European Astronautical Space Transportation) [4]. Flight performance is superior to Ariane 64; therefore, the most powerful XXL-variant would be ready to support also independent crewed European space flight missions.

Figure 7 shows a summary of the LOX-LH2-BB-family's separated payload performance in RLV-mode of the lower stages.

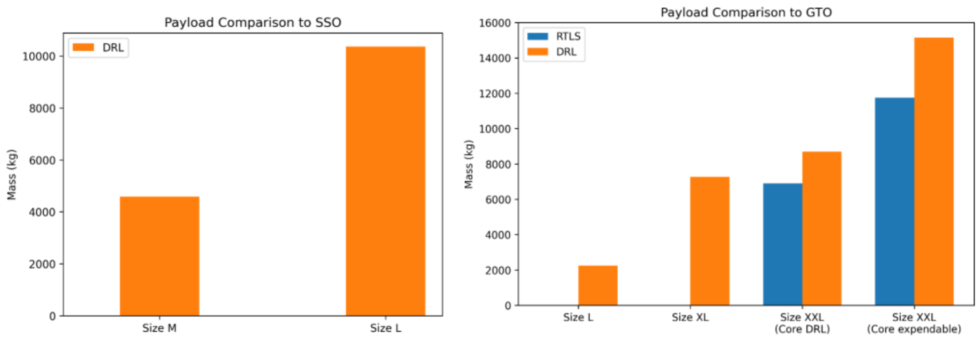

Figure 7: Payload performance LOX-LH2 BB in SSO and GTO with reusable first / booster stages as VTVL

3.1.2 Family of methane "Building Block" launchers

Following the same design approach as for LOX-LH2 and choosing the methane engines M10 and PROMETHEUS Methane Gas Generator in two versions for RLV-Booster and 2nd stage with adapted expansion ratio a total of four different launchers (Figure 8 shows an overview of the complete family with its major dimensions and internal architectures.) based on three building block elements has been defined:

- M-Type: M520 + M15
- L-Type: M520 + M110
- XL-Type: M520 + M110 + M15
- XXL-Type: 2 M520 + M520 + M110

for which the numbers represent again the total nominal propellant loading in tons.

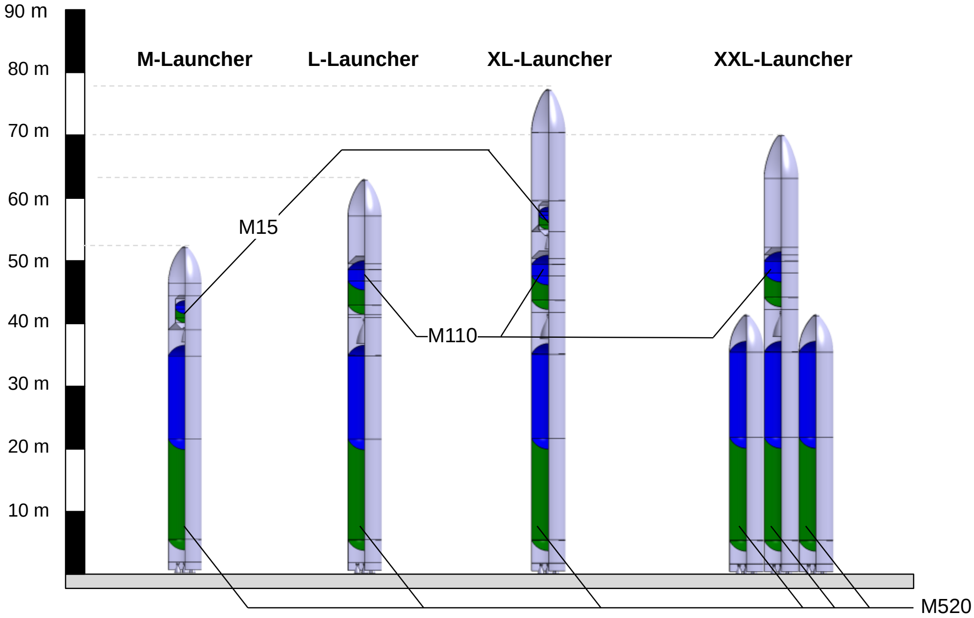

Figure 8: Building-Block launcher family LOX-LCH4 combination

An S-Type was found unfeasible both in ELV and RLV-mode due to insufficient thrust capabilities of the M110 with single methane gas generator engine because T/W at lift-off is merely exceeding 1.0.

The L-launcher is deemed unattractive as RLV to GTO because hardly any separated payload mass can be delivered. The 3STO XL-configuration with two expendable upper stages achieves more than 6300 kg when using DRL. This capacity is below the LH2-XL-type and would not allow the transportation of all existing super heavy satellites. The XXL-version with the three similar H520 stages more than doubles GLOW to above 1800 Mg but with all its lower stages reused would not exceed the

XL-performance. In case, both the core stage and the upper stage are expendable, payload to GTO is elevated and would reach more than 8300 kg in double launch assuming RTLS of the side boosters. If the boosters are performing a DRL-mode return, the payload in GTO could be up to 13900 kg.

Beyond the reference SSO- and GTO-mission also the capabilities of the XXL-configuration in an ISS-transfer orbit for crewed missions have been assessed. Mission constraints are similar to the previously analyzed DLR - ArianeGroup study EURASTROS [4]. Flight performance and safety quality are again superior to those of Ariane 64, therefore, also the most powerful methane-variant would be ready to support independent crewed European space flight missions.

Figure 9 shows a summary of the LOX-LCH4-BB-family's separated payload performance in RLV-mode of the lower stages. Note, payload mass is in many cases significantly below the LOX-LH2 versions presented in Figure 7 despite drastic increases in GLOW. This is not a problem in the concept feasibility assessment but will show its impact in the scenario-based launch cost analyses of [26].

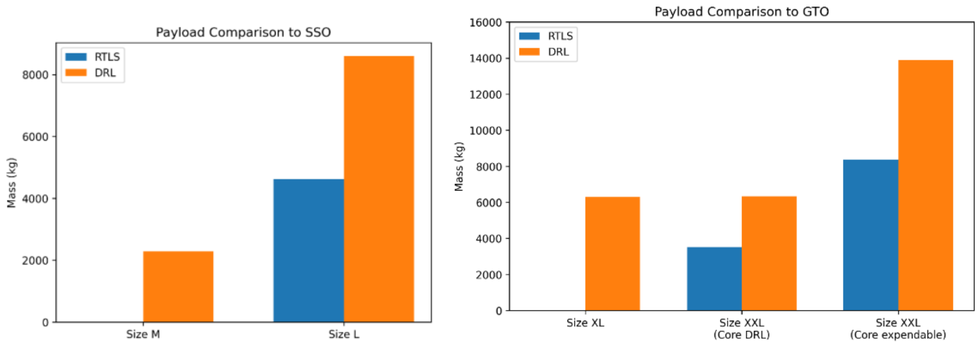

Figure 9: Payload performance LOX-LCH4 BB in SSO and GTO with reusable first / booster stages as VTVL

3.2 *Next-generation winged RLV-configuration*

A somehow different idea in defining the next generation of partially reusable heavy launchers has been under investigation in several system studies. Instead of creating a family with potentially different reusable first stages, the "Big-Size-Fits-All"-approach assumes one sufficiently large reusable stage as the baseline element to be combined with different types of expendable upper stages. The idea is also building on a limited number of elements like similar rocket engines (not much different to BB-families) but would instead allow the use of one single launch-pad for all intended missions.

The system studies at DLR's space launcher system analysis department SART have investigated not only one preferred type but different return and recovery modes, as well as different propellant and engine cycle options [4], [20], [21], [22], [23], [24].

Future European RLV configurations with reusability of 1st or booster stages with tandem arrangement of a large expendable upper stage have been preliminarily designed as TSTO for a GTO-reference mission with 7.5 t payload target, however, reaching significant size of up to 80 m length [20], [21].

Approaching or even exceeding the payload performance expected for Ariane 6 in GTO or Lunar exploration missions would require extremely tall launcher configurations in case of tandem-staged TSTO with reusable first stage. Therefore, for this class of RLV (DLR-internal designation RLV-C4) a parallel stage-arrangement is preferable: a winged stage is connected to an expendable upper segment with potentially various internal architectures. References [22] and [23] have demonstrated that a payload range between 12 to 15 tons GTO-class with multiple payload capability can be achieved by a 3-stage architecture while still remaining at relatively compact size. Less demanding missions to different LEO are better served as TSTO. Beyond the winged VTHL-concepts in focus of this section, similar VTVL options in architecture and size have been studied as a potential alternative [4] and might be reconsidered in future work.

The first stage of all investigated RLV-C4 has been designed as winged RLV, however, in different sizes and lay-outs depending on the propulsion choice. Those alternate variants not using the staged combustion SLME as core engine are not addressed in this paper but extensive discussion is published in [4], [8], [22], [23], [24]. The expendable stage or stages are attached in parallel configuration on top of the 1st stage. An important design constraint is the requirement of using similar engines in the reusable stage and the large expendable second stage, however, with adapted nozzles. This engine similarity allows for reduced development costs and might permit the reusable engine to be expended after certain number of missions on the RLV.

In case of 3STO systems the fairing covers all of the third stage and the payload and hence connects to the upper part of the interstage as visible in Figure 10 at left. The upper stage for high performance missions, mainly GTO-injection, is selected as H14 for all concepts. An external tank diameter of 5.4 m is no longer suitable for that loading if the stage's dry mass should be attractive. Vinci is the sole engine choice in the 3rd stage.

The 2nd expendable stage is defined as an H150 in case of hydrogen and becomes even more compact than the core stage of the classical Ariane 5G. Note the expendable stage arrangement with the H150 forward skirt or 2-3-interstage adjacent to the RLV intertank ring (Figure 10 at left and center).

The third launcher option investigated uses the same winged RLV first stage but a significantly smaller expendable upper stage to serve smaller payloads in low-energy missions. Figure 10 at right depicts a technical solution with the same attachment point on the RLV and the small H14 expendable upper stage of the 3STO powered by Vinci-engine and significantly reduced size of the payload fairing.

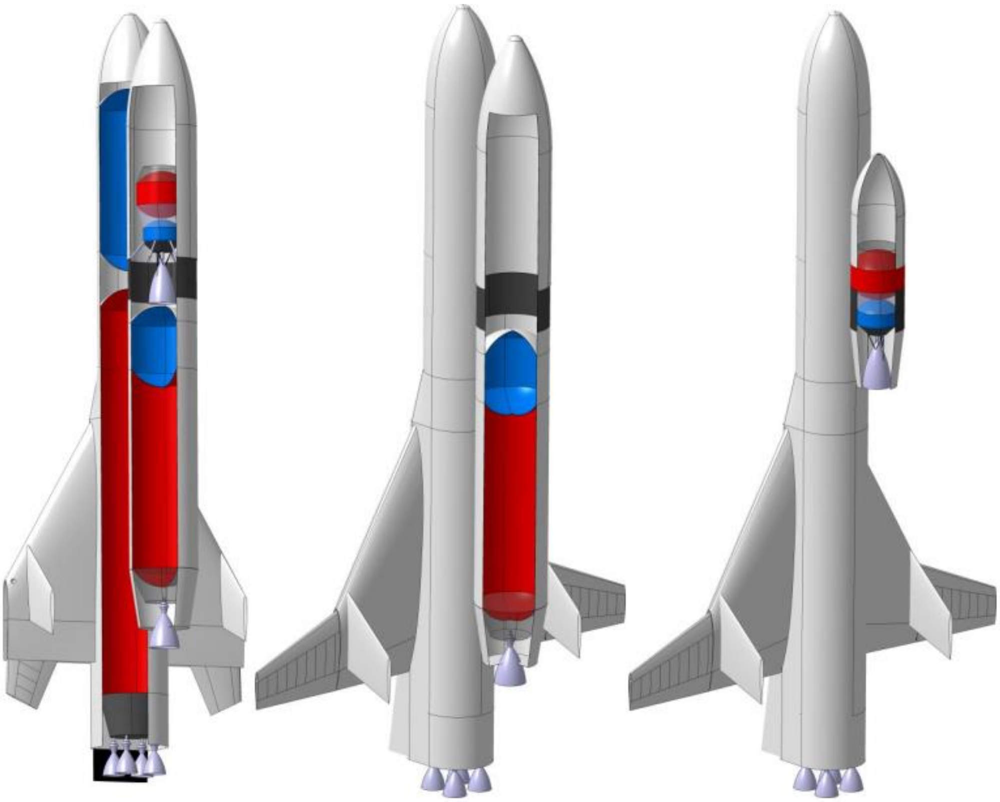

Figure 10: Launcher architecture sketches of RLVC4-B configuration as 3STO (left), TSTO (center) and Mini-TSTO (right)

The baseline version of the RLV-C4 concept to be equipped with staged combustion rocket engines is called variant B featuring the LOX/LH2 propelled SLME engines (Figure 1). Figure 10 shows the RLVC4-B configuration in two sub-variants. on the left a swept-wing concept described in more detail in [22] and a more recent fixed wing design in the center and right part with updated aerodynamic control features (see [8], [24], [25] and briefly in the following section 3.2.2). Characteristics of the RLV-stage like tank size and arrangement are identical for the sub-variants and all are equipped with 4 SLMEs. Currently, no decision has been taken on the preferred wing solution for this RLV. The more compact swept-wing variant is obviously beneficial during launcher ascent and in reentry avoiding interactions between the nose shock and the wing's leading-edge shock [21] but on the downside is coupled with increased complexity and potentially enlarged weight.

Table 1: RLVC4B launcher characteristics for different missions

Mission	GTO	LEO-ISS	SSO
RLV Stage		**H370**	
Dry mass		78.8 t	92.2 t
Total Propellant		378.2 t	
Structural index		20.8 %	24.3%
Engines		4 x SLME	
Fuselage Diameter		5.4 m	
Length		59.1 m	
2nd stage ELV	**H150**	**H150**	**H14**
3rd stage ELV	**H14**	**-**	**-**
GLOM	665.0 t	663.2 t	496.86 t
Payload	13.9 t	> 21 t	5.4 t
Payload ratio	2%	3.16%	1.09%

Since development of advanced closed cycle engines like the SLME has not yet started in Europe, it is also of interest to understand how an RLV powered by a modern gas-generator engine is performing. The general feasibility is demonstrated and latest results on these types have been published in reference [8] but should not be discussed here.

3.2.1 Constraints for GTO-, LEO-ISS-, SSO-missions

The transfer into GTO with a TSTO is straightforward: the insertion is done directly and following SECO the payload is in the specified GTO. Opting for a 3-stage architecture is mainly attractive for the GTO mission (or beyond) because a much smaller inert mass will have to be injected in a high-energy orbit. However, the insertion with a 3STO calls for additional measures in order to ensure that the uncontrolled descent of the expendable second stage safely occurs in the Pacific Ocean.

Thus, the ascent phase is split into two steps: first, the second stage plus third stage and payload are (in case of RLVC4) injected into an intermediate orbit with an apogee height of 400 km and a perigee height of 35 km [22]. The large expendable cryogenic 2nd stage should be designed not to reach a stable orbit but to splash into the Pacific safely off the American West coast. Following separation of the third stage from the second stage the former coasts along a ballistic trajectory. Slightly before crossing the equator the third stage is ignited to insert the payload into a GTO with 350 km perigee and 35786 km apogee and approximately 6° inclination.

In case of LEO-missions the launcher can best be operated as TSTO. An astronautic mission assuming in modeling the addition of a launch escape system instead of conventional fairing has been assessed as relevant example. The crew compartment assumptions are very similar to the Ariane 6 analyses described in [4] but the more powerful upper stage of the RLV-based TSTO reaches roughly 3 tons better payload performance than A64 with its ULPM. Thus, a more robust system is enabled which could have the capability of supporting larger, deep-space missions. The orbital injection conditions of the expendable 2nd stage will require an active deorbiting of the H150 and propellant for the deorbiting burn is required. The stage's splashdown is foreseen in the Pacific Ocean in the vast remote areas east of New Zealand which had been simulated for a similar ISS-resupply mission [23].

The so-called "Mini-TSTO" is another launcher variant potentially showing clearest what the "one-[RLV]size-fits-all"-philosophy of [8] means. Usually, payload mass requirements in SSO are modest, not exceeding 5 t. Therefore, the H14-upper stage with Vinci has been assessed as the only second stage attached to the RLV. In Figure 11 the latest iteration of the ascent trajectory is visible. The separation Mach-number of the RLV-stage would in this case increase to around 16, well beyond the GTO- and ISS-missions for which heavier upper segments are to be accelerated. Such comparatively high speeds could mean an unsurmountable gap if not adequately addressed.

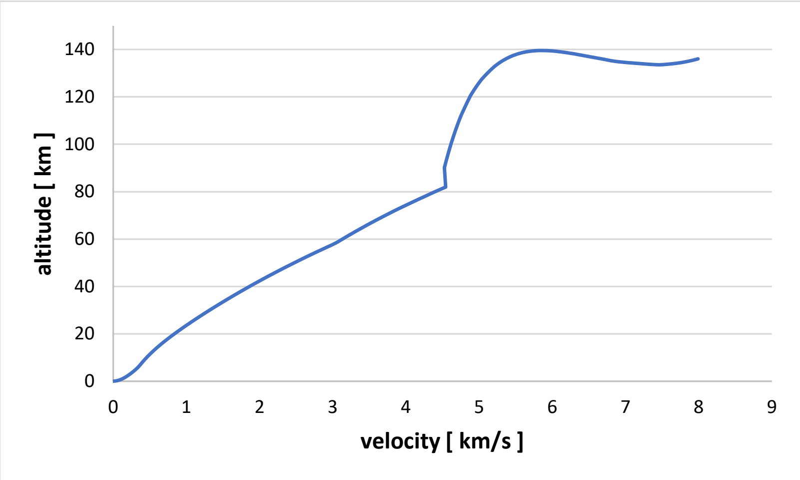

Figure 11: Ascent profile of RLVC4-III-B configuration in 100 km x 500 km, 97.4° transfer orbit for small SSO-mission

This condition will require an adapted, heavier TPS on the RLV for safely performing its reentry. Such preliminary design has not yet been carried-out. However, an assumed additional mass contingency for the RLV has been considered. Further, the ascent profile has been tuned to shallower flight paths in ascent and reentry which significantly reduces the peak stagnation point heat fluxes compared to initial assumptions [8]. Still the maximum value is roughly 5 times above the values of the GTO- and ISS-trajectories with less than half in RLV-separation speed. Maximum mechanical loads of the three different reentry profiles are kept very close.

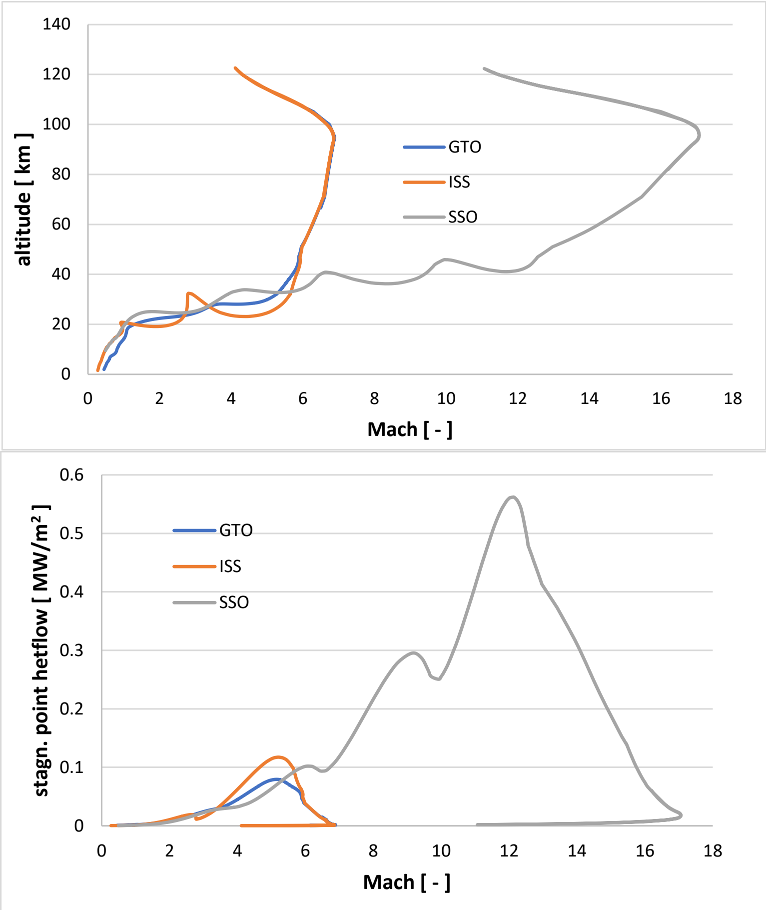

Figure 12: Descent profile of RLVC4-III-B configuration for GTO-, ISS-, and SSO-missions and corresponding stagnation point heat flux

Under such conditions, the separated payload in circular 700 km orbit is calculated still at around 5.4 t. Alternatively, a lower separation Mach-number could result in reduced payload mass, nevertheless fully sufficient for typical SSO-missions, and good potential to significantly reduce the thermal loads.

3.2.2 Feasibility of RLV flight control during reentry

Designing an aerodynamically controlled vehicle reentering the atmosphere at hypersonic velocity, subsequently slowing down to subsonic velocity and finally reaching equilibrium gliding flight conditions, is a very challenging task. The stage covers a vast range of flight conditions at which it has to be controllable to allow a safe reentry while also fulfilling the gliding flight requirement necessary for executing a successful In-Air-Capturing maneuver [16]. Understanding the flight dynamics of a winged vehicle reentry already in the early design phase is necessary to identify challenges with regards to controlling and actively steering such a high-performance vehicle in order to arrive at a feasible and robust design that does not fail to converge in later design iterations.

Therefore, the RLVC4-III-B concept was subjected to a thorough analysis of reentry aerodynamics and its effect on flight dynamics. This includes studying the impact of design changes to the initial aerodynamic configuration, investigating the dynamic motion and stability of the stage and, finally, studying control possibilities and simulating 6-DOF flight maneuvers [24], [25].

The wings feature two vertical fins located mid-wing (Figure 10) improve directional stability. Further, the vertical stabilizers are reaching significantly below the wing because in hypersonic reentry with high AoA-flight, those portions located on top of the wing show limited efficiency due to shading effects. Furthermore, this RLV version features a rather large bodyflap extending over some part of the lower fuselage in order to improve pitch trim characteristics (see figures in [8], [24]). The bodyflap will be fully extended only during hypersonic reentry and at high AoA. Adding sidewalls to the flap further helps reducing the vehicle's yaw instability. A preliminary assessment of the aerodynamic coefficients indicates that pitch maneuvering is stable in almost the complete reentry flight while yaw movement with respect to sideslip is stable in subsonics but unstable in the hypersonic regime [24], [25].

A simplified approach to determining flight dynamics at certain flight points is the linearization of the equations of motion. This method allows to derive linear, time-invariant equations that are valid in a range of small disturbances around an equilibrium point of the vehicle (usually trim points) and are suitable for describing the flight dynamics in this area [24], [25]. By checking the real and complex parts of the eigenvalues at specific points in the trajectory one can determine if the vehicle is stable or unstable throughout the flight regime.

References [24] and [25] show that the longitudinal motion is mostly stable throughout the trajectory. Only in the region of Mach 5 to Mach 3 at high to medium AoA and in the region of maximum dynamic pressure active control is crucial to keep the commanded AoA profile. Contrary to that, the lateral motion is unstable throughout most of the flight.

The analysis of dynamic stability in [24], [25] has revealed the need for an active and fast control in order to stabilize the vehicle throughout reentry flight. For an early check on feasibility, an active control loop has been simulated with full state feedback and infinitely fast actuators. This simplification was deemed suitable at the early design state. Including realistic actuator and sensor models could be focus of future work. Furthermore, no wind or atmospheric disturbance was assumed yet.

For pitch control, the inner trailing edge flaps are used, for roll control the outer flaps are used, and for yaw control the vertical fins had been assumed to be deflectable entirely. Additionally, an RCS system in the nose (similar to the Space Shuttle) is required for exo-atmospheric control. For each axis, 4 RCS engines with a thrust of 650 N each are foreseen. The preliminary, simplified 6-DOF analysis presented in [24], [25] using RCS and aerodynamic control surfaces (see actions in Figure 13) to steer the vehicle, shows that the reference profile in AoA and bank angle can be followed and, thus, the RLVC4-configuration is feasible in principle. However, a more detailed simulation including wind, actuator models and realistic sensor models will increase the insight and might trigger further design improvements.

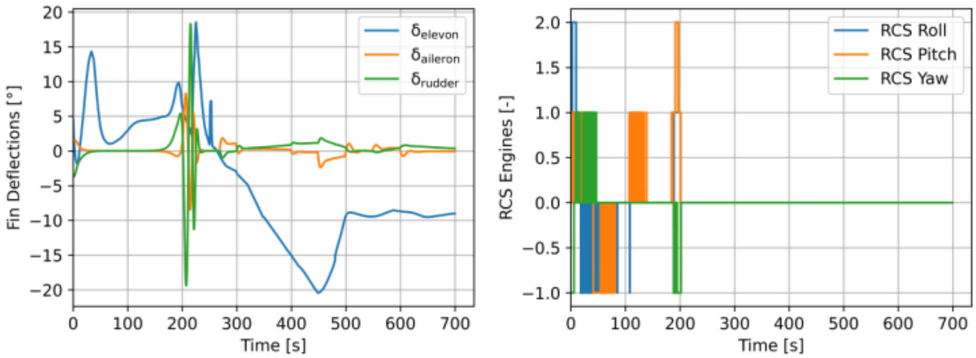

Figure 13: 6DOF-simulated aerodynamic and thruster controls of RLVC4-III-B configuration in complete reentry flight of GTO-mission [24]

4 Evaluations of European RLV concept options

The technical study results presented here are complemented by two additional papers which address the launch cost estimation considering the uncertainties of future transportation scenarios [26] and by an evaluation of their Life Cycle Assessments (LCA) on environmental impact [27]. These important aspects for the selection of most suitable next generation European launchers will not be discussed in this paper.

4.1 Critical points of "Building Block" launchers

Overall, the payload performance of the LOX-methane BB-launchers with reusable RLV-stages in VTVL-mode is significantly lower than that of similar LOX-LH2 variants. The roughly 90 s lower Isp of LOX-LCH4 compared to LOX-LH2 is to be compensated by a significantly higher propellant mass needed for reentry and landing maneuvers. Thus, less fuel is available for the ascent acceleration, reducing payload mass.

As minimum payload mass requirements are not defined for the reference missions and the focus of the investigation has been on the principal feasibility of a family of BB-launchers, LOX-LCH4-variants have not been iteratively sized for the same performance as their LOX-LH2 counterparts. It should be noted that only the strongest methane versions XL and XXL are capable of delivering any payload to GTO with the VTVL-RLV first stage although the L-size TSTO's GLOW is already approaching 750 Mg. A methane-based BB family with similar performance as a hydrogen-based BB family would need about twice the number of engines and roughly the same tank sizes despite its increased propellant densities.

In the past, separation velocities only up to 3.5 km/s (~Mach = 12) have been observed for VTVL first stages. Any separation conditions above this value require further analyses to determine the potential impacts on the system design. Such critically high speeds are relevant for the M- and the XXL-class of both investigated propellant combinations. Therefore, these classes might be unfeasible as VTVL or need to be modified resulting in reduced payload performance.

The preliminary sizing process of all building blocks assumes ambitious but still realistic stage masses. However, the BB with potential applications in several different launcher configurations and for a variety of missions would need to be designed for the most demanding structural load cases. In order to keep the family concept flexible for future evolution and potential growth and also considering the stiffness requirements for ascent control of all variants, the actual stage masses might significantly increase. Any definitive answer on the impact and potential restrictions require a considerably more detailed analysis followed by thorough evaluation of obtained results.

4.2 Overall performance and mass comparison

This paper has not the intention of comparing different launcher concepts in a generic way with exactly the same modelling assumptions for engine- or structural efficiency and identical performance requirements. Nevertheless, the stage and engine building blocks and mission constraints have overall sufficiently good similarities that a comparison of the launcher types makes sense.

Maximum payload performance, such as that required for GTO missions or manned ISS flights, requires the use of the XXL-type BB-VTVL-launchers with both core and upper stages expendable. Despite all the differences in architecture, this configuration's performance is pretty close to the one of RLVC4-VTHL 3STO. On the other end of the spectrum, the SSO-mission can be served by the M- or L-versions of the BB-TSTO or by the Mini-TSTO of the VTHL. Achievable payload ratios of the VTVL are in general below the VTHL using IAC with the exception of the LOX-

LH2 M-size BB reaching 1.5% above 1.14% for the Mini-TSTO (see Table 1). This is the consequence of using a large RLV-stage also for smaller missions.

While the relevant missions can be served by all investigated (family) concepts, the range in necessary lift-off weight could be vast. In the GTO-example almost the same separated payload could be lifted by RLV-C4-IIIB with LOX-LH2-staged combustion propulsion at GLOW 665 t or by VTVL with methane gas-generator type in the XXL-configuration and reusable side-boosters at 1842 t (+177%). The launcher with reusable first stage and lowest lift-off weight reaching still meaningful payload is the LOX-LH2-M-size BB with slightly below 300 tons.

5 Conclusion

Different options for the next generation of European RLV-launchers have been investigated. Option 1 regarding "Building Block" families with 1st stage as VTVL-RLV are found technically feasible when assuming 3-stage and 2-engine BB-elements. In case of LOX-LH2 five different launchers are identified while for LOX-LCH4 only four different sizes are feasible. The GLOW of LOX-LCH4 is always found roughly 80% above LOX-LH2, although the payload capacity of the methane concepts as RLV is constantly significantly lower.

The second option with a "Big-Size" VTHL-RLV and side-mounted expendable upper stages is also confirmed to be technically feasible as 3STO to GTO, TSTO for heavy payload to LEO-ISS and as an innovative Mini-TSTO for smaller SSO-missions. The feasibility and related constraints of the very high-speed reentry with small upper stage have been analyzed and 6DOF-simulations of the RLV-reentry with simplified controls have been performed for the GTO-mission.

The preliminary launcher system sizing approach revealed that seemingly contrarious options have many characteristics in common if the number of launcher configurations in the BB-family are limited to a maximum of 3 different variants. Further refinements of the models are recommended for future work.

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