EXPLOITING TECHNOLOGICAL SYNERGIES FOR FUTURE LAUNCH VEHICLES

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Abstract

Two launch vehicle concepts based on technologies available today or in a short term future in Western Europe are presented. The design of both launchers has the goal of exploiting synergies with current European programs to limit development and operational costs. Technologies of particular interest here are the high performance solid rocket motors with carbon-epoxy filament wound monolithic motor cases and the future high performance cryogenic expander cycle engine Vinci.

The first concept dubbed ANGELA (A New GEneration LAuncher) is a study financed with funds of the German Ministry of Economics and managed by the DLR Space Administration. The project, which started in the summer of 2012 aims at designing a low cost versatile launcher able to place payloads between 2 and 5 tons into GTO. Three architectures have been considered during the first phase of the study. This phase was concluded in March 2013 with the preliminary stagings, which will be the starting point of more detailed analyses. The first architecture is made out of an H110 (stage with 110 tons of LOx/LH2) equipped with two Vulcain 2 engines with shortened nozzles and an H29 propelled by a Vinci engine. In addition the variation of the number of P36 solid rocket boosters allow to reach the entire range of payload performance. The second architecture differs from the first one only by the use of a new staged-combustion engine instead of two Vulcain 2 engines. The new engine, which should deliver 1800 kN in vacuum, allows a reduction of the size of the stages to H90-H24, enhanced with P34 boosters. The third and last architecture is a so called Multi PPH. The first stage is a bundle of 2 or 3 P120 solid rocket motors. The second stage is made out of one single P120, strictly similar to those used for the first stage. Finally the upper stage is an H23 equipped with a Vinci engine, the same as the two other architectures.

The second launcher concept described in this paper is the small TSTO launch vehicle. It consists of a large solid rocket motor first stage P175 and a cryogenic upper stage propelled by the Vinci engine, H26. The preliminary design performed at DLR-SART considers two target performances. The light version of the small TSTO shall perform Galileo satellite replacement single launch missions to MTO corresponding to a payload performance of about 1400 kg in GTO. A heavy version of the launch vehicle shall be able to launch payloads up to 3000 kg in GTO. The performance increase for the heavy version is made possible by the addition of two pairs of P23 boosters, the second pair being ignited with a delay.

Nomenclature

g	gravity acceleration	m/s^2
I_{sp}	specific Impulse	s
M	Mach-number	-
m	mass	kg
q	dynamic pressure	Pa
T	Thrust	N
v	velocity	m/s
W	weight	N
ε	Expansion ratio	-
α	angle of attack	-
γ	flight path angle	-

Subscripts, Abbreviations

ANGELA	**A** **N**ew **Ge**neration **La**uncher
AP	Ammonium Perchlorate
FLPP	Future Launchers Preparatory Programme
GLO mass	Gross Lift-Off mass
GTO	Geostationary Transfer Orbit
HH-2V	Fully cryogenic two stage to orbit launcher with 2 Vulcain 2
HH-SC	Fully cryogenic two stage to orbit launcher with a staged combustion engine
Hx	Cryogenic stage with “x” tons of

	ascent propellant	Px	Solid rocket motor with "x" tons of ascent propellant
HTPB	Hydroxyl Terminated Poly Butadiene	RCS	Reaction and Control System
ISS	International Space Station	SI	Structural Index (m_{dry} / $m_{propellant\ total}$)
LEO	Low Earth Orbit	SRM	Solid Rocket Motor
LH2	Liquid Hydrogen	SSO	Sun Synchronous Orbit
LOx	Liquid Oxygen	TSTO	Two Stage to Orbit
MR	Mixture Ratio	VEGA	Vettore Europeo di Generazione Avanzata
MTO	Medium Transfer Orbit	VENUS	**VE**GA **N**ew **U**pper **S**tage
Multi PPH	3 stage launcher: 1st stage: several SRM 2nd stage: SRM 3rd stage: cryogenic stage	cog	centre of gravity
NGL	Next/New Generation Launcher	sep	separation

1. Introduction

The maiden flight of the small Vega launch vehicle last year, was the first in-flight demonstration of several new technologies developed by the ESA member states. One key technology is the high performance solid rocket motors based on carbon-epoxy filament wound monolithic motor cases. At the same time, the development of the future high performance cryogenic expander cycle Vinci engine is on-going. Extensive tests are continuing to be performed at the DLR's engine test facility in Germany. Anticipating these results, since 2007 the DLR's group for Space Launcher Systems Analysis (SART) has been studying launch vehicle concepts based on these technologies to exploit synergies with the other programs such as Vega and Ariane 5 ME. A special attention was given to a small TSTO (Two-Stage To Orbit) launch vehicle. A second and bigger concept is also currently under investigation by a consortium of industries working with DLR in the frame of the study: ANGELA (A New GEneration LAuncher).
The project ANGELA is a study financed with funds of the German Ministry of Economics and managed by the DLR Space Administration. Astrium is leading the industrial study. Several concepts, based on the technologies described previously but also the Vulcain 2 engine, are pre-sized and analysed. The goal is to launch payloads between 2 and 5 tons into GTO. The variation of the performance is made possible through the different number of solid rocket boosters. Both fully cryogenic configurations (HH) and configurations with solid rocket motors and a cryogenic upper stage (Multi PPH) are considered. The first phase of the study was concluded recently. The preliminary staging resulting from this work is presented for each of the three configurations.
The second launcher concept described in this paper is the small TSTO launch vehicle. It consists of a large solid rocket motor first stage and a cryogenic upper stage propelled by the Vinci engine. The preliminary design considered two target performances. The launcher in its light version should be able to perform Galileo satellite replacement single launch missions to MTO, corresponding to a payload performance of about 1400 kg in GTO. A heavy version of the launch vehicle, to which boosters have been added, shall be able to launch payloads up to 3000 kg in GTO. Preliminary structural sizing have been performed and the thrust laws of the solid rocket motors have been tweaked to limit the upper stage structural mass. This paper presents the current state of the SART group's investigation for the small TSTO launch vehicle.

2. ANGELA: A New Generation Launcher

2.1 Background and study logic

In mid-2012, a launcher system study funded by the German Ministry of Economics and managed by the DLR Space Administration was started. This study, dubbed ANGELA (A New Generation Launcher), is performed by Astrium Space Transportation in cooperation with DLR-SART, MT-Aerospace and MBDA Bayern Chemie. The underlying programmatic is based on the results of an in-depth analysis conducted by the DLR Space Administration on the possible evolution of the launch service market worldwide and the possible impacts on the European market share. A low-cost modular launch vehicle with a payload performance ranging from 2 to 5 tons in GTO would be the best answer in unfavourable market conditions according to the analysis. This would guarantee an independent launch capability for European institutional satellites at lowest total cost for governments.
The lower limit of the payload capacity corresponds to about 4 to 4.5 tons into LEO which is sufficient to launch institutional earth observation satellites beyond Vega payload performance. The upper limit of the payload performance range was determined to be compatible with the launch of GEO weather satellites and institutional telecommunication satellites. It should also allow for medium size scientific missions beyond GEO. Not having an independent launch solution for heavy science missions seems acceptable as those missions are typically performed

in an international cooperation scheme. Even in favourable market conditions, the concurrent utilisation of Ariane 5 ME and ANGELA could be difficult to justify from an economical point of view depending of the evolution of the payload mass repartition. However, DLR-SART believes that technological synergies could be exploited with Ariane 5 ME and depending on the chosen architecture with Vega.
Three different configurations have been selected and are studied in the frame of this project which is planned to end in 2015. Two are fully cryogenic configurations (dubbed HH), however with different engines to propel the first stage. In one case, two Vulcain 2 engines are considered. This architecture is referred to as HH-2V in the subsequent chapters. In the second case a new staged-combustion engine is used to propel the so-called HH-SC launch vehicle. In order to reach the whole range of payload performance, solid rocket boosters are added and their number is varied between 2 and 6. The third configuration is a three-stage architecture. The upper stage is cryogenic and the lower stages are solid rocket motors. In order to simplify the design and reduce the recurring and non-recurring costs, it has been decided to consider a single type of solid rocket motor. By varying the number of solid rocket motors, it is possible to reach the whole range of targeted payload performances. This architecture is dubbed Multi PPH, as it consists of a cryogenic stage sitting on top of several solid rocket motors: one solid rocket motor second stage and a bundle of 2 or 3 identical solid rocket motors for the first stage.
The first phase of this project, during which the preliminary design and staging of the different launcher versions was performed by DLR-SART, was completed in March 2013. Based on the selected configurations (staging and engines), a sensitivity analysis has been done for each of the three architectures. Two goals are pursued: first to perform a cost optimisation and second to optimise the work during the concurrent engineering (CE) studies.
For this reason, the sensitivity analysis considers the influence of a large number of parameters such as the propellant loading for each stage, the engine/motor performance (thrust, Isp), the structural index, the aerodynamic characteristics of the launcher or the coasting time before the ignition of the upper stage.
The preliminary design performed by DLR-SART seeks to minimize the gross lift-off mass which in most cases and a given set of technologies tend to be close to the configuration minimizing costs. The real cost optimization is however performed in a second step by Astrium, starting from the configurations pre-designed by DLR-SART and using the results of the sensitivity analysis. The resulting cost-optimized configurations will be considered as a starting point in the CE studies. One CE study will be done for each of the three architectures. These CE studies will be performed at the DLR Bremen CEF (Concurrent Engineering Facility) in the coming months. They will allow consolidating the preliminary design for each of the architectures. The process will take advantage of the experience gathered during the CE studies conducted in the frame of the VENUS (VEga New Upper Stage) project ([7] and [12]). In the end, the two most promising concepts will be the object of more detailed studies.

2.2 Commonalities with existing European launch vehicles

The launch vehicles considered in the frame of ANGELA are for a large part, utilising technologies already available in Europe with the goal to reduce development costs, and if possible to exploit synergies with other launcher programs. For the preliminary design of the three architectures, the same upper stage engine is considered: the Vinci cryogenic expander cycle engine with a deployable nozzle extension as foreseen for Ariane 5 ME see Table 1. Reusing this engine and part of the feed system would allow limiting the development costs compared to a completely new design with a new engine.

	Vulcain 2 (ε = 58.5)	**Vulcain 2 (ε = 48)**	**Vinci**
Specific impulse [s]	310 (s.l.) / 432 (vac)	332 (s.l.) / 426.8 (vac)	464 (vac)
Mass flow rate [kg/s]	320	320	39.5
Mixture ratio [-]	6.1	6.1	5.8
Mass [kg]	2100	2100[1]	589
Coasting time before ignition [s]	-	-	25

[1]Mass reduction due to the shorter nozzle not taken into account the preliminary design, as the sensitivity analysis showed a very small influence on the payload performance

Table 1: Characteristics of the Vulcain 2 and Vinci engine

The HH-2V exploits another synergy with the Ariane 5 launch vehicle. Indeed the main cryogenic stage is equipped with 2 Vulcain 2 engines. To avoid any new development, these engines are unchanged compared to those in use currently, apart from the nozzle extension. The expansion ratio was optimised in the range between 32, the position of the TEG (turbine exhaust gas), where the gas from the gas generator is injected in the main nozzle and 58.5, the current expansion ratio of the nozzle used on Ariane 5. The lower limit was set to 32 for two main reasons. Firstly, too small expansion ratios would be advantageous for the thrust at lift-off but would reduce the system performance. Second, a shorter nozzle would imply to renounce the TEG and come back to a separate gas generator exhaust or to design a new TEG, gas generator und turbo-pump to allow the reinjection of the hot gas at a lower expansion ratio and thus at a higher pressure. An expansion ratio, larger than 58.5, would imply manufacturing difficulties and further decrease the nozzle exit pressure which is already considered to be close to the acceptable minimum. The characteristics of Vulcain 2 are summed up in Table 1. The diameter of lower stage was set to 5.4 m as currently on Ariane 5.
All architectures are making use of solid rocket motors, either as boosters (HH-2V and HH-SC) or as the main stage (multi PPH). Each of these motors is considered to be using the same technologies as the P80 FW, the first stage of Vega launch vehicle. This should provide for optimal synergy and lowest cost at a first glance. However, this assumption would have to be consolidated in a subsequent step. For this reason, parameters such as propellant composition, maximum combustion pressure and stage/booster diameter should be identical or close to those of the motors of Vega (see Table 2). According to studies conducted by Herakles, it would be possible to increase the maximum combustion chamber pressure up to 110 bars for future solid rocket motors [1]. A more conservative value of 100 bars is considered for each of the solid rocket motors utilised in the ANGELA study.

Motor casing	Carbon-epoxy filament wound monolithic motor case protected by EPDM
Propellant	HTPB1912 19% aluminium 12% HTPB 69% AP
Diameter	P80 FW: 3 m Z23 and Z9A: 1.9 m
Maximum P_{CC}	Up to 95 bars

Table 2: Vega solid rocket motors characteristics

2.3 Mission requirements

To allow for a comparison between the different concepts studied within the various programmatic frameworks, mission requirements based on those of FLPP (Future Launch Preparatory Program) are considered. They are summarized in Table 3. The staging has been optimized for GTO missions. The accepted performance range is situated between 2 and 2.2 tons for the light version of ANGELA and between 5 and 5.2 tons for the heavy version of the launch vehicle. For the multi PPH, the range for the light version was enlarged to 2 to 2.4 tons, as only two versions are considered 2PPH and 3PPH. This is not the case for the fully cryogenic architectures which also have a third intermediate version with 4 solid rocket boosters.

Reference Mission	
Launch Place	CSG, Kourou
Coordinate of Launch Pad	52.77° W / 5.24° N / Z = 0 m
Launch Azimuth	Free during preliminary design study
Orbit	
Apogee	35 786 km
Perigee	200 km
Inclination	7°

Performance Target	
Payload with low number of boosters	2.0 – 2.2 tons (2.4 tons for Multi PPH)
Payload with high number of boosters	5.0 – 5.2 tons
Launch Trajectory Constraints	
Maximum Longitudinal Acceleration	5.5 g (5.0 g for Multi-PH)
Maximum Dynamic Pressure	60 kPa
Maximum Dynamic pressure at Booster Separation	4.0 kPa
Fairing Jettison Aerothermal Flux	1 135 W/m^2
Fairing diameter	5.4 m

Table 3: Mission general requirements for ANGELA [11]

2.4 Mass budget

During the preliminary analysis, masses have been assessed with the help of the structural index law, determined on the basis of the results from FLPP and existing stages. The primary goal of ANGELA is to size a low cost launch vehicle. For this reason, the use of expensive manufacturing processes should be avoided if they are not bringing a cost advantage for the whole system. At this stage of the study no decision has been taken concerning the tank architecture or the stage diameter.
As a consequence of the French Space Operations Act adopted in 2008, the upper stage of the ANGELA launch vehicle, independently of the chosen architecture, will have to perform a controlled re-entry. No technical solution has been selected for the de-orbit kit and a fixed mass of 500 kg was assumed during the initial sizing. Preliminary analysis are showing that for a de-orbitation using the Vinci engine the mass of the additional equipment and propellant together will amount to between 350 kg and 500 kg. Later analysis should refine this value. Fluid mass budgets (reserve, residual and inert) have been assessed, based on values of Ariane 5 ME. One large fairing has been selected. Indeed the least powerful version of each launcher is intended to be used mainly for launch in LEO and thus will also require a large fairing in most cases.

2.5 HH-2V

Based on the assumptions presented in the previous chapters, a preliminary design and staging was performed and converged towards an H110-H29 with P36 solid rocket boosters. The first stage containing 110 tons of LOx and LH2 is propelled by 2 Vulcain 2 engines with a nozzle shortened to an expansion ratio of 48 (see characteristics in Table 1). Indeed, the driving parameter was the accommodation of two engines under a 5.4 m diameter stage, limiting the expansion ratio at 48. Lower expansion ratio would give lower performances.

Number of Boosters	Payload to GTO[1] [kg]	Max acc [g]	Max q [kPa]	Mach Number at Max q [-]	q at Booster separation [kPa]	GLO mass [tons]	Payload Fraction [-]
2	2170	4.55	34.9	1.60	1.66	252	0.86
4	3840	4.42	42.0	1.76	1.14	334	1.15
6	5140	4.60	47.8	1.90	1.06	415	1.24

[1] Payload performances are given with 500 kg for the de-orbitation kit already considered

Table 4: Characteristics of the ascent trajectory to GTO for the HH-2V architecture

The upper stage, equipped with the Vinci engine, is loaded with 29 tons of LOx and LH2 propellant. This value is situated between the optimal propellant loading for the 2 booster and 6 booster versions. This is slightly more than in the new upper stage which is now under development for the Ariane 5 ME launch vehicle. The version with 2 boosters is able to launch almost 2.2 tons to GTO. With 6 boosters the performance increases to more than 5.1 tons which is in agreement with the requirements. An intermediate performance is reached with 4 P36, which is also shown in Table 4. Maximum accelerations and dynamic pressure are well below the limits which were set.

2.6 HH-SC

For this preliminary staging, different first stage engines with vacuum thrust situated between 1800 kN and 2250 kN have been analysed. The engine technology is chosen to be similar to the one of the staged combustion engine considered in the frame of FLPP. The optimisation led to the choice of an engine with a vacuum thrust of 1800 kN and an expansion ratio of 42 (see characteristics in Table 5), propelling an H90 first stage. The upper stage is an H24. The variation of the performance is achieved by varying the number of P34 solid rocket motors from 2 to 6.
The characteristics of the ascent trajectory are given in Table 6. As expected, the higher performances of the staged combustion engine allows for a sizable reduction of the gross lift-off mass of the launcher compared to the HH-2V configuration. This difference could even increase considering the lower acceleration and dynamic pressure reached by this architecture. However the development and the production cost for the first stage engine might be a critical factor.

	SC1800E42 ($\varepsilon = 42$)
Specific impulse [s]	373 (s.l.) / 442 (vac)
Mass flow rate [kg/s]	415
Mixture ratio [-]	6
Mass [kg]	3140
PCC [bar]	145

Table 5: Characteristics of the HH-SC first stage engine

Number of Boosters	Payload to GTO[1] [kg]	Max acc [g]	Max q [kPa]	Mach Number at Max q [-]	q at Booster separation [kPa]	GLO mass [tons]	Payload Fraction [%]
2	2160	3.80	28.7	1.41	3.18	216	1.00
4	3640	3.68	34.6	1.61	2.55	293	1.24
6	5180	4.24	44.2	1.90	1.79	370	1.40

[1] Payload performances are given with 500 kg for the de-orbitation kit already considered

Table 6: Characteristics of the ascent trajectory to GTO for the HH-SC architecture

2.7 Multi PPH

For the last architecture which is similar to the one proposed by CNES for a future Ariane 6, strictly identical solid rocket motors are used for the first and the second stage of this 3 stage launch vehicle. The goal is to reduce development costs with the development of a unique motor with a unique nozzle and to reduce production costs with a high production rate. Indeed three to four of this motor are used for each launch. Two to three are used for the first stage and another one for the second stage. For this reason, contrary to the fully cryogenic architectures, there is no intermediate version of the Multi PPH. Thrust law and propellant masses have been optimized leading to a P120. The upper stage is cryogenic and equipped with the Vinci engine as already previously mentioned. An ascent propellant loading of 23 tons is sufficient to reach the required performances. The characteristics of the ascent trajectory are shown in Table 7. The 2PPH version is able to launch almost 2.4 tons to GTO. This is about 10 % more compared to the light versions of the HH configurations presented previously (chapter 2.5 and 2.6). This was done to partially compensate the lack of an intermediate version. Acceleration and especially dynamic pressure levels are considered as very low, which will be beneficial for the structural design.

Number of 1st stage motors	Payload to GTO[1] [kg]	Max acc [g]	Max q [kPa]	Mach Number at Max q [-]	q at 1st stage separation [kPa]	GLO mass [tons]	Payload Fraction [%]
2	2370	4.35	15.8	1.25	1.15	430	0.55
3	5120	4.28	20.4	1.12	0.23	565	0.91

[1] Payload performances are given with 500 kg for the de-orbitation kit already considered

Table 7: Characteristics of the ascent trajectory to GTO for the Multi PPH architecture

3. Small TSTO

3.1 Background, study logic and synergies

The other concept under study at DLR-SART is the small TSTO launch vehicle. This concept has the goal to be a complement to Vega and Ariane 5 ME. It would also have the ability to replace Soyus, if this launcher for one reason or another would not be available any longer for launch from Kourou.
The preliminary design considered two performance targets. The launcher should be able to perform Galileo satellite replacement single launch missions to MTO corresponding to a payload performance of about 1400 kg to MTO. A boosted version of the launch vehicle shall be able to launch payloads up to 3000 kg in GTO, to fulfill mission currently performed by Soyuz. In contrast to ANGELA, the primary goal of the small TSTO is not to replace Ariane 5 ME. It would be used only as a complementary versatile rocket to launch smaller geostationary satellites, Earth observation satellites and Galileo satellites, which are too small for Ariane 5 and too big for Vega.
The investigation of this concept started in 2007 in the frame of the VENUS (**Ve**ga **N**ew **U**pper **S**tage) study ([8] and [9]). Considering the technologies available in Europe a two stage to orbit launch vehicle appears to be the simplest and most cost effective option for a new launch vehicle. A large monolithic solid rocket motor was selected for the first stage in order to take advantage of the experience gathered during the development of the lower stages of Vega. For the upper stage, the high performances Vinci engine was chosen, though it is the most powerful upper stage engine available in Europe. An optimization of the thrust level was not done, even if it is expected that a thrust higher than 180 kN would be beneficial for the staging ([11] and [10]). Indeed, it is known that an increase of the thrust level of the Vinci engine is not possible without a costly and thorough redesign of the engine. In addition the expander cycle also implies a limit in terms of maximum thrust. The characteristics of the Vinci engine considered in this study are summarized in Table 1. Such architecture would allow exploiting synergies with Vega for the lower stage and with Ariane 5 ME for the upper stage. Synergies would also be guaranteed with the concept of Ariane 6 currently under study. Synergies between ANGELA and the small TSTO launcher would be possible; however both launch vehicles have probably a too close payload performance range to justify a concurrent utilisation.
Based on previous analysis (see [3] and [4]) and new developments for future solid rocket motor (see [1]), a new optimisation of the launch vehicle staging has been performed. For this update the mission requirements have been changed to those considered for the ANGELA project and summarized in Table 3, with the goal to ease comparison between the launcher concepts.
To comply with these new requirements each stage of the launch vehicles was re-optimised. The thrust law and propellant loading of the first stage and the upper stage propellant loading were re-assessed. The booster thrust law and ignition strategy was chosen to keep the loads (acceleration and dynamic pressure) for the light and heavy version of the small TSTO launch vehicle as close as possible to each other. The resulting launch vehicle is a P175 – H26 to which 4 P23 boosters can be added for the heavy version. The characteristics of the different stages of the small TSTO launch vehicle are described in the subsequent chapters.

3.2 Structure and thrust law of the first stage and boosters

For the design of the small TSTO launch vehicle, a maximum combustion chamber pressure of 90 bar was assumed until now. Reaching this value is feasible directly with technologies used on Vega motors (see Table 2). New analyses however show that higher combustion pressure (up to 110 bar, [1]) should not lead to particular problems with the current technology. As a consequence the authorized maximum combustion chamber pressure for solid rocket motors was increased to 100 bar (same value as for ANGELA). This value is higher than for Vega motors but still considered to be on the safe side.
The new studies also concluded that the structural index of large solid rocket motors with about 180 tons of propellant is expected to be as low as 6 to 7% [2]. For this reason, the value of 8.5% considered until now in the

frame of the small TSTO design was kept for the motors. Although the maximum combustion chamber pressure increased, this value for the structural index can still be considered as conservative. This structural index is, here, defined as the ratio of structural mass without inter-stage to the propellant loading. Moreover a mass surplus estimate was added for motors with an expansion ratio larger than 16 (reference value of P80FW, first stage of Vega). The smaller strap-on boosters were assumed to be characterised by a higher structural index: 11%, to take into account the effect of the smaller size and the additional aerodynamic elements (e.g. nose cone) which have to be added.
Both the strap-on boosters and the main solid rocket motors are loaded with HTPB 1912, the same propellant as for Vega. A finocyl-type grain shape is also utilised.
The thrust laws have been optimised to reduce the loads (acceleration, dynamic pressure) during the ascent, while achieving the targeted payload performance. To that purpose structural analyses have been performed to size the upper stage to withstand the loads resulting of each variant of thrust laws (see chapter 3.4). In addition, each thrust law was the object of a performance analysis to determine its particular characteristics such as specific impulse.
The chosen first stage is the so called P175 type 3 with an expansion ratio of 22 (referred to as P175 in the subsequent chapters). It has an ascent propellant mass of 175 tons and burns for 150s. Its diameter was set to 3.5 m. The performance computations performed with the in-house SRP program allowed an assessment of the average specific impulse. At lift-off, at sea level conditions, the specific impulse is 250 s. The average specific in vacuum conditions is as high as 288.5 s. Additional characteristics of this motor are summarized in Table 8. Its thrust law is plotted in Figure 1.
To avoid too high an increase of the loads for the version with the boosters, both thrust law and ignition strategy of the boosters have been varied. A P23 solid rocket booster with 23.2 tons of HTPB 1912 proved to be optimal. Due to an expansion ratio of 16 its specific impulse at sea level is, at 255.4 s, higher than the P175. Its average specific impulse in vacuum is 280 s. Further information about this booster is summarized in Table 8.
The heavy version of the small TSTO launch vehicle is equipped with 4 P23 type 5. At lift-off, only 2 boosters will be ignited. The second pair of booster is ignited only 65 s into the flight. At this instant the dynamic pressure is decreasing rapidly and the thrust of the first pair of booster reaches a relatively low level. After 80 s, the first pair of boosters burn out and are separated. The second pair of P23 provide a thrust surplus almost until the burn-out of the P175. For this reason the second pair of booster are not separated from the first stage. The corresponding thrust law and ignition strategy is shown in Figure 1.
Analyses have shown that shorter booster firing times would lead to higher dynamic pressure and an earlier ignition of the second pair of booster would lead to high acceleration around 110 s into the flight. Indeed at this time, the total thrust would be still quite high and the mass of the booster already quite low. A too early ignition of the second pair of boosters can also prevent the reduction of the dynamic pressure. Indeed in some cases, after an early ignition of the second pair of boosters, the dynamic pressure would still continue to increase.

	P175 type 3 (ε = 22)	**P23 type 5 (ε = 16)**
Specific impulse [s]	250 (s.l.) / 288.5 (vac)	255.4 (s.l.) / 280 (vac)
Propellant mass [tons]	175	23.2
Diameter [m]	3.5	1.53
Maximum vac. thrust [kN]	5480	1350
Nozzle throat diameter [m]	0.62	0.32
Nozzle exit diameter [m]	2.9	1.26

Table 8: Characteristics of small TSTO launch vehicle lower stage and strap-on booster

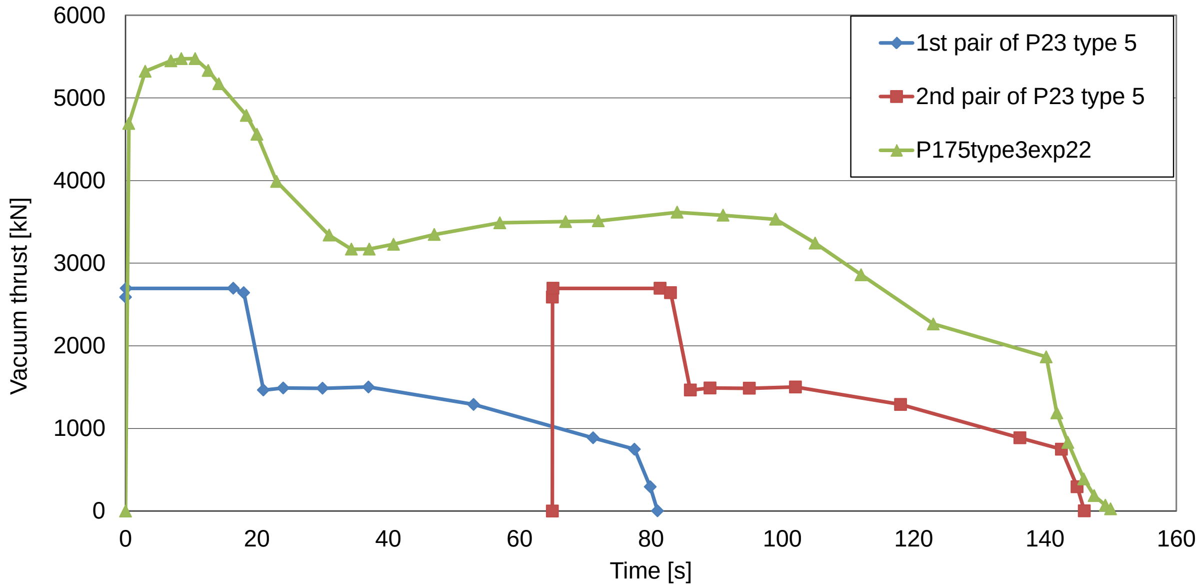

Figure 1: Assumed vacuum thrust law of P175 type 3 (ε = 22) core motor with superposed thrust law delivered by both pair of P23 type 5 strap-on booster according to the selected ignition strategy.

3.3 Upper stage propellant management system preliminary design:

The feed and pressurisation systems of the cryogenic upper stage have been pre-sized with the latest version of the DLR in-house preliminary design and simulation program PMP (Propellant Management Program). The common bulkhead architecture, which turned out to be the best option for GTO in analyses performed previously (see [3], [4]) was kept unchanged. Figure 2 displays the preliminary H26 upper stage concept with the feed lines, and the pressurisation system. A rough sizing of the tank insulation was also performed.

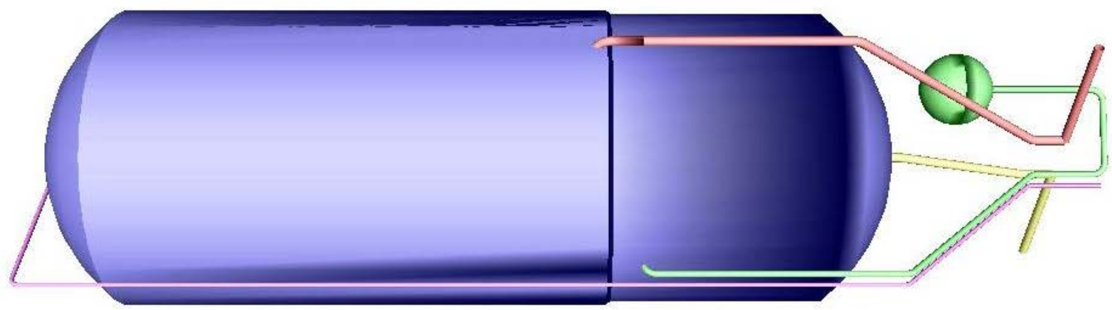

Figure 2: Visualisation of the H26 upper stage with preliminary designs of the feed and pressurization system and the tank insulation.

Revision and extension of PMP allowed improved modelling and assessment of the pressurization and venting phases, compared to previous analyses. In addition, conclusions of cryogenic propellant pressurization ground experiments on thermodynamic and fluid-dynamic effects during tank pressurisation and the influence of the pressurant gas temperature, conducted at ZARM in Bremen, [6] were also taken into account for the preliminary design of the pressurisation system.
To guarantee, that the pressure and temperature of the propellant, which is fed to the engine, are in its allowed operation range, an ideal tank pressure variation strategy has been generated (see Table 1). Based on this strategy, the evolution of the pressure in the tanks has been computed. This analysis takes the heat entering the tanks, venting and a maximum pressure variance of ±0.1 bar with respect to the target tank pressure into account. The results of the PMP calculations for the pressure evolution of both tanks for a LEO mission with re-ignition of the Vinci engine are shown in Figure 3. It can be seen how the pressure in each tank varies between the limits which have been set. Note that at the end of the ballistic phase the chosen feedback control has some difficulties to keep the pressure in the LH2 tanks within the limits. The error is however small. For a GTO mission, only one boost of Vinci is required. In this

case, the pressure variation is similar to what is observed during the first 830 s in Figure 3. Under such conditions, it was calculated that 7 kg of helium are needed to pressurise the LOx tank until the end of the first boost of Vinci. On the LH2 side, due to heat coming from the environment, about 100 kg of LH2 will evaporate, and contribute to the tank pressurisation. In addition to this, 9 kg of GH2 will be needed to be tapped off in the engine.
During the ballistic phase, no pressurisation gas is needed. Moreover, it was possible to reach the pressure required before re-ignition of Vinci on the LOx side with the insulation and venting strategy which were chosen, but without re-pressurisation. On the LH2 side, a propellant reconditioning manoeuvre is needed to reduce the propellant temperature after the ballistic phase. To achieve this, a pressure drop to 1.6 bar is intended. This is followed by a re-pressurisation with helium to 3 bar. In total, 15 kg of helium are needed to prepare the second boost. Note, that in Figure 3, the pressure in the LH2 tank does not decrease sharply at the end of the ballistic phase. This is due to restrictions in calculation methods of PMP. The influence of this limitation on the results has been taken into account. Based on the results of the analysis, it was decided to use one helium vessel with a capacity of 7.5 kg at 400 bar for the GTO mission. For a LEO mission, 2 additional helium vessels are installed on the stage. It was estimated that such a helium vessel would have a mass of about 31 kg.

	Pressure in LOx tank	**Pressure in LH2 tank**
P175 boost	2.8 bar	3.0 bar
Vinci 1st boost	2.8 → 2.64 bar	2.8 → 3.3 bar
Ballistic phase	2.64 → 2.5 bar	3.3 → 1.6 bar
Re-pressurisation	-	1.6 → 3 bar
Vinci 2nd boost	2.5 → 2.4 bar	3.0 → 2.9 bar

Table 9: H26 tanks pressure variation strategy for a LEO mission

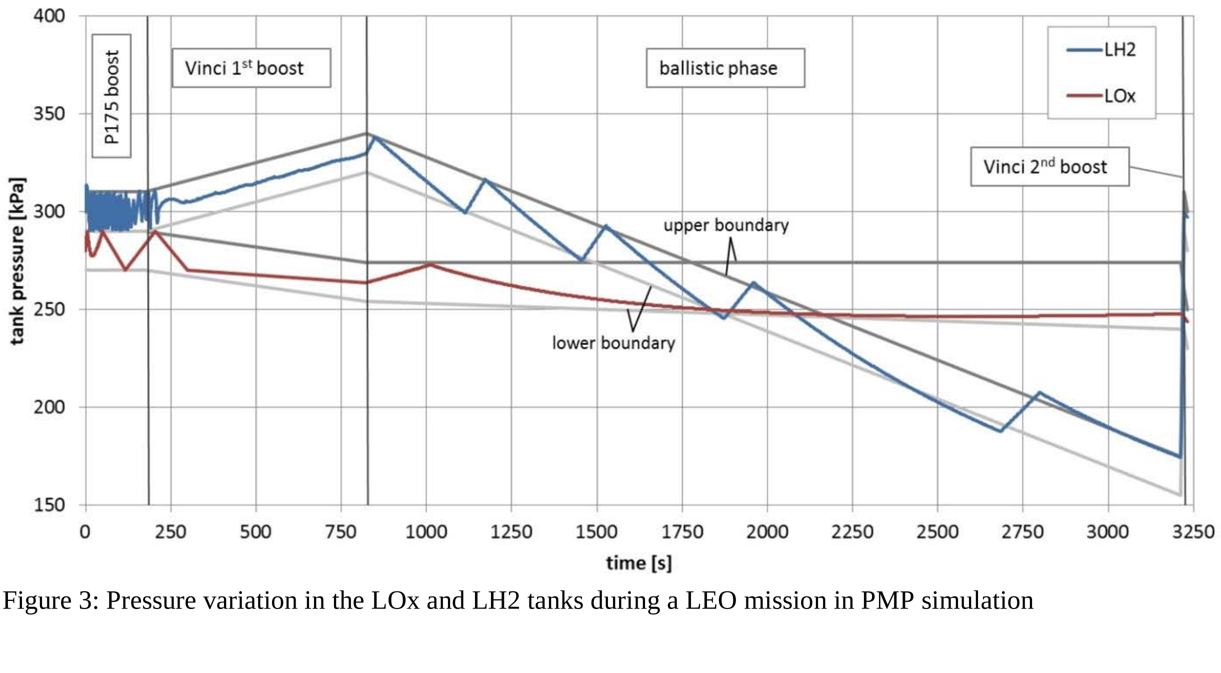

Figure 3: Pressure variation in the LOx and LH2 tanks during a LEO mission in PMP simulation

3.4 Upper stage mass budget and structural design

The mass budget of subsystems is, as in previous analyses of the small TSTO launch vehicle, based on heritage. For instance the pressure control assembly, the actuators and the reaction and control system propellant mass are based on data available for Ariane 5 ME upper stage. The engine thrust frame for the upper stage is also derived from the Ariane 5 ME upper stage. The avionics is based on Vega with duplicated set to add redundancy. Possible mass increases due to modifications required by the small TSTO launch vehicle are covered by a 10% margin.
The preliminary structural design of the upper stage has been performed with the help of the SART in-house program LSAP. The sizing method already described in [4] considers the launcher as a 1-dimensional bending beam with

rotational symmetry. The structure is sized to withstand a number of standard loads case, such as the maximum dynamic pressure (max q), the maximum product of dynamic pressure and angle of attack (max qα) and the maximum acceleration. To account for dynamic loads, the axial accelerations have been increased by 1.0 g for the max q and the max qα cases and by 1.25 g for the maximum acceleration cases. A margin of 10% has been added on top of the resulting structural masses. For the sizing the GTO mission was considered.
The resulting upper stage structural index (excluding: engine, de-orbitation kit and inter-stage) is:

- 11.5% for the P175 – H26 (small TSTO light)
- 12.7% for the 2+2P23 – P175 – H26 (small TSTO heavy)

The loads on the structure are higher for the heavy version than for the light one. These differences can be explained by different maximum accelerations; aerodynamic loads, fairing length and mass, payload mass (see Table 10). All in all, it results in a upper stage dry mass 330 kg heavier when designed for the small TSTO heavy compared to a sizing performed for the small TSTO light. From an economical point of view, it does not make much sense to develop two different versions of a given stage. Consequently a concurrent utilisation of the boosted and un-boosted version of the small TSTO would lead to use the heavier upper stage for both versions. As a consequence the payload performance of the light version of TSTO would decrease by 330 kg to 1325 kg. This is slightly lower than the target payload performance of 1400 kg in GTO. However to be comparable with the ANGELA launch vehicles presented in chapter 2, the same mass has been assumed for the de-orbitation kit: 500 kg. This value corresponds to the higher limit of estimations performed for launch vehicle in the class of Ariane 5 ME / Ariane 6. A reduction of this mass would probably be possible. The utilisation of a small solid rocket motor to perform the de-orbit boost could even in certain conditions be much more efficient than a re-ignition of Vinci [3].

Launcher	Payload to GTO[1] [kg]	Max acc [g]	Max q [kPa]	Mach Number at Max q [-]	q at booster separation [kPa]
P175-H26	1655	4.01	42.7	1.62	-
2+2P23 - P175-H26	2990	4.58	43.0	1.52	18.6

[1] Payload performances are given with 500 kg for the de-orbitation kit already considered

Table 10: Characteristics of the GTO ascent trajectory used for the upper stage structural sizing for small TSTO light and small TSTO heavy

3.5 Payload performance and trajectory

With the help of the DLR in-house program tosca_ts1.2 for trajectory optimisation, the payload performance of the light and heavy version of the small TSTO launch vehicle have been assessed for four different orbits:

- GTO-1 (200 km x 35786 km, 7°) similar to ANGELA
- GTO-2 (250 km x 35943 km, 5.4°) reference orbit of Ariane 5 ECA
- MTO (200 km x 23222 km, 55.3°) for Galileo satellite injection
- LEO (700 km x 700 km, 90°) reference orbit of Vega

The results of these trajectory optimisations are summarized in Table 11. The characteristics of the trajectories are very similar for GTO-1, GTO-2 and MTO for a given version of the small TSTO launch vehicle. For LEO due to the higher payload mass both the maximum acceleration and dynamic pressure are reduced. Note that the performances calculated for LEO assumed the same fairing as for the GTO-1. The structural masses are the same for each ascent trajectory and based on the sizing described in chapter 3.4 for the heavy version of the small TSTO launch vehicle. The payload performance to MTO is almost 1.4 tons for P175+H26. After a more accurate analysis of the mass required for the de-orbitation kit, an increase of this value is expected. The heavy version of the small TSTO can launch almost 3 tons to GTO which also correspond to the target performance. The ascent trajectory, as well as some other characteristics of the ascent are plotted in Figure 4. All requirements are met, except the dynamic pressure at booster separation. This value is indeed high. A more detailed analysis is needed to assess its criticality. A delayed separation of the booster would allow to significatively reducing the dynamic pressure at booster separation, at the cost of a reduction of the payload performance.

	P175 + H26				2+2P23 + P175 + H26			
Trajectory	GTO-1	GTO-2	MTO	LEO	GTO-1	GTO-2	MTO	LEO
Acc_max [g0]	4.01	4.01	4.01	3.9	4.58	4.58	4.58	4.41
q_max [kPa]	42.7	42.7	42.1	39.8	43.0	42.6	42.3	40.8
q @ booster separation [kPa]	-	-	-	-	18.6	17.1	16.0	14.7
Payload mass[1] [kg]	1325	1235	1350	3700	2990	2895	3065	6435
GLO mass [tons]	225	225	225	228	330	330	331	334
Payload fraction [%]	0.59	0.55	0.60	1.63	0.90	0.88	0.93	1.93

[1] The influence of the 500 kg for the de-orbitation kit and the structure mass designed small TSTO heavy are already considered in the payload performance

Table 11: Main characteristics of the ascent trajectory to GTO-1, GTO-2, MTO and LEO for the light and heavy versions of the small TSTO

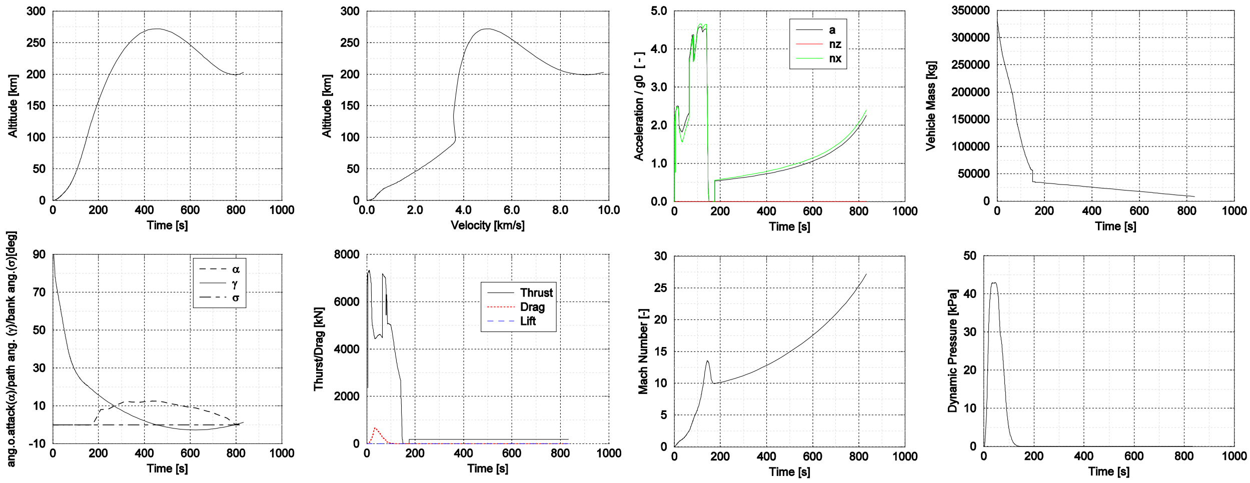

Figure 4: Ascent trajectory to GTO (200 km x 35786 km, 7°) of 2+2 P23 +P175 + H26 (small TSTO heavy)

4. Conclusion

Two launch vehicles concepts based primarily on technologies and components available today in Western Europe have been proposed. Their designs place an emphasis on exploiting synergies with current programs. They are the answer to two different scenarios. The ANGELA launch vehicle should guarantee an autonomous access to space for Western European institutional payload at the lowest cost in unfavourable market conditions. Three architectures have been studied for this launch vehicle and a preliminary design and staging optimisation has been performed in the frame of this study managed by the DLR Space Administration. To reach the payload range situated between 2 and 5 tons, an H110-H29 with 2, 4 or 6 P36 is proposed, with a first stage propelled by two Vulcain 2 with a nozzle shortened to an expansion ratio of 48. If the two Vulcain 2 are replaced by a new staged combustion engine the optimal staging is an H90-H24 with 2, 4 or 6 P34. For this architecture a staged combustion engine with a vacuum thrust of 1800 kN would be needed to be developed. The last architecture is the multi-PPH. The optimisation of the staging converged on a 2/3 P120-P120-H23. These three preliminary designs will be optimised for recurring cost reduction and consolidate in the coming phases of the ANGELA project.
An updated version of the small TSTO launch vehicle, studied at DLR-SART, demonstrates the possibility to fill the gap of performance between Vega and Ariane 5, while exploiting synergies with these two launchers. A re-optimisation of this cost effective concept to take into account updated requirements and a higher maximum combustion pressure of SRM than previously assumed, converged on a P175-H26. This light version of the small

TSTO launch vehicle is able to launch 1350 kg to MTO (transfer orbit to Galileo satellites orbit). A heavy version, equipped with 2 pairs of P23 solid rocket boosters would be able to launch up to 3 tons to GTO. More detailed studies of the controllability, especially at booster separation, and of the required mass for the controlled re-entry of the upper stage need to be performed to consolidate the design.

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Further updated information concerning the DLR-SART space transportation concepts is available at:
http://www.dlr.de/SART