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Fully Reusable Launch Vehicles: Coping with Technical Challenges for All Classes

Grazia Piccirillo[*][†], *Francesco Cascone*[*], *Giuseppe M. Infante*[*], *Francesca M. Pisano*[*], *Mario De Stefano Fumo*[*], *and Giuseppe Rufolo*[*]

[*] *Space Directorate, Italian Aerospace Research Centre*

Via Maiorise, 81043 Capua (Italy)

g.piccirillo@cira.it – f.cascone@cira.it

[†] Corresponding Author: g.piccirillo@cira.it

Abstract

This paper presents a preliminary system-level assessment of fully Reusable Launch Vehicles (RLVs) across all classes, with a specific focus on upper stage re-entry, recognized as one of the most critical technical challenges. While interest in fully RLVs is increasing, European research efforts are still evolving, with future directions yet to be defined. To begin studying these emerging systems, the paper reviews potential landing strategies, vehicle configurations, and Thermal Protection Systems (TPS) for reusable upper stages. Technical considerations, along with promising TPS technologies, are outlined to support future trade-off analyses and European efforts toward next-generation reusable launch systems.

1. Introduction

Reusable Launch Vehicles (RLVs) have emerged as a key technology to reduce space access costs, which has become an increasingly urgent objective for the space transportation sector due to rising launch demand and industry competitiveness. RLVs enable the recovery and refurbishment of key components for multiple uses, offering the potential for substantial cost savings per launch. Beyond this, reusable systems also aim at supporting the long-term sustainability of space operations. As orbital regions become progressively more congested with satellites, spent stages, and mission-related debris, the need to mitigate further accumulation has become even more critical [1].

U.S. private companies like Space X and Blue Origin have recently driven significant progress in this area, marking a notable advancement compared to past efforts. Space X's Falcon 9 has proven the technical and economic feasibility of partial reusability with its first-stage recovery via Vertical Landing (VL) [2]. Building on this success, the company is now testing Starship, a fully reusable launch system designed to further reduce costs and support high-frequency missions to Low Earth Orbit (LEO) and even beyond [3]. Similarly, Blue Origin's New Shepard has proven Vertical Take-off (VT) and VL for suborbital vehicles [4], and is now progressing toward New Glenn, a heavy-class launch vehicle featuring a reusable first stage [5]. Following the lead of Space X and Blue Origin, other companies and startups, such as Rocket Lab and Relativity Space, are also investing in reusable space systems technologies [6, 7, 8].

Currently, the configurations receiving the most attention are vertically launched, rocket-based systems, spanning various launcher classes and levels of reusability, considering both partial and fully recoverable systems. Nevertheless, recent studies and market forecasts indicate reusability is more viable for medium to heavy launchers, with the delivery of larger payloads via super-heavy launchers representing the most cost-effective solution [9]. Demand for small launch vehicles has declined over the past year, as larger launchers offer more competitive launch cost per kilogram of payload and higher launch frequency, largely due to the ridesharing possibility [10].

Regarding the level of reusability, the recovery of the first stage has already proven to be a feasible and efficient technology, whereas no comparable technical solution yet exists for the recovery of stages that reached the orbit. However, interest in the development of reusable upper stages is steadily growing, not only as a step toward full launcher reusability, but also as a compatible component with expendable first-stage configurations [11]. Upper stages can account for up to 30% of a launcher's hardware costs, making their reusability a potentially key factor in further reducing launch cost [12]. Besides this, reusable upper stages can enable new mission architectures (e.g. interplanetary transfers with in-orbit refuelling, secondary missions, and cis-lunar operations), hereby improving the competitiveness of future space systems and opening new frontiers for space economics. Moreover, considering the recovery of the payload fairing presents an additional opportunity to improve the system's sustainability by helping to reduce the amount of orbital debris generated during missions.

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Despite the promising potential of fully RLVs, current European research in this area remains predominantly at conceptual level. The most critical challenge lies in the development of reusable upper stages, which necessitates innovative designs capable of withstanding atmospheric re-entry at orbital velocities, ensuring safe and controlled recovery, and supporting multiple reuse cycles [13].

These aspects are being addressed within the framework of the Future Launchers Preparatory Programme (FLPP), an initiative launched by the European Space Agency (ESA) in 2004 [14]. The FLPP aims to foster the development of advanced technologies to strengthen Europe's competitiveness in the global space sector. As part of this long-term vision for next-generation launch systems, the programme also investigates fully reusable architectures.

The Italian Aerospace Research Centre (CIRA) is actively contributing to this effort by identifying key challenges in the domains of aeroshape design and Thermal Protection Systems (TPS), including hot structures, innovative materials and design choices to enable launcher reusability. This paper presents CIRA's pre-design considerations on fully RLVs across all launcher classes. A systematic analysis to identify and consolidate the most promising configurations and enabling technologies, particularly for reusable upper stages, is still lacking. This study seeks to address this gap by reviewing the current state of research and evaluating viable and potential architectural options to support the development of fully reusable systems, specifically coping with one of the main technical challenges: the atmospheric re-entry of the upper stage. By evaluating technical feasibility and limitations, this work intends to support future European efforts toward the next-generation reusable launch systems.

2. State of the art

The first significant advancement in reusable spaceflight was achieved through the NASA's Space Shuttle in the early 1980s. Featuring a winged spaceplane design capable of Horizontal Landing (HL) on runway, the Shuttle was the first operational spacecraft integrating reusable elements, specifically the orbiter and solid rocket boosters. Despite its pioneering nature, the Shuttle program ultimately failed to deliver on its promise of low-cost spaceflight, due to high refurbishment costs, complex maintenance procedures, and safety concerns [15]. Even so, throughout the Shuttle era, considerable effort went into exploring reusable spaceplanes with HL capabilities. However, these systems, such as Hermes studied by the ESA or Hope (H-II Orbiting Plane) investigated by the Japan Aerospace Exploration Agency (JAXA), were typically designed as orbiters only, without autonomous launch capability [16].

From the 1990s onward, research focused on developing fully reusable systems capable of independently launching, reaching orbit, and returning. Single-Stage-To-Orbit (SSTO) architectures were initially proposed to simplify launch systems by eliminating staging, enabling a single vehicle to reach orbit [17]. Most SSTO concepts, like Skylon and Lockeed Martin X-33, adopted winged spaceplane configurations for HL. However, they encountered major technical hurdles, particularly in achieving the mass efficiency, propulsion performance, and TPS requirements necessary for both ascent and HL recovery. To address these challenges, especially those related to propulsion complexity during HL, the first VL demonstrator, McDonnell Douglas DC-X (later DC-XA), was developed in the same years. Concepts for reusable launch systems with TSTO architecture and VTVL capability also emerged. The Kistler K-1 [18] was introduced as one of the first commercial efforts toward a fully reusable TSTO vehicle. Designed for orbital missions with both stages recoverable, the program was cancelled in 2007 before reaching flight.

Heritage from past RLV programs has guided current research toward TSTO architectures. However, the recovery of the orbital stage continues to represent one of the main technical barriers. Table 1 provides a classification of the concepts currently under development along with recent research initiatives, organized by launcher class (defined by payload capacity to LEO) and degree of reusability.

One of the main factors that distinguishes the mission and system architecture between the classes is the recovery strategy for the reusable stage. For small-lift vehicles, parachute-assisted splashdown followed by ocean recovery has been evaluated for stage retrieval by PLD Space's Miura 5 and Rocket Lab's Electron. In contrast, medium- and heavy-lift vehicles are expected to perform propulsive landings on either ground-based pads or sea-based platforms.

Partial reusability through the recovery and reuse of the first stage, is the most extensively studied option from small to heavy-lift classes. Increasing attention is being directed toward fully reusable architectures, targeting the recovery of both stages. The British company Astron Systems is currently developing a fully reusable launcher for small payloads, named Aurora, with both rocket stages employing a parafoil recovery system. Stoke Space is developing Nova, a fully reusable, medium-lift VTVL launch vehicle concept, including a reusable payload fairing. Pushpak RLV-TD, a heavy-lift vehicle, is testing HL, adopting a spaceplane-like configuration. Similarly, SpaceX is exploring VTVL for its fully reusable super heavy-lift launcher, Starship. Specifically, the Super Heavy booster is intended to be caught by ground-based mechanical arms, known as the "Mechazilla" tower, and the Starship upper stage will likely be recovered similarly using tower-assisted capture. For the same launcher class, ESA's Pathfinder initiative, is investigating advanced concepts for future fully reusable European launch systems in the super-heavy segment.

Given the complexity of developing reusable upper stages, recent European research initiatives, such as the Smart Upper Stage for Innovative Exploration (SUSIE) developed by Arianegroup, Reusable Upper Stage (ReUps) project promoted by ESA, and DEMESURE, a newly project call from Centre national d'études spatiales (CNES), are

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specifically focusing on this challenge, targeting heavy and super-heavy launch vehicles. These latest initiatives build upon previous European programs, that have intensified since 2016 through dedicated projects. Examples include ENTRAIN project [19, 20], aimed at identifying landing strategies for first-stage recovery, and the development of technology demonstrators such as CALLISTO [21], a collaborative effort by DLR, CNES, and JAXA, and ReFEx [22], led by DLR. More recent activities, such as the Horizon Europe projects RETALT [23] and SALTO [24], along with ESA's FLPP are further advancing the critical technologies required for future fully reusable launch systems.

Table 1: Classification of current RLVs concepts and research initiatives

Launcher class	**Reusable 1st stage**	**Reusable 1st and 2nd stage**	**Reusable upper stage**
Small *Payload: < 2 tons*	Miura 5 [25], Electron [6]	Aurora [26]	-
Medium *Payload: 2-20 tons*	Falcon 9 [2], Neutron [7], Tianlong 3 [27], Amur [28], Long March 10A/8A [29]	Nova [30]	SUSIE [11], ReUps [31]
Heavy *Payload: 20-50 tons*	Falcon Heavy [32], New Glenn [5], Terran R [8], Gravity [33]	Pushpak RLV-TD [34]	DEMESURE [35]
Super-heavy *Payload: > 50 tons*	-	Starship [3], ESA Pathfinder activity [36]	-

3. Concepts of Operations

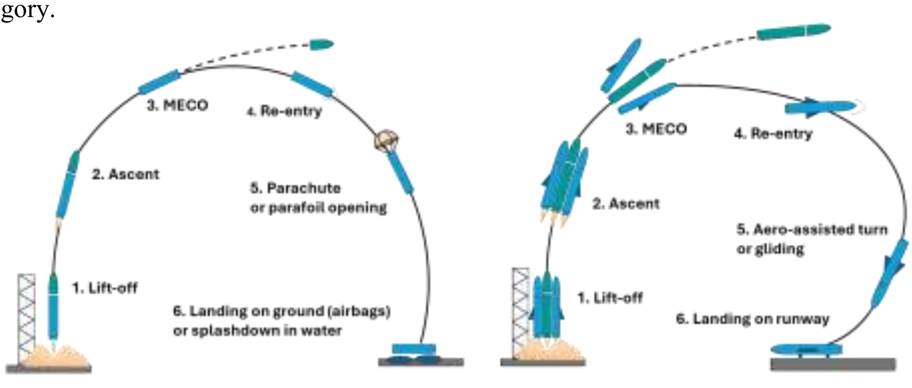
Fully RLVs can support a broad range of mission types, from conventional payload delivery to Earth orbit to more advanced operations. This is made possible by the upper stage's ability to remain in orbit and continue operating. Unlike expendable systems, where the upper stage is discarded or deorbited after a single use, a reusable upper stage can support extended and innovative missions, such as cis-lunar or interplanetary transfers, and even in-orbit servicing or secondary payload deployments. A comprehensive overview of these missions based on a review of literature and ongoing development concepts is presented below [37, 11, 38, 3]:

- Deliver payload to Earth orbit: missions can target LEO or MEO (Medium Earth Orbit) for deploying small satellite constellations used in Earth observation, broadband communications, or space telescopes; GEO (Geostationary Orbit) for large communications or weather satellites; SSO (Sun-Synchronous Orbit) for scientific satellites focused on climate monitoring, environmental research, or remote sensing; and GTO (Geostationary Transfer Orbit) as an intermediate orbit used to transfer payloads to GEO or higher orbits.
- Cislunar missions in the space between Earth and the Moon to support logistics, technology demonstrations, and preparation for deep space exploration.
- Interplanetary missions, such as delivering space probes, planetary landers, Mars/habitat logistics modules.
- Freight or crew delivery to space stations, transporting cargo resupply modules, habitat expansion modules, scientific experiments or crewed spacecraft.
- Secondary missions: in-space or in-orbit servicing operations, such as refuelling or transportation of refuelling modules, active debris removal, satellite maintenance/repair payloads, orbital assembly components, space situational awareness sensor, scientific experiments in orbit.

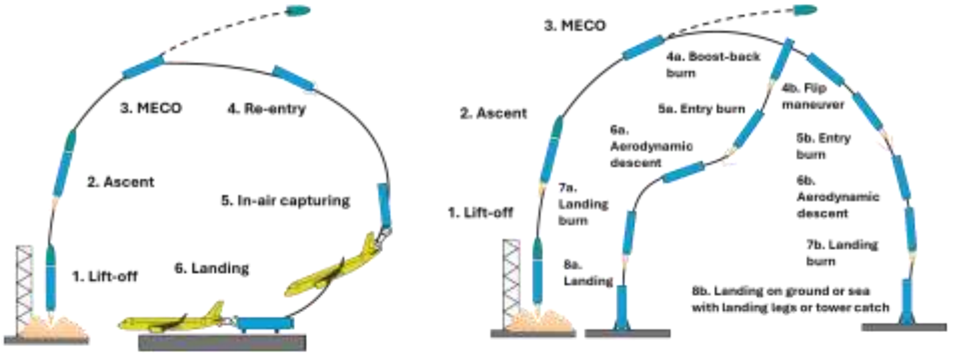
In a TSTO architecture, mission phases are typically divided between the two stages. The first stage performs lift-off, ascent, and returns via a controlled landing after re-entry within the upper atmosphere. The second stage is responsible for payload release, followed by its own controlled descent and landing from space.

Re-entry and landing are the key phases that distinguish the Concept of Operations (CONOPS) of RLVs from expendable systems. The first stage re-enters at suborbital velocities, encountering moderate thermal and structural loads. In contrast, the upper stage must withstand re-entry from orbital velocity (approximately 7.8 km/s for LEO, and up to 11 km/s for higher-energy trajectories) resulting in harsher conditions due to prolonged hypersonic flight, intense aerodynamic heating, and high deceleration. Controlled landing is critical for both stages to preserve structural integrity and minimize refurbishment efforts. Since the choice of return method significantly influences the launcher architecture and related technologies numerous studies have evaluated and compared various reusability methods.

In the European context, most of this research has focused on first-stage return, primarily evaluating HL versus VL for medium and heavy launcher's classes. Fig. 1 summarizes the identified landing options for lower stages for each launcher category.



Horizontal landing with decelerators **Lifted or gliding horizontal landing**



Mid-air retrieval **Propelled vertical landing: RTLS (a), DRL or tower catch (b)**

Figure 1: Possible return methods for lower stages

As part of ESA's FLPP, a system-level trade-off study was conducted in collaboration with CNES to assess possible recovery strategies for the first stage of Ariane 6 [39]. Three main recovery concepts were evaluated: "Toss-Back", "Gliding", and "Fly-Back". The "Toss-Back" strategy involves propulsive VL, intended either as Return To Launch Site (RTLS) or Downrange Landing (DRL). In the RTLS case, the stage performs a rotation and a boost-back burn after separation, requiring precise guidance and deep engine throttling for a controlled touchdown. The DRL option follows a ballistic trajectory, reducing propellant consumption but necessitating a recovery platform downrange, typically at sea. The other two strategies are based on HL. The "Gliding" concept refers to a controlled descent of the vehicle without power, relying solely on aerodynamic forces to guide the vehicle to the ground. While this simplifies propulsion requirements, it introduces significant mass and aerodynamic penalties during ascent, adds structural complexity, and demands the use of dedicated ground infrastructure. The "Fly-Back" concept builds upon the Glider configuration by integrating air-breathing engines, enabling the stage to return actively to the launch site under its own power on runway. Although more efficient in the return phase, "Fly-Back" increases system complexity and requires additional subsystems, such as turbojets adapted for the space environment. Due to its higher development cost and complexity, the "Fly-Back" option was ultimately excluded from further consideration, with the analysis focused on "Toss-Back" and "Gliding" modes. A similar trade-off analysis was carried out within the ENTRAIN project, focusing on a heavy-class launcher [19, 20]. Both VL and HL strategies were considered, including RTLS and DRL for VL, and Fly-Back (FB) and In-Air Capturing (IAC) for HL. The latter, further explored in DLR's FALCon project [40], involves a towing aircraft retrieving the stage mid-air and guiding it to a runway landing, thus avoiding the need for onboard jet engines and additional return fuel.

Launcher mass significantly impacts the selection of the recovery method. While the strategies described above have been evaluated for medium and heavy launch vehicles, alternative HL approaches using passive deceleration systems, such as parachutes, parafoils, and airbags, traditionally used for recovering lightweight components or payloads, are now being explored for reusable small launch vehicles, like Miura 5 and Aurora. Specifically, this approach is considered the most suitable option given the strict mass and volume constraints of small vehicles, which make the integration of propulsive systems or aerodynamic surfaces for runway landings technically and economically unfeasible [18, 41]. No specific recovery strategies are currently being studied in Europe for super-heavy reusable lower stages. An emerging solution is the “Mechazilla” system, envisioned for recovering Starship's Super-Heavy stage. The landing follows a propelled VL profile, but instead of touchdown, the stage is captured mid-air by mechanical arms mounted on the launch tower. This eliminates the need for landing legs, reducing structural mass, simplifying thermal protection and recovery operations.

Currently, no specific landing strategy has been extensively studied for upper stage recovery, except for SpaceX’s Starship, which is expected to use the tower catch method also for upper stage. Although upper stages are generally lighter than lower stages, they face more challenging conditions during re-entry, requiring dedicated design considerations. As highlighted in [13], conventional recovery solutions, such as capsule-based or Shuttle-derived systems, are being reconsidered for compact upper stages. However, elongated configurations present added challenges due to aerodynamic instability and shifting mass distributions during re-entry. While inflatable and rigid deployable decelerators show promise, further research is needed to validate their applicability. Therefore, in this preliminary analysis, landing strategies analogous to those employed for lower stages, considering the technical limitations related to the vehicle’s mass, are assumed. Accordingly, Fig. 2 outlines potential upper stage landing strategies, referencing those already considered for lower stages.

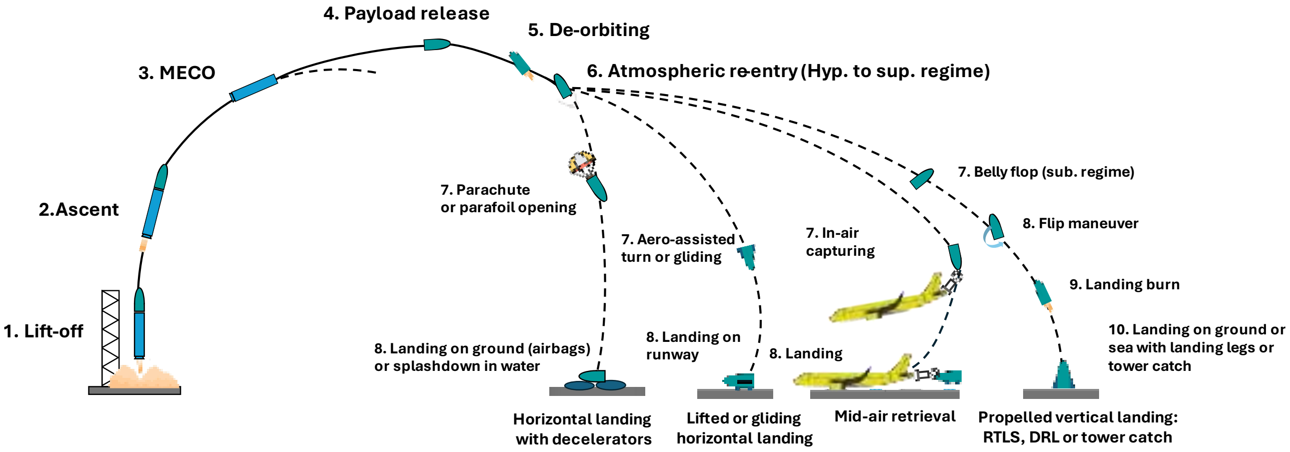


Figure 2: Possible return methods for upper stages

4. Technical Challenges and Enabling Technologies

Based on the identification of possible mission profiles and return methods, some general technical challenges and associated enabling technologies for fully RLVs have been outlined in Table 2, aiming at providing a preliminary framework for guiding more detailed system design activities.

Table 2: Challenges and related technologies needed to enable full launcher’s reusability

Challenges	Enabling Technologies
Perform ascent and controlled re-entry	Vehicle configurations and propulsion systems capable of operating across varying flight conditions and regimes, from high-thrust ascent to precise, controlled descent
Survive re-entry	Mass efficient ascent/entry TPS technologies, advanced modelling/simulation tools and effective thermal sensors and measurement systems
Perform precision landing	Aerodynamic/control surfaces, throttleable engines, advanced GNC algorithms and GNSS systems, control, stabilization systems (e.g. grid fins, cold gas thrusters), reliable structures to support touchdown
Guarantee safe recovery	Dedicated landing and post-landing facilities (e.g. ground landing sites, drone-ships, recovery facilities)
Ensure structural integrity for reusability	Optimized structures, advanced materials, modular and serviceable system architectures

Unlike expendable systems, where vehicle configuration and engines are optimized solely for ascent, RLV shall be able to perform both efficient ascent and controlled re-entry. Specifically, RLVs' aeroshape strongly depends on the selected return method, as landing strategy has a direct impact on the vehicle's structural layout, mass distribution, and overall system architecture. For HL, engines must adapt to aerodynamic constraints and deliver sustained, controllable thrust [17]. In VL scenarios, they must enable retro-propulsion with precise throttle control and high reliability [23].
One of the most critical challenges in enabling fully RLVs is ensuring the structural and functional integrity of the system during atmospheric re-entry. This aspect, particularly relevant for upper stages returning from orbital velocities and exposed to severe aerothermal loads, represents the primary focus of this study. During re-entry from space, the vehicle experiences extreme thermal gradients, high-pressure shock layers, and material ablation risks. TPS must not only withstand these harsh conditions but also support repeated use without significant degradation. In this context, enabling technologies include high-performance, low-mass TPS for extreme entry conditions (e.g., >5000 W/cm² and entry velocities >11 km/s, such as for high-mass Mars entries), advanced modelling and simulation capabilities for TPS behaviour prediction, and integrated sensing systems to monitor in-flight TPS performance [42].
Additionally, perform precision landing is essential to preserve the integrity of the component. To ensure that, it is necessary to develop and integrate into the design advanced systems to support descent and touchdown depending on the chosen landing approach. These may include aerodynamic and control surfaces, throttleable engines, advanced guidance, navigation, and control (GNC) algorithms, GNSS systems, stabilization mechanisms such as grid fins or cold gas thrusters, and robust structural elements capable of withstanding landing loads [43, 44].
To guarantee safe recovery and reuse, appropriate landing and post-landing infrastructures must be developed. These may include dedicated landing platforms (such as drone ships, if required) and ground facilities for vehicle recovery and refurbishment, all designed to handle the vehicle without causing further damage. Lastly, maintaining structural integrity over multiple missions requires durable materials and modular designs, and easy-to-service components. The structure must balance strength and weight while allowing straightforward inspection, refurbishment, and replacement.

5. Preliminary System-Level Assessment across Launcher Classes

As outlined in Section 3, despite significant research interest, there is still no clear consensus on the optimal configuration and technological solutions for future European fully RLVs. In this context, a system-level evaluation of all existing options is proposed to identify the most suitable design alternatives for each launcher class, before refining them in more detailed studies. Fig. 3 describes the methodology followed to conduct the preliminary system-level assessment. The analysis specifically focuses on re-entry challenge and has the objective to map potential solutions for both lower and upper stages across various launcher categories. This analysis ultimately aims to match the most suitable landing strategies and technological solutions to each RLVs concept.

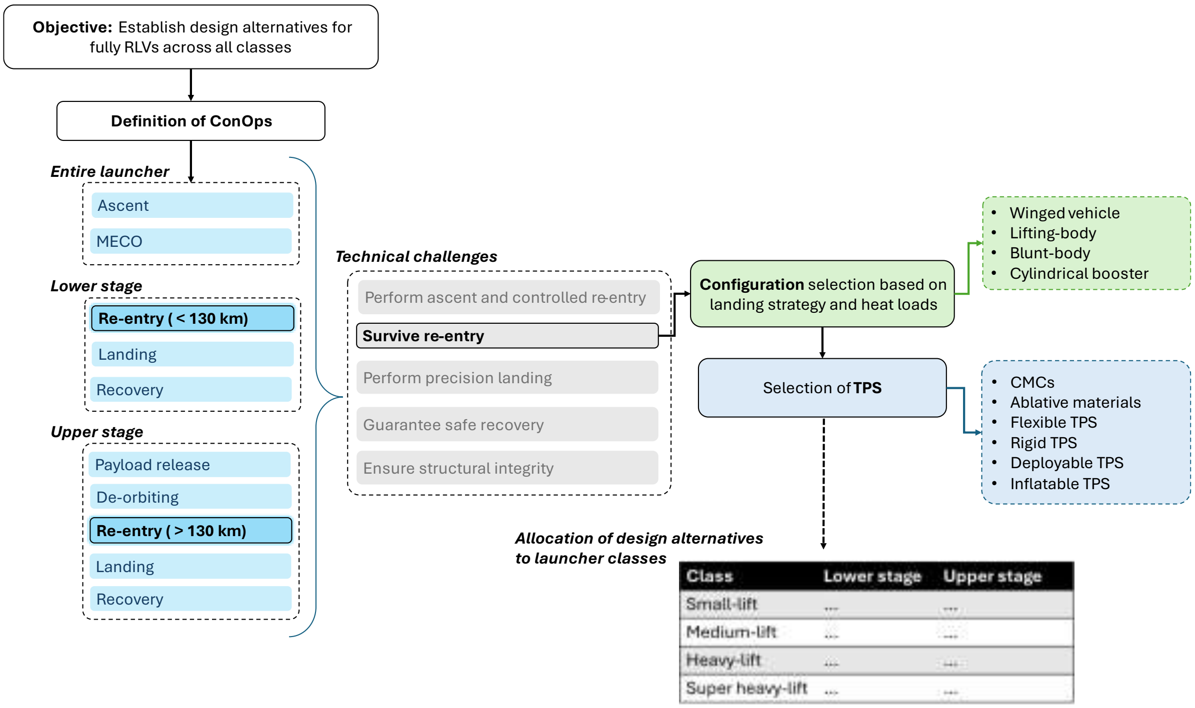


Figure 3: Methodology for preliminary system-level assessment of RLVs

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5.2 Options for System Architecture

To ensure re-entry survivability and maintain system integrity, the vehicle must adopt a configuration that is not only compatible with the selected landing strategy but also effective in minimizing aerodynamic heating and thermal flux along the re-entry trajectory. This must be complemented by an efficient TPS capable of managing heat loads without compromising the structural integrity of the vehicle. Therefore, this section reviews the available system architecture options, focusing on configurations and TPS alternatives, covering both well-established solutions and emerging approaches for reusable space systems and re-entry vehicles. These options will subsequently be evaluated in the preliminary system-level assessment across all launcher classes.

5.2.1 Configuration

Re-entry vehicles typically adopt winged, lifting-body, blunt-body, or cylindrical booster configurations. Table 3 offers a comparative summary of their aerodynamic characteristics, re-entry methods, pros and cons, as well as indicative ranges for the performance parameters considered, while further details are provided in the paragraphs below.

Table 3: General characteristics of re-entry vehicles configurations

Configuration	Aerodynamic efficiency (L/D)	Ballistic coefficient (C_B)	Re-entry strategy	Pros	Cons
Winged	$4-5$ in subsonic flight $\cong 1$ in hypersonic flight	$500\ -3000\ \mathrm{Kg/m^2}$	Steep descent path with high AoA and lifted descent	Low g-loads, cross-range, runway landing	Heavy wings/TPS, complex structure
Lifting-body	$2-3$	$200\ -2000\ \mathrm{Kg/m^2}$	Steep descent path with high AoA (typically higher than winged vehicles) and gliding	Simpler than wings with a moderate lift	High heating, no powered landing
Blunt-body	< 0.5	$300-400\ \mathrm{Kg/m^2}$	Rapid descent from hypersonic to subsonic regime and landing with decelerator devices and/or airbags/retro-rockets	Simple structure, high payload fraction	High g-loads, expendable TPS
Cylindrical booster	$\cong 0$	$100-2000\ \mathrm{Kg/m^2}$	Vertically propelled trajectory (lower and upper stage) or ballistic unpropelled trajectory (lower stage)	Engine-based control, rapid VTVL recovery	Complex landing hardware, high heating

5.2.1.1 Winged vehicle

Winged configurations, or spaceplanes, shown in Fig. 4, represent one of the most extensively studied architectures for space vehicles designed for orbital return and reuse. Adopted in the Space Shuttle Orbiter and in the Boeing X-37, this type of configuration is also being considered for future reusable stages, as demonstrated by ReFex project. Winged vehicles feature large lifting surfaces that enable controlled aerodynamic descent with relatively high subsonic lift-to-drag ratios (e.g. Space Shuttle L/D rises to ≈4–5 in approach [15]). This allows for precision landings and high cross-range capability. However, at hypersonic speeds (e.g. Mach 20), their effective L/D drops to ≈1, requiring steep descent paths or high angles of attack early in re-entry. Additionally, winged designs have variable effective ballistic coefficients (expressed as $C_B = m/C_dA$, where C_d is the drag coefficient and is A the cross-sectional area). By orienting "belly-first" at high attitude they can achieve low aerodynamic speed and drag (keeping re-entry shallow), whereas other configurations, such as capsules, have fixed high C_B. For example, analyses show winged boosters (LFBB concept) can attain C_B of 500–3000 kg/m² (at high AoA) vs. ≈7900 kg/m² for a small unguided capsule [22].

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Control is maintained through aerodynamic surfaces and thrusters, enabling lifting re-entry trajectories rather than ballistic ones. This configuration enable re-entry from orbital speed ($\gtrsim$Mach 25 at $\sim$120 km) with a high AoA to produce drag and lift, then perform gradual pullouts and banked turns. Hypersonic heating is intense but spread over longer time; peak heating occurs in upper atmosphere. Typical Mach vs. altitude profiles show winged vehicles maintaining lift into the high Mach regime (e.g. Space Shuttle decelerating from Mach 25 to subsonic over 50–60 km). Despite their advantages in enabling controlled orbital re-entry, winged configurations present several structural and operational drawbacks. Their long wings and lifting fuselages must withstand significant aerodynamic and manoeuvring loads, requiring reinforced airframes and heavy landing gear for runway landings. Additional systems such as wheels or skids further increase dry mass and complexity. These factors reduce the payload fraction: for example, the Space Shuttle orbiter had a dry mass of ≈78 t for a maximum payload of ≈24 t, whereas a blunt capsule of similar mass could carry substantially more. Furthermore, HL operations require dedicated runway infrastructure, adding logistical complexity compared to vertical recovery. Ultimately, winged vehicles have primarily operated in the medium (e.g. X-37, ≈2–3 t to LEO) and heavy-lift classes (e.g. Shuttle, ≈24 t to LEO).

Figure 4: Examples of winged configuration

5.2.1.2 Lifting-body

An alternative similar to winged vehicles is the lifting-body, such as NASA HL-10, the Dream Chaser or ESA IXV, all depicted in Fig. 5. This configuration uses a fuselage-shaped body to generate lift, with little or no distinct wing. Their aerodynamic L/D ratios are modest, with a maximum L/D ≈2–3. Steering is via small fins and body flaps; control authority is lower than winged vehicles, especially at high AoA. Lifting bodies typically have lower frontal area (and thus higher C_B) than capsules of equal mass. For example, HL-10 and M2-F2 had significantly lower maximum L/D than Shuttle, resulting in steeper descent. In practice, lifting bodies re-enter at high angle-of-attack (≈40–50°) to maximize drag. Consequently, their trajectories are steeper and shorter than winged vehicles, but often shallower than pure ballistic. ESA's IXV for instance re-entered from Vega orbit at Mach 25 into controlled glide down to Mach 2, then deployed parachutes [45]. Thermally, lifting bodies share capsule-like regimes: blunt-shape shock layers and high convective heating. The underside heating is intense; like capsules, many lifting-body demonstrators have used ablative or expendable TPS on nose/underbody. Structural design is robust (steep re-entry loads), and there is no heavy wing structure, as the body itself must carry heat loads and lift. This allows good structural efficiency due to no wing bending but still requires stiff high temperature materials on leading surfaces. For recovery, lifting bodies typically performs HL like small gliders. The original HL-10 and X-24 flights were unpowered glides to runway, often following steep re-entry "dives". IXV flew like a guided lifting body then landed via parachute in the ocean. No lifting-body vehicle has flown powered vertical (VTVL) recovery. In general, lifting bodies have been mainly proposed for small to medium classes.

Figure 5: Examples of lifting-body configuration

5.2.1.3 Blunt-body

Blunt-body or capsules (e.g. Apollo, Soyuz, Dragon 2 in Fig. 6) are characterized by a rounded, conical or spherical frontal shape and no aerodynamic surfaces. They are ballistic re-entry vehicles: L/D is very low (typically <0.5) and cannot be altered except by attitude trim. Capsules decelerate deep in the atmosphere, sustaining very high peak heating and loads. For instance, Apollo Command Module (mass ≈6 t, ≈3.9 m diameter) had C_B of order 300–400 kg/m². The blunt shape creates a detached shock that keeps heat away, but leading edges can reach >1500 °C. For this reason,

capsules typically use single-use ablative TPS (e.g. PICA on Dragon, AVCOAT on Orion) rather than reusable tiles. Control during re-entry comes from natural trim (using an offset of the Center of Mass) and/or small thrusters.
The re-entry profile is steep: capsules enter at orbital velocity (Mach ≈25) and follow a near-ballistic arc. Deceleration peaks (7–8g) occur at Mach ≈3–5 and 10–20 km altitude. Unlike winged vehicles, capsules cannot extend flight time; they rapidly slow to subsonic and then typically use parachute or parafoil for final descent eventually with or with airbags/retro-rockets for ground touchdown. (e.g. Soyuz Descent Module). Structurally, capsules are strong and compact. The lack of wings or large control surfaces means low structural mass overhead, giving high payload fraction. Historically, capsules have been the main human reentry vehicles (Mercury, Gemini, Apollo, Soyuz, Shenzhou, Crew Dragon, Starliner) and large robotic landers. All have been small (Mercury ≈1 t) to heavy (Apollo ≈6 t, Orion ≈25 t) class; capsules scale easily with size and have been favored for heavy-lift and beyond-LEO missions (e.g. Orion for deep space). Recent developments focus on reusability: Dragon 2's heatshield is partially reusable [46], and NASA is studying replaceable TPS for Orion [47].

Figure 6: Examples of blunt-body configuration

5.2.1.4 Cylindrical booster

Lastly, newly investigated designs for reusable stages increasingly consider also cylindrical booster shape. This alternative refers to rocket boosters, typically first stages, shaped like cylinders with small fins or grid-fins for control (e.g. Falcon 9, New Glenn and Starship, presented in Fig. 7). Aerodynamically, these bodies produce negligible lift (L/D ≈ 0), so they behave ballistically during re-entry (high C_B), flying nearly vertical trajectories. After stage separation, boosters travel up and turn to re-enter head-first, using retro-thrust during entry burn in the atmosphere to reduce speed. Without lift, peak deceleration and heating occur deeper in the atmosphere. However, descent altitude can be modulated by timing of engine reignition. Indeed, control authority comes from retro-propulsion and small actuated surfaces. For example, Falcon 9 first stage reignites one or more engine burns to bleed off velocity before atmospheric entry, then uses grids and final flip & landing burn at ∼1 km to land.
Structurally, boosters are thick-walled pressure tanks with engines. They support engines and fuel, not large wing loads. This type of layout is currently being considered for launchers ranging from small- to super-heavy-lift. Potential landing strategies include decelerator-assisted recovery for small-lift launchers, and vertically propelled landing for larger classes. In the latter case, the architecture must account for additional engines and propellant to support re-entry and landing, unlike winged configurations which rely on aerodynamic surfaces. Further system complexity may arise from the integration of landing legs or other landing-support structures, as well as dedicated infrastructure for ground- or sea-based landing platforms. This configuration is considered particularly promising for first-stage applications, while no practical implementations for upper stages have been demonstrated so far, except for SpaceX's Starship, for which a dedicated testing campaign is currently underway.

Figure 7: Examples of cylindrical configuration

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5.2.2 Thermal Protection Systems

Various TPS technologies are currently available, each offering distinct advantages and limitations. Their suitability for different stages of RLVs depends on technical and mission-specific constraints. In scenario where repeated use, structural integrity, mass efficiency, and ease of maintenance are essential, careful evaluation of their properties is fundamental. Therefore, the following paragraphs present a review of the main TPS materials and architectural options typically adopted for re-entry vehicles, analysing their characteristics to support the assessment of their use for both lower and upper stages of fully RLVs.

5.2.2.1 Ceramic Matrix Composite (CMC)

Ceramic Matrix Composites (CMCs) are advanced materials made by reinforcing a ceramic matrix with ceramic fibres [48]. Compared to traditional metals and many engineering materials, they are much lighter and far more resistant to high temperatures and harsh environments. Initially developed in the 1970s for aerospace and defence, CMCs were designed to meet the demanding needs of reusable spacecraft, especially in TPS. Since then, their use has expanded, including in propulsion components like nozzle extensions and combustion chambers, and even in lightweight satellite structures for communication systems. CMCs are especially valuable in areas exposed to extreme heat during atmospheric re-entry, where temperatures can exceed 1600°C and rise rapidly within seconds. To protect critical parts such as nose caps and wing edges, early spacecraft like the Space Shuttle used carbon-carbon materials with special coatings. Later, LSI-based C/SiC composites were employed in the Soviet Buran program and in European projects like Hermes [16], X-38, and EXPERT. A major milestone was the successful flight of ESA's IXV which featured a complete CMC-based TPS. Today, Europe continues this development with the Space Rider vehicle, whose TPS made from ISiComp® (a type of LSI C/SiC) is currently undergoing qualification within CIRA facilities.

5.2.2.2 Ablative TPS

Rigid ablative materials are a class of TPS designed to handle extremely intense heat loads during atmospheric entry, withstanding heat fluxes from 1,000 up to 7,000 W/cm² or more. They work by gradually breaking down under heat: as the material chars and erodes, it absorbs energy and protects the underlying structure of the spacecraft. This makes them ideal for missions that face extreme re-entry conditions, such as Mars return missions or high-speed Earth entries. In the United States, several types of rigid ablators have been developed and tested, including PICA (Phenolic Impregnated Carbon Ablator), Avcoat, and carbon-phenolic materials, each with different performance limits depending on the environment. For example, carbon-phenolic has been used in conditions exceeding 540 W/cm² and very high pressures, while others like SLA-561V have flown successfully on Mars entries at much lower heat flux levels [49]. In Europe, various ablative solutions have also been developed and tested, such as cork-based P50, SV2A, Norcoat 62250 FI, and Aleastrasil, some of which were flown on vehicles like Ariane 5, VEGA, and ESA's Atmospheric Re-entry Demonstrator (ARD). However, it should be noted that, due to the material's consumption during each re-entry, ablative TPS requires inspection, refurbishment, or complete replacement of the charred layers before subsequent flights. As a result, despite their robust performance, ablative systems cannot be considered fully reusable. Nevertheless, it is included here as it may still offer the most cost-effective solution for small- and medium-class vehicles. Current research is also investigating low-ablation variants such as ASTERM, a rigid, carbon-felt-based material similar to PICA, which has shown promising results in small-scale ground tests. If the heat flux environment is low enough, these materials could enable reusability for upper stages, although further testing and qualification are required.

5.2.2.3 Flexible TPS

Flexible thermal protection systems have played a key role in past reusable spacecraft, offering a lightweight and easily maintainable solution for areas exposed to moderate temperatures. For example, NASA's Space Shuttle used Advanced Flexible Reusable Surface Insulation (AFRSI), stitched ceramic fabric blankets with silica fiber filling, designed for temperatures up to around 1000°C. Lower temperature zones were protected using Felt Reusable Surface Insulation (FRSI), suitable up to 500°C, while ceramic-based thermal barriers could operate above 1200°C. In Europe, Flexible External Insulation (FEI) systems have been developed and partially qualified, covering temperature ranges from 300°C to 1100°C. These systems are particularly promising for reusable applications due to their low mass, ease of inspection, and potential for long-term reusability, especially on the leeward side of a spacecraft, which experiences lower thermal loads during re-entry. Different fiber materials are used depending on the temperature range: S-glass for up to 380°C, silica fibers for intermediate ranges, and alumina-rich ceramics for the most demanding conditions. To enhance performance during re-entry, flexible insulations are typically coated with thin high-emissivity, low-catalytic layers that also help protect against erosion. While Europe has not yet flown a flexible TPS, experience from internal insulation applications, like those beneath C/SiC shingles, could be leveraged to redevelop and qualify such systems.

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5.2.2.4 Rigid TPS

Rigid thermal protection systems made from silica-based materials have a long history of successful use in spaceflight, most notably on NASA's Space Shuttle. Tiles like LI-900, LI-2200, and more advanced variants such as FRCI-12 and AETB were used across 135 missions, offering protection up to about 1200°C. Over time, these materials were improved by combining silica and alumina fibers to increase mechanical strength, and by applying tougher coatings like TUFI to enhance durability. More recently, NASA developed TUFROC (Toughened Uni-piece Fibrous Reinforced Oxidation-resistant Composite), which represents the latest generation of low-cost, lightweight, and reusable rigid TPS. TUFROC is a two-layer system: a high-temperature-resistant carbon cap on top of an insulating silica base, with both layers bonded securely. This technology has already flown multiple times on the U.S. Air Force's X-37B spaceplane and is now being integrated into Sierra Nevada's Dream Chaser. Compared to earlier systems like the reinforced carbon-carbon (RCC) used on the Shuttle, TUFROC offers similar thermal performance at a fraction of the weight and cost, though RCC remains more robust against impacts due to its density. Overall, modern rigid TPS solutions like TUFROC offer an attractive balance between performance, weight, and affordability for reusable space vehicles.

5.2.2.5 Deployable TPS

Mechanically deployable heat shields are an innovative solution for atmospheric re-entry, offering the key advantage of increasing the effective surface area of the vehicle without requiring a larger launch volume. By expanding after launch, these systems reduce the vehicle's ballistic coefficient, which in turn lowers both peak aerodynamic forces and thermal loads during re-entry. This makes it possible to use lighter materials and simpler thermal protection, since the overall heat flux and operational temperatures are significantly reduced. Deployable heat shields are particularly effective for diameters up to about two or three meters, where they outperform inflatable systems in terms of structural simplicity and reliability. For these sizes, the complexity of inflation systems, such as gas tanks and tubing, is often unnecessary. Additionally, deployable designs help limit the contact area between the flexible TPS and the underlying structure, reducing the amount of insulation required. However, as the shield size increases, the longer structural arms needed to deploy the system may become prone to buckling due to aerodynamic forces. In Europe, CIRA has been a leader in this field, successfully demonstrating deployable heat shield technology through ground tests and flight experiments. The MINI-IRENE mission, launched on a VSB-30 rocket, reached 260 km altitude and 12g peak deceleration, validating both the aerothermal performance and flight stability of the deployable capsule, which was safely recovered after re-entry.

5.2.2.6 Inflatable TPS

Inflatable Heat Shields (IHS) represent a breakthrough in re-entry technology, offering a flexible solution that overcomes the limitations of rigid heat shields, while also providing good scalability for components of moderate size. Unlike traditional systems, IHS can be folded for launch and later inflated in space, enabling significantly larger diameters than what launcher fairings allow. This leads to lower ballistic coefficients, smoother deceleration profiles, and reduced thermal and mechanical loads, key factors that make IHS highly attractive for both Earth and Mars entry missions. IHS systems are particularly suited for future space transportation needs, including safe return of launch vehicle stages, satellites, and cargo from LEO, while also supporting space debris removal strategies. Their scalability makes them ideal for large robotic or crewed Mars missions, where conventional entry systems fall short in terms of mass, size, and landing precision. The recent NASA LOFTID mission successfully demonstrated an IHS-based re-entry and recovery, validating the concept in flight and paving the way for applications such as recovering rocket engines. In Europe, CIRA has been actively advancing this technology through EU-funded projects: EFESTO, EFESTO-2, and now ICARUS. These efforts have developed and tested inflatable structures and flexible TPS at increasing scales and complexity, with ICARUS targeting a TRL ≥6 via both ground testing in the SCIROCCO plasma wind tunnel and a suborbital flight of a 3-meter demonstrator. These steps aim to validate deployment, inflation, and aerodynamic stability during a full re-entry trajectory, positioning IHS as a cornerstone for future reusable and sustainable space systems.

5.3 Allocation of Design Alternatives across Launcher Classes

Table 4 presents the resulting association between landing strategies, vehicle configurations, and TPS options, categorized by launcher class and stage type. Technical considerations are discussed for each class to provide a clear basis for identifying feasible options and supporting future trade-off analyses.

As indicated, a primary distinction can be made between lower and upper stages. Independently of the specific landing strategy or configuration, the thermal environment encountered during lower stage re-entry is not as severe as that of the upper stage, thus eliminating the need for particularly advanced TPS technologies. Thermal protection can be achieved through the localized application of ablative materials in high-heating areas, with materials such as cork-

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based or equivalents, commonly used for these hot spots. Other viable options include deployable and inflatable TPS systems, which may be used for the recovery of key components, such as liquid-propellant boosters. However, such systems may face scalability limitations for heavy and super-heavy classes. Although theoretically scalable, the mass and dimensions of boosters used in heavier launchers may exceed practical limits for these TPS architectures. As a result, they have not been considered viable design options for the heavier launcher classes. Lastly, in zones exposed to more moderate thermal loads, such as leeward surfaces, Flexible TPS solutions may also be considered.
A more careful assessment is required for the upper stage. In this case, the re-entry conditions are significantly more demanding, necessitating a focused evaluation of current TPS technologies to identify potential performance gaps and inform future research and development efforts. TPS must ensure adequate thermal protection during re-entry from space, while also meeting the mass and mission constraints of the launch vehicle. Therefore, a more detailed analysis is provided in the following paragraphs for each launcher class, with specific reference to the upper stage.

Table 4: Preliminary system-level assessment matrix for re-entry

Launcher class	Stage	Landing strategy	Configuration	TPS
Small *Payload: < 2 tons*	Lower	HL with passive recovery systems (parachute, parafoil and or/airbags), mid-air retrieval	Cylindrical booster	Local hot spots, Deployable TPS, Inflatable TPS, Flexible TPS
	Upper	HL with passive recovery systems (parachute, parafoil and or/airbags), mid-air retrieval	Cylindrical booster	CMCs, Ablative, Rigid TPS, Deployable TPS, Inflatable TPS
Medium *Payload: 2-20 tons*	Lower	HL with passive recovery systems (parachute, parafoil and or/airbags) and/or runway landing, gliding and VL (RTLS, DRL), mid-air retrieval	Winged vehicle, Lifting-body, Cylindrical booster	Local hot spots, Deployable TPS, Inflatable TPS, Flexible TPS
	Upper	HL with passive recovery systems (parachute, parafoil and or/airbags) and/or runway landing, gliding and VL (RTLS, DRL), mid-air retrieval	Winged vehicle, Lifting-body, Cylindrical booster	CMCs, Ablative, Rigid TPS, Deployable TPS, Inflatable TPS
Heavy *Payload: 20-50 tons*	Lower	VL (RTLS, DRL, tower catch)	Cylindrical booster	Local hot spots, Flexible TPS
	Upper	HL (runway landing, gliding) and VL (RTLS, DRL, tower catch)	Winged vehicle, Lifting-body, Cylindrical booster	CMCs, Ablative, Rigid TPS
Super-heavy *Payload: > 50 tons*	Lower	VL (RTLS, DRL, tower catch)	Cylindrical booster	Local hot spots, Flexible TPS
	Upper	VL (RTLS, DRL, tower catch)	Cylindrical booster	CMCs, Ablative, Rigid TPS

5.3.1.1 Small-lift

Based on the recovery options currently being explored in concepts such as Miura 5 and Aurora, along with a review of all feasible CONOPS, HL with passive recovery systems and mid-air retrieval have been identified as potentially applicable to both lower and upper stages of small-lift launchers. Although the latter has not been specifically investigated for this vehicle category, it could be a technically possible option. For this class, a cylindrical booster configuration is the most effective. The choice of landing strategy and vehicle configuration is heavily influenced by the stringent mass and volume constraints typical of small-class vehicles, which make the integration of active propulsion systems or complex aerodynamic surfaces impractical. The associated TPS requirements are equally constrained by vehicle size and mission profile.

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- Given the higher thermal loads experienced by the upper stage, CMCs and other rigid TPS solutions represent an optimal choice in terms of performance, owing to their high durability, thermal resistance, and reusability. However, their economic viability, particularly for CMCs, remains to be assessed, as these materials are currently associated with high production costs.
- Ablative TPS may not represent the most efficient solution, primarily due to their relatively high mass and system complexity compared to the payload. However, an exception can be made for innovative low-ablation materials, which, due to their reduced material loss during re-entry, have potential for reuse.
- Deployable and inflatable thermal protection technologies offer advantages in flexibility and mass efficiency, making them promising candidates for small-lift launchers. These systems have already been tested on capsules to demonstrate their reusability, although they have not yet been applied to upper stages.

5.3.1.2 Medium-lift

The selection of a recovery strategy strongly depends on the mass of the component to be recovered, and the associated impact of additional mass related to landing sub-systems on overall vehicle performance. Therefore, medium-lift launchers offer greater flexibility. Both HL and VL return methods, including mid-air retrieval, can be applied to both lower and upper stages. However, as stage mass increases, mid-air recovery and HL may become less practical due to structural and operational complexity, making propulsive landing more suitable for heavier stages. TPS technologies for upper stages of this class can include:

- CMCs and rigid thermal protection systems, which represent a promising solution also for medium-lift upper stages launchers, due to their superior performance and mass efficiency, with limited refurbishment needs.
- High-performance ablative materials may be considered for these configurations. Vehicles like Falcon 9 and Neutron already employ lightweight ablative coatings. However, while suitable for high-energy missions, ablative systems can limit payload capacity due to their added mass, thus not representing an optimal solution.
- Deployable and inflatable thermal protection systems could be employed for medium-class upper stages carrying small payloads. However, due to their limited scalability with increasing system size, they are unlikely to represent a promising technology for future large-scale applications.

5.3.1.3 Heavy and Super heavy-lift

For heavy and super heavy reusable launchers, VL is the most viable recovery strategy. For this class, HL becomes impractical due to the significant aerodynamic and structural penalties associated with large wings or control surfaces. While upper stages have lower mass and may still support alternative HL configurations, such solutions may be feasible within the heavy launcher class but are unsuitable for super-heavy vehicles. For TPS:

- Due to their high-temperature resistance and excellent structural integrity, CMCs and rigid TPS are particularly well-suited for upper stages of heavy and super-heavy launchers. While technically feasible for small and medium-class vehicles, CMCs may be less cost-effective at this scale compared to their higher value in heavy and super heavy launchers, where their benefits better justify the investment.
- High-performance ablative materials may also be employed as complementary solutions, particularly in areas exposed to intense thermal loads. For example, considering a VL scenario, additional thermal protection may be required near the engine section during the landing phase.

6. Conclusions

Several RLV configurations are being investigated worldwide, with growing interest in fully reusable systems. Despite the promising potential, research in fully RLVs in Europe is not yet mature, with the most viable missions, configurations and technologies still to be clearly defined. One of the most critical technical challenges to achieving full reusability lies in the re-entry phase, particularly for upper stages, which face harsher conditions when re-entering from space. To start addressing this challenge, the paper presents a combined evaluation of landing strategies, vehicle configurations, and TPS technologies for both lower and upper stages across all launcher classes. The preliminary system-level assessment enabled the identification of key technical considerations to support future trade-off analyses aimed at selecting the most promising system architecture for reusable launchers.

Among the evaluated TPS options, CMCs emerged as the most technically promising solution for all launcher classes. Their high-temperature capability and structural robustness make them particularly well-suited for upper stage applications. While their cost and complexity may limit applicability to small and medium-class launchers, CMCs are particularly suitable for heavy and super-heavy launch systems. These classes not only face more demanding thermal environments but also represent the most economically attractive candidates for full reusability, due to the potential for significant long-term operational cost savings. Future work may extend this study through more detailed trade-off analyses that incorporate both technical and economic criteria, to systematically identify optimal configurations for next-generation fully reusable launch systems.

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