RocketHandbrake Executive Summary

Final Deliverable

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Index of contents

1. Abstract

The ESA funded project 'RocketHandbrake' investigates the reusability of upper stages and boosters re-entering earth´ atmosphere at high angles of attack as a means for aerodynamic braking. More specifically, Supersonic Braking Devices (SBD) are used to control the vehicle during the aerodynamic descent, eliminating the need for additional Supersonic Retro Propulsion (SRP) fuel – besides the final landing burn – however, at the cost of SBD. Three companies are part of the project RocketHandbrake, namely the German Aerospace Center (DLR) in Cologne and Braunschweig (Germany), Polaris in Bremen (Germany) and Deimos Space in Madrid (Spain).
The main objective of the project is to understand the key technologies required for a reusable upper stage configuration under a multitude of aspects, and to improve prediction tools. The project also features wind tunnel tests to generate data for physical understanding and validation of numerical tools.

The concept chosen for evaluation utilizes the fuselage as a main drag generator, together with small flaps in the front and rear to provide the required control authority. The vehicle re-enters earth' atmosphere at high angles of attack, thus requiring a suitable Thermal Protection System (TPS) for the fuselage and flaps, as well as corresponding Guidance, Navigation and Control (GNC) routines. This concept is based on the approach taken by SpaceX with their Starship launcher.

During the project, an aerodynamic Database was generated and later on verified through supersonic wind tunnel tests, showing a good agreement. However, Reynold Number effects were observed, highlighting the need for further future investigation, especially within the trans- and subsonic regime. On the structural side, the flaps, the fuselage and their connection as well as actuation were designed. Initial TPS investigations for the worst-case scenario showed a feasible concept, requiring some adaptation for certain hotspots. In future iterations the thickness can likely be reduced when orientated on the reference trajectory. Currently the TPS contributes to a large part of approximately 25% to the empty vehicle mass. More precise material data and a different reference case can reduce this factor. Through Mission analysis, a flyable reference trajectory as well as a thermal sizing trajectory were established, while further evaluation of the aerodynamic database allowed the definition of a permissible Center of Gravity (CoG) position range. Furthermore, GNC algorithms were obtained and extensively tested within the Flight Engineering Simulator (FES). Monte Carlo simulations proofed the validity and the robustness of the proposed mission and GNC solutions, even though the aerodynamic database assumed an initial (pre- wind tunnel tests) uncertainty of 20%, which can be reduced to approximately 10% for most cases.

A final outcome of the project is the Technology Roadmap and Design Guidelines, describing the application and required steps for application of the Supersonic Braking Concept.

2. Short Project History [1]

The Project was segmented into 4 Phases.
The *first phase* was used to find a suitable launcher for the concept of RocketHandbrake. One configuration was a Vega E-like and one an Ariane Next-like launcher. At the end of Phase 1, the Ariane Next[1] configuration was chosen for further assessment during the study. The main reasons were the complete reusability of the future launcher system, but also the indication of a trimmable and stable vehicle.

During the *second phase*, the vehicle was analyzed in details for the areas of the work packages, namely:

- Aerodynamics and Aerothermodynamics (WP 3)
- Structures and Mechanisms (WP 4)
- Mission Analysis, GNC & Flight Dynamics (WP 5)
- Wind Tunnel Testing (WP 6)

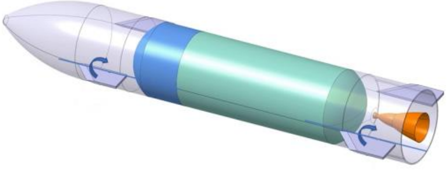

Figure 1: General Concept

Phase 3 covered the Wind Tunnel Test Preparation and Model production. *Phase 4* is effectively divided into two parts, one the Wind Tunnel Tests, and second their evaluation with complete project evaluations.

3. Reference Concept Design (WP 2)

The main purpose of the SBDs is not the drag generation, but the moment control of the fuselage. With sufficient moment control, the upper stage can be hold at high angles of attack during the aerodynamic descent. Thus, the cross-sectional area in the oncoming flow is maximized, as the fuselage is nearly perpendicular to the oncoming airflow, creating a large and meaningful drag force. Following this, the upper stage can brake aerodynamically while descending through the atmosphere, without the requirement for supersonic retro propulsion. For the landing, the vehicle needs to be rotated with the aid of the SBD and the main engine, which is then also used for the final deceleration at touch down.

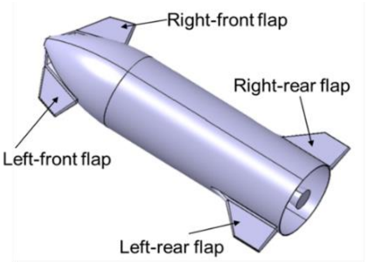

Figure 2 Ariane Next

The upper stage, including its Supersonic Braking Devices (SBD), also simply called flaps, is shown in Figure 2. They can be deflected (nearly) parallel to the length axis (x-axis) of the vehicle (see also Figure 1).

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[1] For improved readability, the '-like' is omitted, but still meaning the -like configuration considered in this study.

The Ariane Next launcher was used as a baseline for the application of the aerodynamic braking concept with supersonic braking devices, forming the Ariane Next -like concept analyzed in the project. The launcher specifications were taken from available, non-classified literature. Thus, important information like detailed engine specifications were not available and were estimated with the help of available tools and programs.

The main specifications of the Ariane Next configuration are:

Ariane Next		***Unit***
Nose to Base	57.5	m
Nosecone	7	m
1st stage	36.5	m
2nd stage	21	m
Engines	< 2	m
Diameter (ø)	5.4	m

Table 1 AN Launcher Dimensions [2]

Ariane Next	***Total***	***1st Stage***	***2nd Stage***	***Unit***
Number of Engines	10	9	1	-
Fuel		LOX – LCH4	LOX – LCH4	
Mass flow		366.66 * 9 = 3300	366.66	$\frac{kg}{s}$
Initial acceleration	1.314	1.314	(1.126)	$[g\text{-}force]$
TOM	766’566	623’810	142’756	kg
Stage Rate		80.86	19.14	%
Structure Coefficient (incl. Landing Legs)	7.66	7	10.9	$\% \frac{m_{structure}}{m_{stage_{total}}}$
Mass Structure	58’749	43’667	15’082	kg
Mass Propellant	703’583	580’143	123’440	kg
Ascent Rate		91.8	95	%
Descent Propellant		39’891	5’440	kg
Burn Time Ascent		159.2	314.2	s
Max. acceleration		53 , 5.4	64 , 6.5	$[m/s^2]\,,[g\text{-}force]$

Table 2 AN Launcher Overview per Stage [2]

As stated above, this concept minimizes the required fuel for upper stages, however, at the cost of SBD and landing legs as well as the final landing fuel. On a system level, the costs of reusability were estimated based on an engineering approach, described in [2], section 4.3.6 and [3]. Before the detailed design phase, the possible payload of a non-reusable launcher was estimated to be 5 times greater compared to a reusable one [3].

During descent, high thermal loads occur requiring a TPS. The structure and TPS have been sized and the results are shown in "Structures and Mechanisms (WP 4)", section 5 below.

Aerodynamic have been calculated numerically and described in section 4 below. In the last project phase, supersonic Wind Tunnel Tests were conducted, greatly improving the aerodynamic understanding in this flight regime, described in section 7 below. All aerodynamic results were used for further analysis by the work package (WP) 5 of "Mission analysis, GNC and Flight Dynamics", see section 6 below.

The work package "Mission Analysis, GNC and Flight Dynamics" used the mass, size and aerodynamic data to come up with a reference trajectory and a thermal sizing trajectory. Latter one was used to size the TPS, whereas the reference trajectory was again used by the for structural sizing. Further extensive analysis was performed, shown in section 6 below.

4. Aerodynamics and Aerothermodynamics (WP 3)

The latest CFD Database (AEDB 3.0) covers the sub-, trans- and supersonic flight regime. In total 3080 simulations were conducted using the Navier Stokes equations and Spalart-Alamars turbulence model, providing a meaningful insight to the aerodynamics of the launcher.

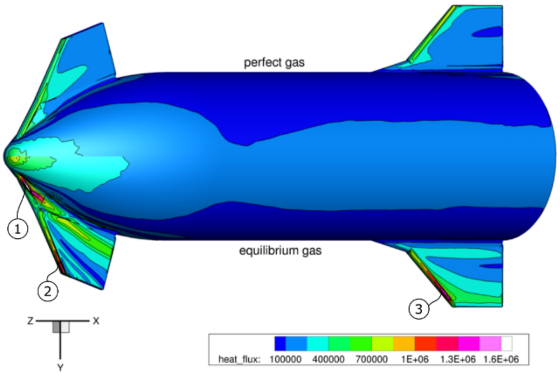


Figure 3 Heat flux comparison (luv side) between perfect gas and equilibrium gas model

A high-fidelity aerothermal database (ATDB), representing 8 relevant flight points of the thermal sizing trajectory, was numerically simulated and used for surface temperature predictions. Those surface temperatures were then used to for the sizing of the Thermal Protection System (TPS). Additionally, critical areas in terms of heat fluxes were inspected.

<u>Outcomes</u>:
The aerodynamics of the Ariane Next were calculated over a wide range of relevant flight conditions, giving a clear picture for the behavior of the launcher at this stage. The results were intensively analyzed and used, within the work packages 4 and 5. Nevertheless, further analysis is always beneficial to increase the resolution regarding more flap deflection angles and roll angles. Additionally, low speed subsonic calculations, including engine on cases, will yield flow details for the final body flop and landing maneuver.

5. Structures and Mechanisms (WP 4)

The structure of the flaps was designed, optimized and numerically analyzed based on the expected loads obtained via the aerodynamics and trajectory definitions. the flap structure design and actuator sizing only mechanical load cases are considered without thermal loads, since the flap structure is isolated by TPS. The actuator configurations were studied for optimum actuator load. The mass of the flaps is shown in Table 3. Furthermore, the actuation mechanism was defined and an actuator identified.

Table 3 SBD mass contributions [4] (page 40)

No attachments, no TPS	**Mass**	**Unit**
Front Flap (each)	~ 110	kg
Rear Flap (each)	~ 170	kg
SBD (excl. actuation)	~ 560	kg

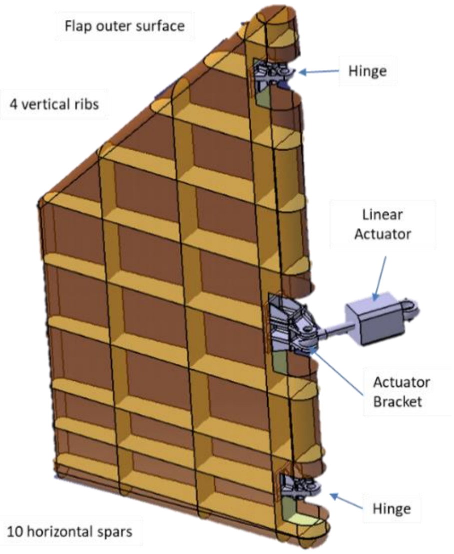


Figure 4 flap structure concept [4] (page 20)

Preliminary sizing and analysis were also done for the fuselage and tank structure (see Figure 5). The analysis was focused on the most critical load cases for the preliminary sizing of the primary rocket structure with the consideration of structural dynamic effect in the analysis and simplification of the model. The factors for the structure analysis were defined and applied in the structure simulation model. The total dry mass of the vehicle is currently about 15 tons, including a mass increase due to refinement of 10%, a final dry mass of ~17 000 kg is expected. It shall be noted, that this mass estimation is based on a first loop analysis

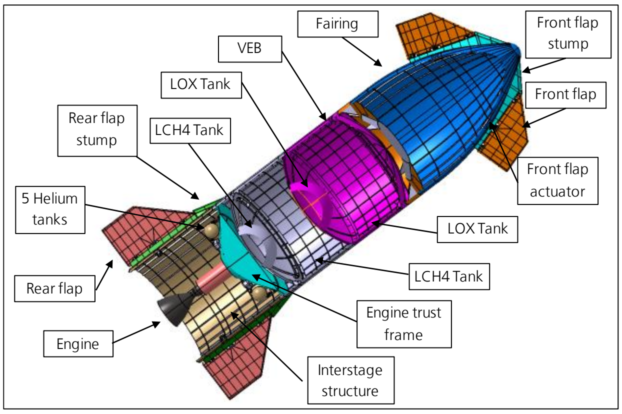


Figure 5 internal structure preview

Another outcome is the design, sizing, mass determination and comparison of the TPS variations to protect the upper stage of the high thermal loads and fluxes during aerodynamic braking and descent (see Figure 6). The TPS mass was found to be around 4200 kg (case 4, [4]).

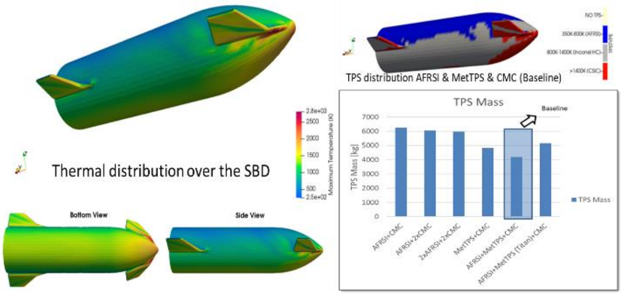


Figure 6 Thermal and TPS distribution over SBD

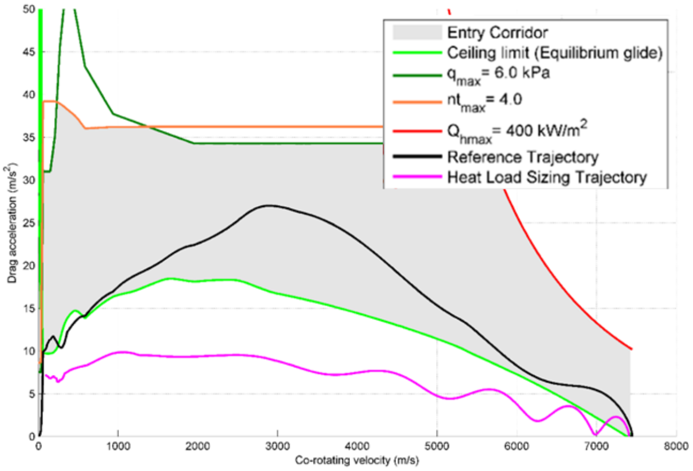
Outcomes:

The structure of the SBD was designed in detail with some simplification, yielding a sound design able to withstand the expected forces and moments, as well as the definition of the actuation system. The optimal actuation configuration for the flap kinematic system was identified. Furthermore, a TPS concept was designed for the worst-case scenario, the thermal sizing trajectory. Additionally, future design optimizations for the SBD and TPS were identified.

6. Mission Analysis, GNC & Flight Dynamics (WP 5)

The aerodynamic results were evaluated from a controls perspective, generating a reference trajectory which was later on updated using the AEDB 3.0. A thermal sizing trajectory was defined as the worst-case trajectory in terms of heat loads, providing the input for the TPS sizing. Mission Analyses were performed, creating possible entry corridor maps. It was found, that a feasible entry corridor exists, as long as the CoG stays within a defined range. The formulated control algorithms relate the classical control inputs like pitch, roll and yaw to the individual flap deflections forming the SBD, allowing an assessment of the vehicle control performance. The analysis incorporated evaluating the control limits of the individual flaps, static and dynamic stability assessment and definition of the requirements for a stable and trimmable vehicle and entry corridor. Furthermore, entry conditions at earth´s interface point were defined and the longitudinal and lateral ranges capability assessed and verified. Further it was found that a Reaction Control System (RCS) is required, and it was therefore sized. The performance of the control solution was assessed carrying out multiple Monte Carlo flight dynamics simulations to verify the robustness of the proposed solutions.

<u>Outcomes</u>:
A feasible entry corridor was obtained and verified together with the GNC algorithms within the Flight Engineering Simulator (FES) under the influence of perturbations and aerodynamic uncertainties. Additionally, future design optimizations were identified, including a permissible CoG position range; to comply with the latter one, the launcher requires some readjustments.



7. Wind Tunnel Tests (WP 6)

Figure 8 Wind Tunnel Model

The supersonic Wind Tunnel Tests were conducted within DLRs Trisonic Wind Tunnel (TMK) facility in Cologne, with a model of scale factor 0.79%. The model allows flap deflection of 0°,30°,60°, 90° and a no flap case. It was tested at Mach numbers of 1.5, 2 and 3 with an Angle of Attack range from -15 to 50° and 40° to 110° and two roll setting of 0° and 10°. Forces and Moments were measured and a schlieren system allowed to record highspeed schlieren images as well as higher resolution images. Additional oil film pictures show separation, reattachment and recirculation regions.

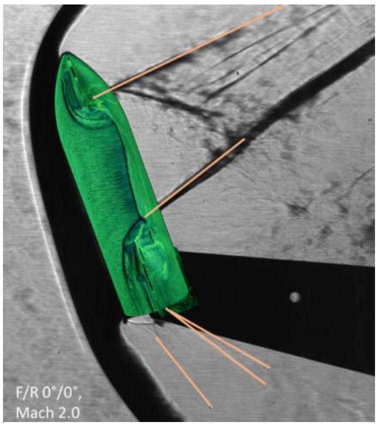
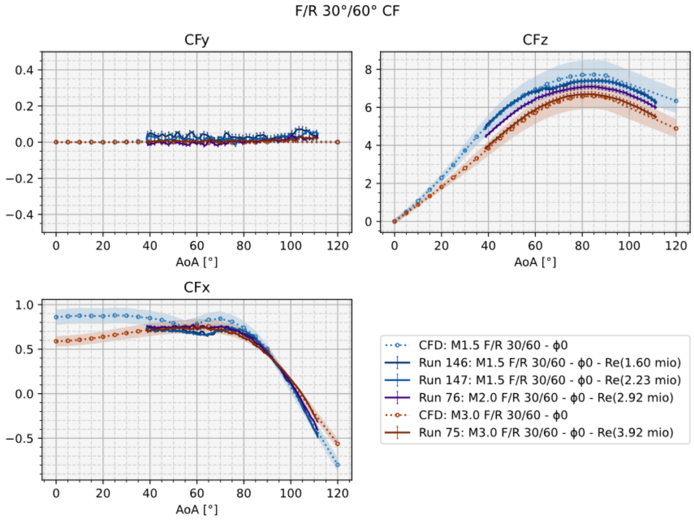


Figure 7 schlieren and oil film picture

Outcomes:

In general, the tests allowed to reduce the estimated CFD uncertainty by 50%. For Mach numbers of 1.5 Reynolds Number effects were observed. Future tests shall incorporate sub- and transonic tests. Additionally, more flaps settings were found to be beneficial for the downstream analyses.



8. Technology Roadmap

The goal is to design, build, test and fly reusable upper stages. The next step is to target a down-scaled flight test campaign with all the required development steps. Additionally, on the materials side more data and materials need to be available within Europe, best independent of non-EU countries. Once those prerequisites are available, a full-scale flight test is the ultimate goal.

9. List of Figures

10. List of tables

11. List of literature

[1] C. Hantz and e. al, "D4.2 Roadmap for Technology Maturation, Design Guidelines," 2023.

[2] C. Hantz and e. a. DEIMOS, "Deliverable D 1.1 Assessment of the reference mission and preliminary prototype design," Cologne, 2021.

[3] C. Hantz, A. Marwege, J. Klevanski, B. Reimann, G. De Zaiacomo, R. Marey, J. Gutiérrez, G. Medici, A. Kopp and A. Gülhan, "SUPERSONIC BRAKING DEVICES FOR REUSABLE UPPER STAGES – OVERVIEW OF ROCKETHANDBRAKE," in *2nd International Conference on Flight Vehicles, Aerothermodynamics and Re-entry Missions & Engineering (FAR)*, Heilbronn, 2022.

[4] C. Hantz, Polaris and DEIMOS, "RocketHandbrake D2.1 b – Phase 2 to Design Review Report," 2023.

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12. List of abbreviation

AoA	Angle of Attack
DLR	German Aerospace Center
WP	Work Package