SUPERSONIC BRAKING DEVICES FOR REUSABLE UPPER STAGES – OVERVIEW OF ROCKETHANDBRAKE

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ABSTRACT

This paper provides an overview of the project 'RocketHandbrake', which investigates the reusability of upper stages re-entering the earth's atmosphere at high angles of attack as a means for aerodynamic braking, using Supersonic Braking Devices. For a maximum benefit, this concept takes so-called Ariane Next and Vega E -like launchers as reference configurations. However, the project does not aim to develop those launchers completely, but to clarify and focus on the required aerodynamic control surfaces, the entailed aerodynamics and resulting flow physics, flight dynamics, control laws, and structures, based on and for those example configurations.

Furthermore, the results of phase one of the project are described and the decision process for choosing the Ariane Next as baseline configuration for the next project phases is detailed. This includes first aerodynamic, and mission analyses of reusable Ariane Next and Vega E upper stages featuring supersonic braking devices.

Index Terms— ***s****upersonic braking devices, reusable launch vehicle, aerodynamic braking, vertical landing, upper stage*

1. INTRODUCTION

The ESA TRP project 'RocketHandbrake' investigates the reusability of upper stages and boosters reentering earth´ atmosphere. More specifically, high angle of attack aerodynamic deceleration under the aid of supersonic braking devices (SBD) is studied. This eliminates 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.

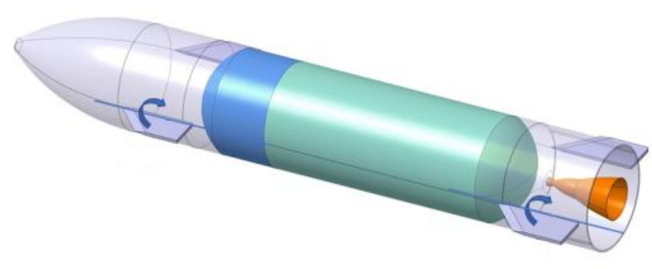

Figure 1: General Concept Layout

For a maximum benefit, this concept takes a so-called Ariane Next-like and Vega E-like configuration as reference. However, the project does not aim to develop those launchers completely, but to clarify and focus on the required aerodynamic control surfaces, the entailed aerodynamics and resulting flow physics, flight dynamics, control laws, and structures.

The project RocketHandbrake is divided into *four phases*:

The *first phase* consists of the initial design and assessment of the two referred configurations, yielding preliminary launcher specifications tailored to the concept under study, based on the publicly available and published literature. At the end of the first phase, the Ariane Next like configuration was chosen for further evaluation

The *second phase* deals with the detailed design and evaluation of the Ariane Next reusable upper stage (meaning: Ariane Next like configuration) in terms of:

- Aerodynamics
- Aerothermodynamics and Heat Loads
- Structures
- Flight dynamics and Control laws

Phase three covers the preparation of the wind tunnel test, namely the design of the model, its manufacturing and the test preparation.

The *last phase* consists of the wind tunnel test execution and its evaluation. The tests will be carried out in the Trisonic Wind Tunnel Cologne (TMK) at DLR´s Supersonic and Hypersonic Technologies Department. Furthermore, the overall project results are summarized and evaluated to determine the developed system performance. Additionally, a roadmap for technology maturation is developed, pathing the way for further investigations but also integration of the concept analyzed.

This paper gives an overview of the project. Furthermore, the results of phase one of the project are described and the decision process for choosing Ariane Next as baseline configuration for the next project phases are detailed. This includes the first aerodynamic, and mission analyses of reusable Ariane Next and Vega E upper stages, featuring supersonic braking devices.

2. PHASE ONE

A meaningful investigation of Supersonic Braking Devices (SBD) requires a suitable launcher with sufficient payload to carry the additional structural components and a promising payload and mission profile. Following this, Ariane Next (AN) and Vega E (VE) like configurations[1] were chosen at the start of the project for reference, having a sufficient, but different payload range and representing a small-scale and large-scale launcher. Since they do not exist yet, their expected capabilities were predicted based on publicly available information mainly from [1] for AN and [2] for VE together with calculations for staging, thrust and fuel masses and initial ascent simulations. Latter one also required initial aerodynamic predication for lift and drag.

2.1. Engine Assessment

The design process of both configurations started with the engine assessment, based on available data [3] [4] [5] [6] [7]. Since not all parameters are publicly available, the complete characteristics were obtained via the program Rocket Propulsion Analysis, yielding a Prometheus-like engine for the AN and a M10-like engine for VE. All engines are required to be able to operate under sea-level conditions for take-off and landing. The thus obtained characteristics are given in the table below:

Table 1 Initial Engine Design Results

Configuration	**AN**		**VE**	
Name	Prometheus		M10	
Stage	1^{st}	2^{nd}	3^{rd}	
Propellant	LOX+LCH4			
Mixture	3.5		3.4	
Pressure	100	100	60	bar
Thrust (SL/ vac.)	1098 / 1200	1073 / 1243	71 / 98	kN
Expansion (1^{st} / 2^{nd})	15	25	30	-
ISP (SL / vac.)	305 / 334	298 / 346	253 / 348	s
Mass flow	366.6	366.6	28.75	kg/s
Nozzle length (Le)	1493	1906	320	mm
Exit Diameter	1139	1471	345	mm

2.2. Initial Sizing

As mentioned, the Preliminary Design Process started with data collection for the engines as the main design driver, but also for boundary conditions regarding sizes, masses and trajectory with payload data.

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

For the Ariane Next configuration, the engines and initial acceleration define the Take-off weight, which sizes the fuel and structural mass via the structural coefficient. In further design loops the design is based on a more detailed mass assessment together with ascent simulations to get an optimized payload. Due to the desired reusability, the payload consists of the actual payload, but also of the additional masses introduced for the reusability, like fuel, flaps, Thermal Protection System, landing legs and others coming back down with the launcher. They are partly included via the structural index. Numbers are provided in Table 2, the layout of the launcher can be seen in Figure 2, here the red line shows the separation between the stages.

For the Vega E a different approach was applied. As it uses the first and second stage of Vega C, they do not need to be redesigned, but were taken as given. The third and fourth stages of the Vega C were then replaced by a single LOX-LCH4 based stage, forming the Vega E. The new third stage´s boundary conditions (based on the Vega C 2nd - 3rd stage separation conditions for total mass and "ΔV") are shown in Table 2 and Table 3, furthermore Figure 3 shows the layout of the 3rd stage.

After the initial launcher configurations were defined, first aerodynamics and trajectory data had to be determined and evaluated.

Table 2: Initial Configuration Design Results

Configurations	AN 2nd stage	VE 3rd stage	Unit
Nr. Engines	1	1	-
Takeoff mass of stage	142'756	16'312	kg
Structure	15'082	2'761	kg
Propellant	123'440	11'251	kg
Ascent Rate*	95	95	%
Descent Propellant	5'400	562	kg
Diameter	5.4	3	m
Length, total	21	8.3	m
Length, Nosecone	7	3	m
Tank, LOX	89.65	8.539	m³
Tank, LCH4	69.85	6.715	m³

* $Fuel_{Ascent}/Fuel_{Total}$

Table 3: VE 3rd Stage Initial Conditions

Vega E	2nd stage	3rd stage	Unit
Time	245	248	s
Altitude	121	123	km
Velocity	4555	4550	m/s
$\Delta V_{vertical}$		500	m/s
γ_{FPA}		$6.3^{\pm 1}$	°

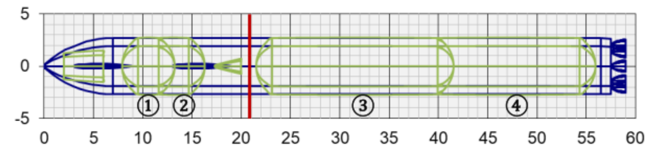

Figure 2: AN Design

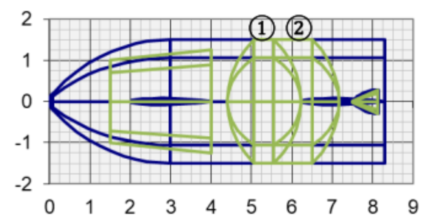

Figure 3: VE Design

2.3. Supersonic Braking Devices

As stated above, both configurations utilize a high Angle of Attack (AoA) descent to perform aerodynamic braking while re-entering earth´s atmosphere. In order to reach and keep the orientation as required, aerodynamic control surfaces are required. Those control surfaces are called Supersonic Braking Devices (also called flaps) in this project. Their mode of operation is to rotate in the length axis (x-axis, or close to it), but not to rotate like canards or ailerons in the axis of their span (y-axis), see also Figure 1.

Frontal and rear SBD do not need to have the same angle setting, but can be different to adjust the moments required. Additionally, a change of deflection between the left and right side could provide further steering or roll control.

2.4. Aerodynamics

An Aerodynamic Database (AEDB) is used for the ascent and descent simulation, whose fidelity is increased over the course of the project.

The initial version V1.0 was generated via the tool HOTSOSE [8], which calculates coefficients based on the Newtonian theory, applied to panels of the surface. It works only within the supersonic regime and uses the superposition principle. With this, AEDB´s can be generated quickly and do not require extensive meshing or calculations. However, this comes at the cost of having no subsonic data and no body interaction effects are considered (superposition principle). Values for Angles of Attack of 90° and above do not yield valid data per se, but those are not in the main focus in this phase anyway.

From those initial results it was observed, that the Fuselage represents the most important factor for the drag and moment generation. The flaps are designed to obtain a stable and trimmable configuration with the main focus on sufficient moment generation. For AN, Figure 4 shows the effect of frontal and rear flaps, in comparison to the fuselage by itself, assuming the COG to be at 11 m. It can be concluded, that some combination for size and deflection of frontal and rear flaps exists, where the stage can be controlled.

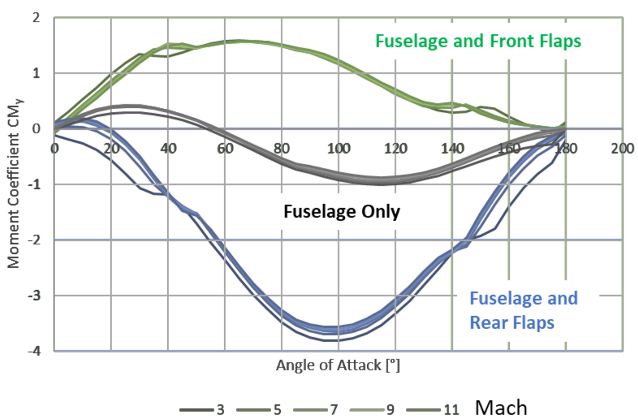

Figure 4: AN First Moment Analysis, CM_y vs. AoA for supersonic Mach numbers and X_{ref} = 11 m

For VE, the fuselage moment curve by itself is already more critical, see Figure 5, indicating that the flaps need to provide even more moment corrections for this case. But one needs to consider, that their sizes cannot be increased overly due to weight constraints and must be positioned along the fuselage for mounting.

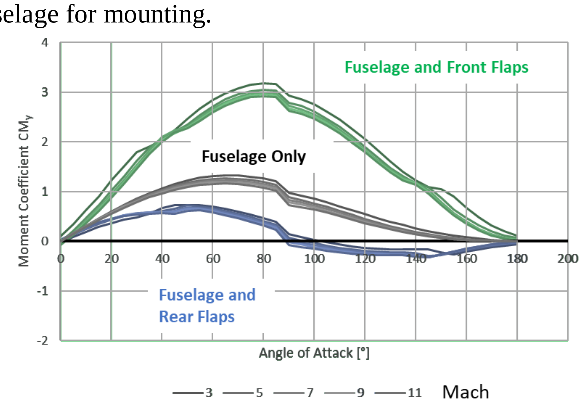

Figure 5: VE First Moment Analysis, CM_y vs. AoA for supersonic Mach numbers and X_{ref} = 5.6 m

Following this result and based on the drag data priority, the aerodynamics model was improved by numerical simulations of the fuselage only (no flaps), using DLR´s numerical flow solver TAU [9].

Thus, the modelling accuracy was increased, but still based on the superposition principle. The drag of the flaps was kept constant for lower Mach numbers. Further numerical simulations are performed in phase two of the project, greatly increasing the fidelity and not relying on superposition anymore.

2.5. Trajectories

For the main focus of the project, no ascent simulation is directly needed. Nevertheless, a complete simulation allows to verify a feasible upper stage design, capable of reaching the target orbit while carrying a useful payload amount.

Using the aerodynamic model, ascent and descent trajectories were calculated. The targeted orbital conditions for both configurations were:

Table 4: Ascent and Descent Orbits

Target Orbit	Apogee, Perigee	Inclination
Ascent	400 km, circular	7°
Descent	400 km, circular	7°

Initial trajectory simulations during the configuration design phase were performed with DLR in-house tool TOSCA, a 3DoF trajectory simulation and optimization tool. Later in the project, simulations of higher fidelity will be carried out for more accurate predictions.

The ascent starts with the vertical phase for launch pad clearing, transition and gravity turn and ends with the final circularization burn, compare with Figure 6 for Ariane Next.

The descent starts with the de-orbit burn in 400 km altitude, targeting an entry flight path angle between -4° and 0° at 100 km altitude, then braking aerodynamically with high Angles of Attack and a body flop maneuver just before the final retro landing burn. Initial assessments utilized a high AoA of 80° for maximum braking, which was later found out to be non-optimal from thermal and GNC perspectives. Nevertheless, it represents a maximum for the allowable AoA, as values above could introduce substantial sloshing effects causing great changes for the center of gravity, which in return could result in an uncontrollable vehicle. The described descent can be seen as an example for Ariane Next in Figure 6.

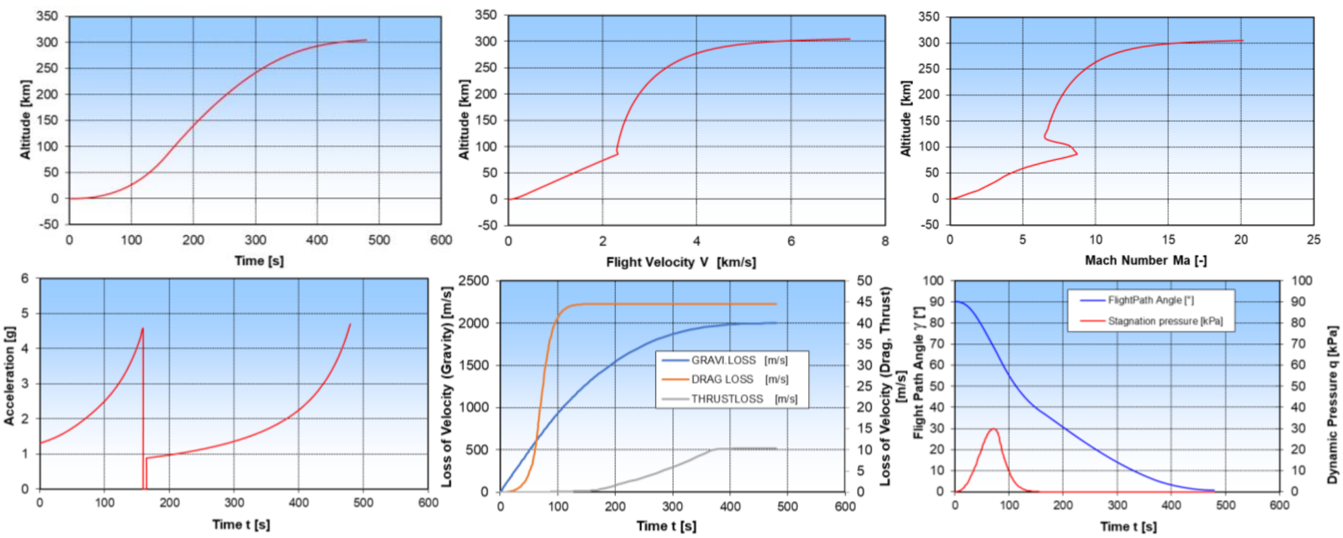

Figure 6: AN Ascent Trajectory

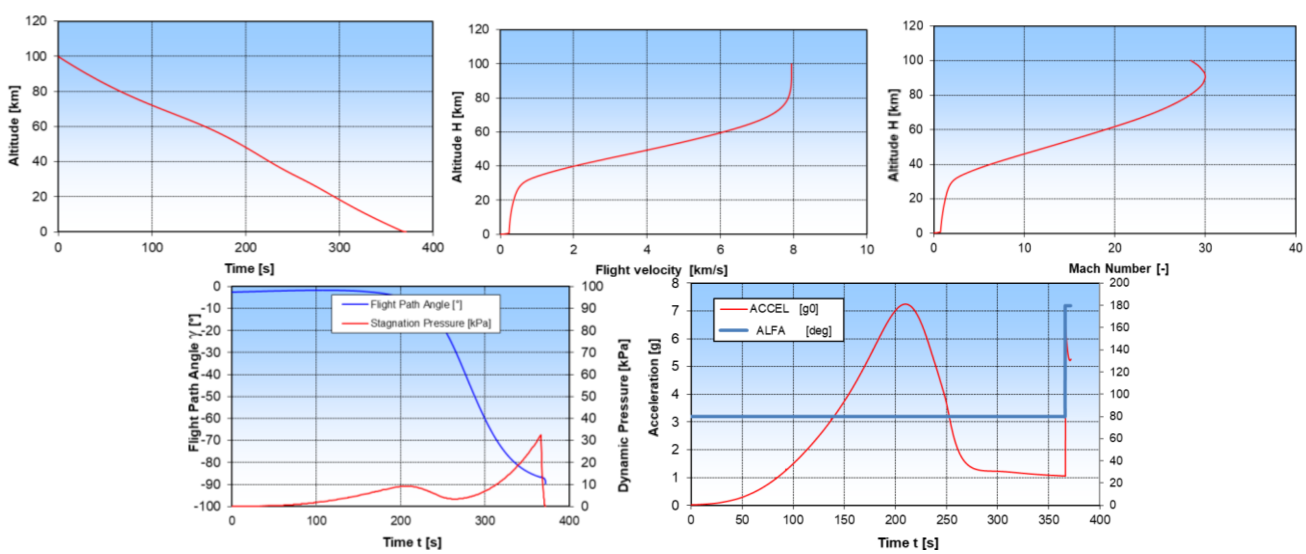

Figure 7: AN Descent Trajectory

2.6. Flight dynamics and control laws

In the context of the phase one of the study, the flight dynamics activities focused on the assessment of the feasibility of using SBD to return and recover the upper stage of future launchers, aiming at:

- The definition of one or multiple reference concepts providing a preliminary sizing of the upper stage featuring braking devices.
- The evaluation of the most feasible supersonic braking concept from an aerodynamic, thermal, structural and flying qualities standpoint.

More specifically, this assessment was done with a parametric analysis that involved at first a preliminary flight mechanics analysis (Flying Qualities Analysis - FQA -) for the computation of the entry corridor to evaluate the capability of the proposed configurations to perform the return mission in trimmable and stable conditions. The Entry Corridor is defined as the region of the Mach-AoA plane fully compatible with the set of flight mechanics constraints considered, and identifies the region in which a trim solution could be identified. Once an entry corridor was defined, the mission feasibility analysis was evaluated through a preliminary assessment of the re-entry trajectory characteristics for the proposed configurations. The end goal is to explore the feasible flight envelope for the re-entry phase to determine the mission needs in term of re-entry conditions to operate the vehicle in a safe range of structural and aerothermal parameters and to reach the landing point.

The parametric analysis is carried out as function of key design parameters of the proposed configurations and re-entry mission, such as the position and size of the fins/wing pairs, or the relevant entry conditions. In this way, performance maps are built with respect to these design parameters. These performance maps can be used to quantify the impact of such parameters on the mission performance, derive dependencies and possible limitations, and identify feasibility regions or a feasible envelope to support the definition of a suitable design solution.

In the case of the Ariane Next configuration, the preliminary analysis demonstrated that fins with reduced dimensions, in the order of 30% of the size originally proposed, would be sufficient to provide the trim capability in the range of AoA of interest (see Figure 8). The corresponding flight envelope is showed in Figure 9, where the expected re-entry environment, in terms of most relevant aerothermodynamic parameters, is mapped with respect to the AoA control law during entry and the flight path angle at the entry interface point (EIP). The results showed that the trajectory control capability provided by the proposed configuration during the re-entry would allow compensating the expected dispersions at the EIP, guaranteeing therefore the feasibility of the return mission.

On the other hand, the VEGA configuration has a CoG position that is too backward, and this affects the flight mechanics performance, and therefore the mission feasibility. To obtain a feasible configuration, much bigger fins should be used (see Figure 10).

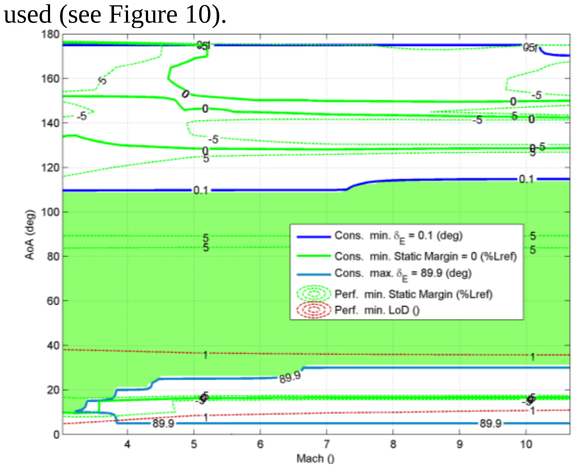

Figure 8 Entry corridor, Ariane next configuration, fins scaled down at 30%

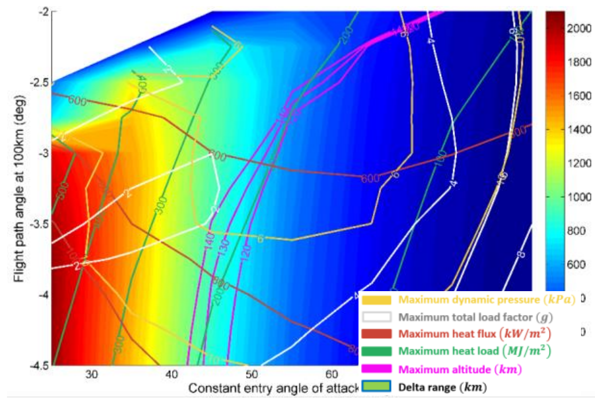

Figure 9 Entry flight envelope in terms of cross range correction capability (in km), Ariane next configuration, fins scaled down at 30%

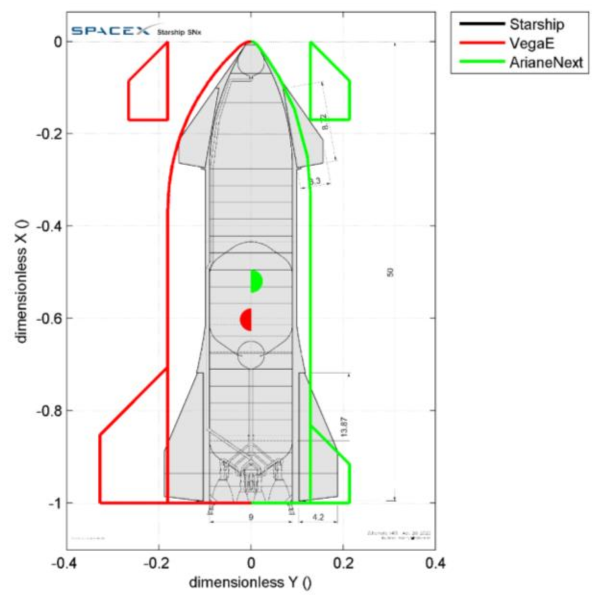

Figure 10 Proposed VEGA-E and Ariane Next feasible re-entry configurations

2.7. Thermal investigation

From the mentioned initial trajectory simulations, first heat load indications were extracted. As they are based on approximations via empirical formulas, they need to be taken with care and will also be updated within the course of the project. High fidelity numerical calculations will provide valuable intel in the upcoming project phase.

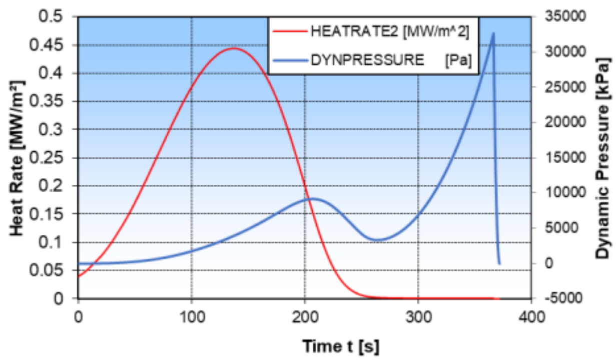

Figure 11: AN Initial Thermal Trajectory Data, Adiabatic Equilibrium

2.8. Result investigation – Additional Reusability Masses

As mentioned, the project investigates reusability of upper stages under the aid of SBD instead of pure retro propulsion. In order to assess the studied concept from an economic or systems standpoint, it needs to be known what is saved and what needs to be paid, e.g. mass wise. For that, a first possible gain and pay estimation compared to a fully expendable launcher was done.

For the estimation, all masses currently foreseen for the descent (e.g. fuel, landing legs) are added together to yield a number representing all reusability costs in terms of mass. This gives a better understanding of how expensive reusability is, and thus enables a better comparison between different landing concepts. Keep in mind, that the presented numbers are based on the first mass assessment, which will be detailed in the course of the project.

2.8.1. Ariane Next

In the Table 5 and Table 6, the basic reusability masses of the Ariane Next are listed and combined underneath. Additionally, the found lower stage masses are then assumed to be upper stage masses and the resulting possible increase of the payload is determined. The thus obtained combination of both stages´ reusability masses yields the overall costs for reusability, in terms of mass.

Table 5: AN Reusability Masses, 2nd stage

2nd stage		
Descent fuel	5’400	kg
Landing Legs & Flaps	4’000	kg
Payload	~ 4’200	kg

Additional mass for reusability of 2nd stage: 9’400 kg

Table 6: AN Reusability Masses, 1st stage

1st stage		
Descent fuel	40’000	kg
Landing Legs	4’000	kg

Additional mass for reusability of 1st stage: ~44’000 kg

This mass could have been used as 2nd stage ascent propellant and payload mass, since it is already brought up to the 1st stage separation point. To convert it, an ascent rate of 80:20 is used:

$$20\% * 44'000kg = 8'800\,kg$$

The results represent the additional non-propellant mass after 2nd stage MECO. Assuming a structure coefficient of 11%, only 89% can be used as additional payload:

$$89\% * 8'800kg = 7'800kg$$

Theoretical payload, expendable:	~ 21’400 kg
Actual payload, reusable:	~ 4’200 kg
Loss of theoretical payload:	~ 17’200 kg

Due to the 2nd stage reusability, only ~1/3rd of the mass (not required for ascent) brought to space is payload. Due to the 1st stage reusability, the upper stage has to be ~6% lighter[2], resulting in nearly 8 tons less of non-ascent relevant mass brought to space, which is about half of the current value. In summary, a fully expandable launcher has a payload ~5 times greater than the current expected one of 4’200 kg. It needs to be mentioned, that this is an initial guess and needs to be evaluated further with detailed aerodynamics and trajectory simulations. Keep in mind, percentages and factors change quickly with a change in absolute masses.

2.8.2. Vega E

In the Table 7, the basic reusability masses of the Vega E are listed and combined below. As the first and second stage are expendable already, they have no reusability mass. Only the upper stage contains ‘reusability mass’, reducing the possible payload.

Table 7: VE Reusability Masses, 3rd stage

3rd stage		
Descent fuel	560	kg
Landing Legs & Flaps	1’500	kg
Payload	~ 2’300	kg

Theoretical payload, expandable 3rd stage:	~ 4’360 kg
Actual payload, reusable 3rd stage:	~2’300 kg

[2] (2nd additional mass) / (2nd stage TakeOffMass)

Additional mass for reusability: ~2'060 kg

Due to 3rd stage reusability, only about the half of the theoretical possible payload is available. It needs to be mentioned, that it is an initial guess and needs to be evaluated further with detailed aerodynamics and trajectory simulations.

3. FINAL DECISION

During the Concept Review Meeting it was decided to go on with the Ariane Next-like configuration. Multiple factors lead to this decision:

- The Ariane Next can be a completely reusable launcher, whereas Vega E does have a reusable 3rd stage, but still requires a solid propellant first and second stage.
- Initial Moment investigations showed feasible results the Ariane Next configuration, meaning a stable and trimmable configuration is nearly reached. Vega E on the other hand, showed critical characteristics to be improved for a stable and or trimmable configuration due to COG problems. As a reiteration of this reference configuration is timewise out of scope, this configuration was not favorized.

4. CONCLUSION

This paper provides an overview of the ESA TRP project 'RocketHandbrake'. First, the project structure with the associated tasks was shown and the term 'Supersonic Braking Device' was defined for this project. Afterwards, the findings of the first project phase were laid out in more detail, providing information on the chosen configurations in terms of engine assessment, launcher parameters, aerodynamics and 'Flight Dynamics and Control Laws' and finished up with an assessment of the 'reusability mass', a penalty analysis for gaining reusability.

At the end of the first phase, it was decided to use the Ariane Next-like configuration for further assessment during this study. The next *phase two* goes into more detail regarding aerodynamics, temperature predictions, the complete Flight Dynamics package and structural layout of the Supersonic Braking Device.

5. ACKNOLEDGEMENT

This work was performed under ESA contract ESA AO/1-10716/21/NL/MG.

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