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Future European Expendable Launcher Options and Technology Preparation

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The paper describes latest results of the most recent activities in Germany in the technical assessment of future European launcher architecture. In a joint effort of DLR-SART with German launcher industry a next generation upper-medium class expendable TSTO and options for new liquid fuel upper stages for the small VEGA-launcher are addressed. The WOTAN study has investigated fully cryogenic launchers as well as those with a combination of solid and cryogenic stages, fulfilling a requirement of at least 5000 kg single payload into GTO. With this study finished, final performance data as well as critical technical and programmatic issues are presented. The VENUS research on potential new VEGA upper stages is now focused on storable and on Vinci-based cryogenic propulsion and includes not only the VEGA solid propellant lower composite, but also its potential more powerful future upgrade.

In its second part the paper gives an overview on advanced cryogenic upper-stage technologies presently under investigation in Germany. A research cooperation of German launcher industry, university academia and DLR has been initiated to work jointly on various identified needs.

Nomenclature

D	Drag	N
I_{sp}	(mass) specific Impulse	s (N s / kg)
M	Mach-number	-
T	Thrust	N
W	weight	N
g	gravity acceleration	m/s^2
m	mass	kg
q	dynamic pressure	Pa
v	velocity	m/s
α	angle of attack	-
γ	flight path angle	-
σ	engine deflection angle	-
ω	angular velocity	s^{-1}

Subscripts, Abbreviations

AP	Ammonium Perchlorate
AVUM	Attitude and Vernier Module
CAD	Computer Aided Design
ELV	Expendable Launch Vehicle
GLOW	Gross Lift-Off Mass
GNC	Guidance, Navigation, Control
HTPB	Hydroxyl Terminated Poly Butadiene
ISS	International Space Station
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MEOP	Maximum Expected Operating Pressure
MMH	Monomethyl Hydrazine
MR	Mixture Ratio
SRM	Solid Rocket Motor
SSME	Space Shuttle Main Engine
SSO	Sun Synchronous Orbit
TRL	Technology Readiness Level
TSTO	Two Stage to Orbit
VEGA	Vettore Europeo di Generazione Avanzata
VENUS	**VE**GA **N**ew **U**pper **S**tage
WOTAN	**W**irtschaftlichkeitsuntersuchungen für **O**rbital-**T**ransportlösungen von **A**riane **N**achfolgeträgern (Economic Assessment of Orbital Transportation Options of Ariane-Succeeding Launchers)
cog	center of gravity
sep	separation

1 INTRODUCTION

The investigation on the future European options in payload delivery to orbit is going on in different national and multi-national contexts. The range of interest reaches from potential adaptation and rearrangement of existing stages to complete new developments. Payload classes vary between small LEO and heavy GTO capabilities.

The system activities in Germany during the last two years focus on a next generation upper-medium class expendable TSTO and options for new liquid fuel upper stages for the small VEGA-launcher. Two DLR-agency funded studies support the investigations of these subjects [5]: WOTAN on the next generation launchers and VENUS on potential new VEGA upper stages. Beyond that effort technology preparation and maturation activities for re-ignitable cryogenic upper stages are under way. All work is performed as a joint effort of DLR with German launcher companies EADS astrium and MT Aerospace.

The study WOTAN has investigated fully cryogenic launchers as well as those with a combination of solid and cryogenic stages with an initial operational capability after 2020, fulfilling a requirement of 5000 kg single payload into GTO. Solid strap-on boosters should allow both versions further payload growth capability.

Advanced upper-stage technologies are one of the primary German investigation areas. These technologies could not only be applied to the above mentioned TSTO but also to a potential upgrade of the Vega small launcher. A broad range of small launcher upper stages have been investigated in VENUS spanning storable as well as different cryogenic propellants. Based on a comparison of achievable performance and required development effort, the preliminary stage designs concentrate on a storable propellant variant with Aestus2 engine and cryogenic LOX-LH2 versions using an adapted VINCI rocket motor. The system investigations in VENUS are not only based on the VEGA solid propellant lower composite currently under final development, but also on its potential more powerful future upgrade.

Note that all presented launcher concepts are under investigation to obtain a better understanding of future ELV options. Study results should support Germany's preparations of the European ministerial council 2008. For none of the launchers, even the most promising ones, currently a development decision is implicated.

2 WOTAN: NEXT GENERATION EXPENDABLE MEDIUM-LIFT TSTO OPTIONS

Subject of the WOTAN study [1] are options for next generation expendable TSTO launchers fully based on European technology. Its major programmatic goals are to foster ELV system expertise in Germany and to promote cooperation and collaboration of German key industrialists and DLR-launcher systems analysis group (SART). The main technical objectives of WOTAN are:

- Perform a pre-design for two pre-selected, promising ELV configurations
- Assess operational constraints
- Establish a parametric cost assessment
- Cost-benchmark with existing launchers

The WOTAN launcher architecture study has been run from November 2006 until July 2008 with a total budget of 1.6 Million €, investigating expendable fully cryogenic (LOX/LH2) TSTO name-coded “K” and solid 1st stage / cryogenic 2nd stage TSTO combinations name-coded “F”. The possibility to increase GTO and LEO performance by means of added solid Strap-On-Boosters is highlighted by an additional "+"-sign.

2.1 Study Logic, Constraints, and Margin Policy

The GTO-launch from the European Space-Port of Kourou (French Guyana) is defined as the reference mission with the requirement of a minimum single payload injection of 5 metric tons. This mission obligates the size of the two core stages. Afterwards, these are kept fixed and the propellant loading of the 6 solid-Strap-On-Boosters is defined in order to reach the augmented-performance aiming at 8 metric tons in GTO.

The maximum diameter of the stages (and the fairing) has been fixed at 5.4 m in order to allow the re-use of Ariane 5 manufacturing and procurement assets. The needed under-fairing volume for the payload is similar to AR5 for a single launch, so the same fairing volume and shape has been used (same class of payload, similar aerodynamics).

For the 2nd stage a design with separated fuel and oxidizer propellant tanks is preferred in order to have a concept which facilitates the performance of versatile missions when requiring multiple re-ignitions (as scientific missions, GTO+, or even GEO).

In the launcher definition process it is tried to use as few liquid engines as possible, while on the other side remaining in a high-thrust range accessible with reasonable technological extension from current and past European high-thrust liquid engines. That drove to the initial choice of a twin-engine 1st stage for the “K” configurations and a single engine 2nd stage for both “K” and “F” configurations (see Figure 1). For the full cryogenic version, 3 different technologies for first stage high-thrust engines had been initially considered, in relation with their expected production cost [4].

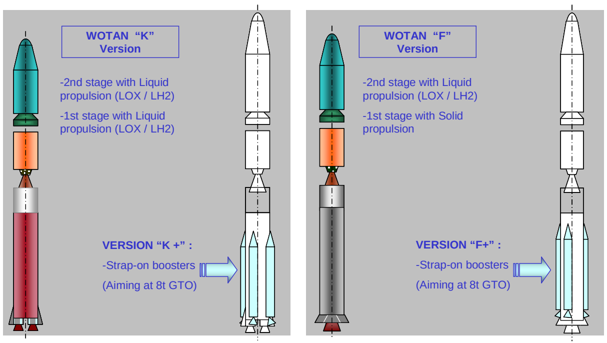

Figure 1: Generic concept definition of WOTAN launchers

The WOTAN-study is subdivided into four subsequent phases including two iterative launcher sizing loops. After an initial launch vehicle configuration phase with a broad investigation of all available options, the stage architectures of two launchers including their engines have been defined. The main goal of this work has been to elaborate the essential functional architecture of the different stages, perform a pre-dimensioning of the main sub-systems in order to elaborate realistic mass and performance characteristics. This mid 2007 status has been presented in [5].

Obtained mass and propulsive characteristics are then used for verifying the initial performance and adjusting the launcher staging as far as necessary. In case of severe divergence, more advanced technological solutions may have to be re-introduced for reaching the payload GTO target while keeping the launch vehicle take-off mass within a reasonable value. This configuration is a result of the second sizing loop.

In phase 3 these latest iterated launcher concepts are used for final performance calculations into different interesting orbits. In the final phase 4 the concepts are evaluated, development and production costs are assessed, and technology development needs are derived.

A general payload performance margin of 200 kg to the reference geostationary transfer orbits is assumed, calculated engine I_{sp} are reduced by approximately 1 % and solid motor I_{sp} by 5 s. Further a small mass margin depending on the used technology is added. Overall, this margin policy can be understood as relatively conservative, allowing a good confidence in the vehicles' simulated performances.

2.2 Preliminary Sizing and Configuration Trade-Offs (Phase 1 and Phase 2)

In a first step SART performed an iterative pre-design and sizing of engines, solid motors and launchers based on similar assumptions. Preliminary data, documented in [4], allowed a down selection on a few most promising configurations. Different cycle complexities of high thrust liquid rocket engines and large solid motors in the first stage were looked upon. The K1-type launcher with 'low-cost' gas-generator cycle engine has been eliminated early from further WOTAN investigations due to its outsize dimensions.

The next step of already more detailed sizing analysis has been performed for the K2 Vulcain-type gas-generator cycle engine, different variants of the K3 high performance staged combustion cycle engine, and two different versions of the solid motor first stage. The launcher sizes are iteratively found in combination of mass estimation and trajectory simulation. [5]

All of the WOTAN stages have been preliminarily dimensioned by DLR-SART such that GLOW is minimal. To stay within the maximum acceleration limitations of 4.5 g during ascent, the two first stage engines have to be throttled to less than 70% of their maximum thrust value. Theoretically, it would be attractive to let stage separation occur at this point. However, limitations on the propellant mass increase of the second stage due to its limited 180 kN Vinci-thrust, and subsequent increase of the losses, exclude this option.

In case of a solid first stage the upper stage thrust limitation with Vinci-engine becomes even more critical. A converging design has been found, however with a high GLOW and resulting poor payload fraction. By using a prospective new 500 kN upper stage engine, the lift off mass has been significantly reduced [4, 5].

A first loop of detailed launcher architectures has been developed by EADS for the two most interesting WOTAN variants: K3 with staged combustion cycle engine and mixture ratio 6.7 in the first stage and the F2 with solid first stage and powerful 500 kN engine in the upper stage. These configurations are published in a 2007 IAC paper [5].

The obtained mass estimations of these architectures delivered very small deviations overall for the first stages compared to the previous assumptions but significant differences for the upper stages. Unfortunately, these stages' burn-out masses (dry weight and propellant residuals) became heavier between 25 % (K3) and 30 % (F2), which forced a complete resizing and optimization of the launchers to allow fulfilling the GTO-payload requirements [7].

The upper stage engine choices of phase 1 have been maintained in this iteration process: Vinci 180 kN for K3 and 500 kN gas generator engine for F2. Therefore, the potential increase in propellant loading for K3's second stage is limited and the bulk of resizing of this launcher is carried by its first stage. Although, the thrust to weight situation is more promising for the second stage of F2, nevertheless, thrust and solid motor grain loading for this variant's first stage has considerably increased. (See section 2.3.3!)

In parallel to the stages and launcher resizing, EADS and MT-Aerospace initiated a structural optimization process, in order to enhance the relatively poor structural indices of the upper stages from the first loop. The architectures are also adapted to the new, larger size (See section 2.4!).

2.3 Latest propulsion system data

All engines in WOTAN had been preliminarily sized in a close iteration between launcher dimensioning and engine cycle analyses at DLR-SART. The mass flow is determined by the minimum lift-off T/W-requirement of 1.3. A preliminary engine component sizing and mass estimation including the definition of more detailed engine architecture is afterwards performed by EADS astrium.

2.3.1 Cryogenic first stage engine

The staged combustion engine mixture ratio had been varied in the range 6 to 6.7. The former is identical to that of the gas generator type K2 while the latter has the same combustion chamber MR as the gas generator main chamber. The engine with higher MR showed a slight edge in overall performance [5] and is therefore the only type maintained in the final phases of WOTAN.

Note that the I_{sp} as used in all trajectory optimizations takes into account a propulsion margin of -1 % with respect to the data provided in Table 1. The throttling of more than 30 % in a 'step-function' is a new requirement for large European engines. A cryogenic staged combustion engine with a vacuum thrust of almost 2700 kN is beyond every such engine type ever developed (SSME with 2280 kN is the largest yet) and therefore has to be assessed as very critical for realization.

Table 1: Calculated characteristic performance data of cryogenic first stage engine K3 (staged combustion cycle)

sea level thrust	kN	2286.7
vacuum thrust	kN	2696
sea level spec. impulse	s	374.12
vacuum spec. impulse	s	440.39
chamber pressure	bar	160
total engine mass flow	kg/s	630
total engine mixture ratio	-	6.7
nozzle exit pressure	bar	0.311
ENGINE SIZE ESTIMATION		
total engine length	m	4.2
nozzle exit diameter	m	2.3
nozzle expansion ratio	-	46

A preliminary engine architecture concept of K3-46 6.7 is depicted in Figure 2.

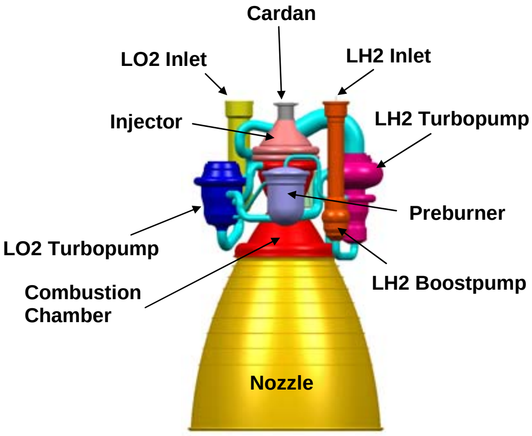

Figure 2: WOTAN K3-46 6.7 engine architecture concept of EADS astrium

2.3.2 Cryogenic upper stage engines

A single Vinci with 180 kN vacuum thrust (Table 2) is the baseline engine for the upper stages. This advanced expander cycle rocket engine is currently under development. Note that Vinci is the largest engine of this cycle ever built.

However, 180 kN thrust is not fully sufficient to propel the heavy upper stage of a large TSTO with a payload requirement of 5 ton in GTO. A double engine solution as used in some Centaur stages is assessed as too complex to be integrated and too costly. Therefore, for launchers with lower performance solid first stages a need exists to raise upper stage propellant loading and hence available thrust. The expander cycle is thought difficult to be enlarged beyond its current size because the chamber wall surface required for the heat transfer does not increase at the same rate as the mass flow. Therefore, DLR-SART defined a generic gas generator engine with 500 kN thrust and a nozzle extension mechanism similar to Vinci. A first impression of the lay-out is presented in Figure 3.

Table 2: Characteristic performance data of cryogenic upper stage engine options

		Vinci 180 kN	WOTAN 500 kN GG
vacuum thrust	kN	180	500
vacuum spec. impulse	s	465	451.8
chamber pressure	bar	60.6	75
total engine mass flow	kg/s	39.46	112.85
total engine mixture ratio	-	5.8	5.8
chamber mixture ratio	-	5.8	6.23
ENGINE SIZE ESTIMATION			
total engine length	m	4.54	3.84
nozzle exit diameter	m	2.32	2.52
nozzle expansion ratio	-	282	150

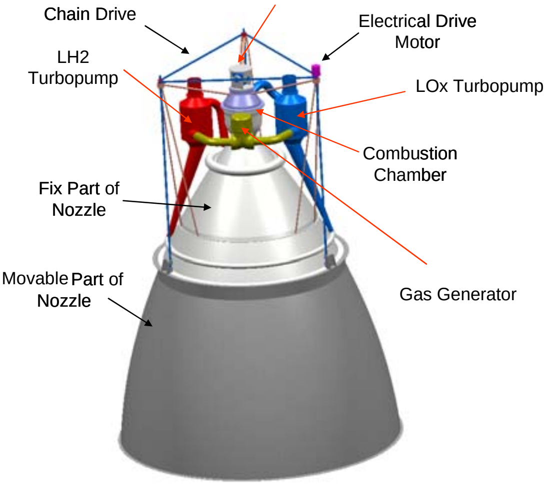

Figure 3: WOTAN 500 kN GG engine with nozzle extension in deployed position (EADS astrium concept)

2.3.3 Solid motors dimensioning

The solid motor characteristics for the very large first stage and for the strap-on boosters have been defined by DLR-SART and EADS according to launcher requirements and trajectory constraints. Figure 4 shows the latest enlarged thrust profile along the approximately 175 s burntime of the F2 first stage. The applied laws are tailored and might require dedicated burning rates. Without detailed analyses, the technical feasibility is oriented towards next generation solid motors as described in [2, 3]. The propellant grain is based on the established HTPB – AP combination and the average combustion pressure is about 90 bars. An average vacuum I_{sp} of 283 s without margin is calculated for the large first stage motors. The strap-on's I_{sp} is lower by 3 s due to their reduced nozzle expansion ratio and to take into account the slight outboard inclination of the fixed nozzles.

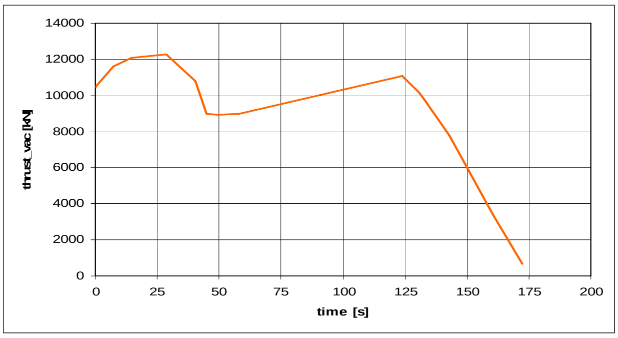

Figure 4: Thrust law of WOTAN F2 first stage solid motor P596

Table 3: Geometry data of F2 first stage solid motor nozzle

Diameter of throat	990 mm
Nozzle area ratio (exit/throat)	15
Diameter of exit	3830 mm

2.4 Refinement of Stages Pre-concept and Structural Re-sizing

The re-sizing architecture studies and structural optimization are performed by EADS astrium with the support of MT Aerospace. These analyses are restricted to the K3-46 6.7 fully cryogenic launcher and to the improved F2 configuration with P596 and H68.

In order to assess the structural dry mass via a pre-sizing, general flight loads have been computed by mean of a simplified pre-project approach. Additionally, a functional general architecture of stages has been established for allowing a pre-sizing when necessary for main sub-systems mass estimates or mass allocation and to propulsion function realization. It concerns typically:

- Functional stage propulsion system conceptual architecture, and flow schematics.
- Propellant loading need, and residual estimate (including thermal).
- Tanks volume need.
- Simplified pressure allocation pre-sizing.
- Pressurization system concept and pressurization-fluid need.

2.4.1 Fully-cryogenic version "K3"

The considerably enlarged configuration, essentially driven by the needed propellant mass, is presented in Figure 5. The aft-skirt and engine bay structure from the first loop [5], capable of attaching 6 SRB, is kept almost unchanged.

The LOX/LH2 first stage concept is built around the following major sub-systems:

- LOX and LH2 tanks with common bulkhead, and external feed-lines
- Liquid Helium supercritical storage for LOX tank pressurization (heater in each engine) – AR5 1st stage technology currently available, and in production - and regenerative heated GH2 (each engine combustion chamber) for LH2 tank pressurization.
- Engine gimballing by a pair of hydraulic actuators each (pitch and yaw), and GH2 roll-control thrusters
- Redundant electrical system for critical functions, batteries on-board for 1st stage flight needs.
- Strap-On-Boosters mechanical connections on the engine-bay (6 boosters, for having reduced length)
- Classical thermal insulation concept (similar to AR5 cryogenic stages), due to the short flight time and large fluid thermal inertia.

The overall dimensions of the WOTAN K3 in comparison to the first loop are:

	Loop 1	**Loop 2**
Total Length (short fairing, GTO):	60.1 m	**66.6 m**
Total Length (Long fairing, ISS):	64.4 m	**70.7 m**
Launcher diameter:	5.4 m	**5.4 m**

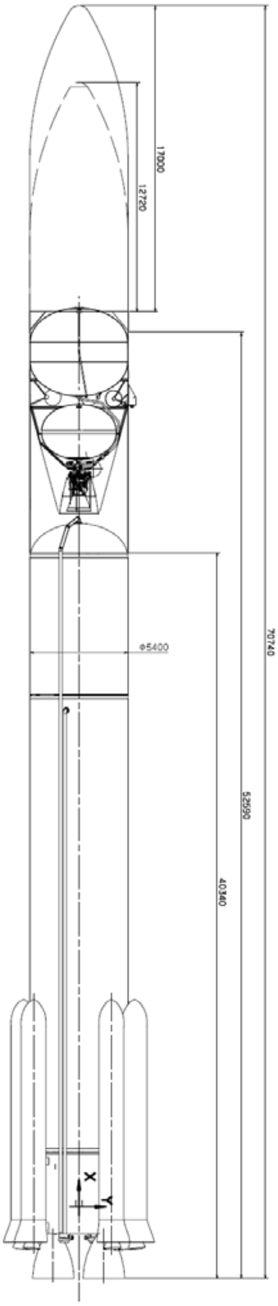

Figure 5: WOTAN "K"3+ conceptual architecture

The lay-out of the engine-bay has been structurally analyzed by the Finite Element Method [6]. An FE-model has been established, reflecting design details for the load introduction and non asymmetric parts. The complete structure is modeled by shell elements including flanges of the ring stiffeners and the corrugation of the circumferential shell (Figure 6). Three different load conditions have been analyzed: ground phase, ignition phase and flight phase (lift-off).

Conventional aluminum and advanced CFRP material have been investigated. The minimum weight to fulfill strength and stability demands is 1980 kg with CFRP and 3750 kg with aluminum [6]. The CFRP-structure is extremely light-weight with respect to the high loads. It is therefore the preferred choice.

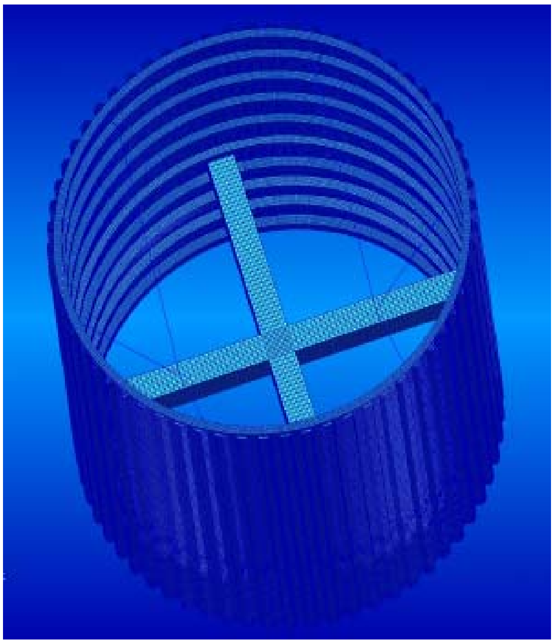

Figure 6: FE-model of WOTAN “K”3 engine bay

The “K3” 1st stage concept general features in comparison of first and second loop are as follows:

	Loop 1	**Loop 2**
Total Length	36 m	**40.3 m**
Stage diameter	5.4 m	**5.4 m**
Stage dry-mass	24.5 t	**27.6 t**
Total propellant loading	234 t	**273.8 t**

The upper-stage concept has taken benefit of the previous studies made for extending mission capabilities of European launchers, and for introducing the Vinci expander cycle in an improved AR5 cryogenic upper-stage. A conceptual geometrical architecture of the resized WOTAN stage is shown in Figure 7.

The LOX/LH2 second stage concept is built around the following major sub-systems:

- Separate LOX and LH2 tanks
- Single engine mounted on a thrust-frame, which also accommodates fluid equipment
- Engine gimballing by a pair of hydraulic actuators each (pitch and yaw), and GH2 roll-control thrusters
- High-pressure (400 bar) ambient temperature Helium storage for LOX tank pressurization, and regenerative heated GH2 (engine combustion chamber) for LH2 tank pressurization.
- Redundant electrical system for critical functions, batteries on-board for 2nd stage and payload-separation flight phase needs.
- Classical thermal insulation concept (similar to AR5 cryogenic stages) for GTO reference mission
- Specific additional equipment (thermal insulation, propellant settling system) as kits for “versatile” missions

The structural optimization process has been quite successful because the slightly enlarged stage of the second loop comes with a reduction of approximately 360 kg (- 7.2 %) in dry mass. The resulting “K3” 2nd stage concept general features in comparison of first and second loop are as follows:

	Loop 1	**Loop 2**
Total Length	11.5 m	**12.9 m**
Stage diameter	5.4 m	**5.4 m**
Total propellant loading	31.5 t	**33 t**
Stage dry mass (w/o fairing and VEB)	5000 kg	**4640 kg**

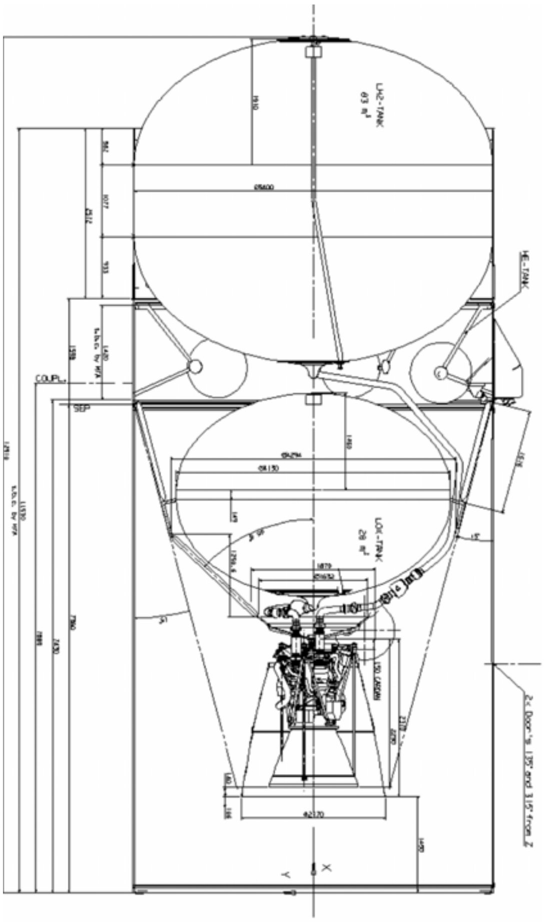

Figure 7: WOTAN “K”3 conceptual architecture of 2nd stage H32

2.4.2 Solid 1st stage / cryogenic 2nd stage version “F2”

The diameter of the first stage solid motor has been kept at 4.6 m despite its considerably increased loading in order to remain comparable with other heavy solid motor pre-project studies made by French industry and space agency [2, 3]. For the upper-stage a diameter of 5.4 m has been retained (same as for the fairing). The WOTAN “F” launcher’s resized concept definition is presented in Figure 8.

General launcher concept data in comparison of first and second loop are:

	Loop 1	**Loop 2**
Total Length (short fairing, GTO)	51 m	**56.3 m**
Total Length (Long fairing, ISS)	56 m	**60.6 m**
Launcher diameter (lower section)	4.6 m	**4.6 m**
Launcher diameter (upper section)	5.4 m	**5.4 m**

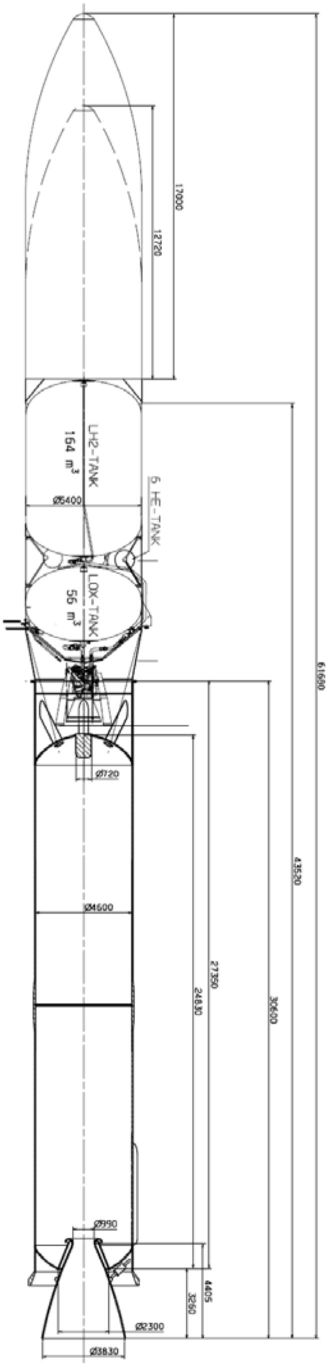

Figure 8: WOTAN "F"2 conceptual architecture

The solid propellant heavy first stage concept is built around the following major sub-systems:

- Composite motor casing, in 2 segments using high performance T800 fiber.
- Propellant grain of new generation, allowing large mass and large geometry casting. Profile and grain structure adapted for limiting the maximum acceleration (compare section 2.3.3 and [2, 3]).
- Flexible nozzle gimballing by a pair of hydraulic actuators (pitch and yaw), and hot gas (hydrazine as reference) roll-control thrusters.
- Redundant electrical system for critical functions, batteries on-board for 1st stage flight needs.
- 6 Strap-On-Boosters with mechanical connections on the aft skirt and a forward position close to the motor casing segmentation interface.
- Special residual thrust-neutralization device for the separation phase [5]. The TRL of this new concept for space launchers is low. Separation or braking rockets might be a potential fall-back replacement of this device.

The resulting "F2" 1st stage concept general features, in comparison of first and second loop are as follows:

	Loop 1	**Loop 2**
Total Length	25.5 m	**30.6 m**
Stage internal diameter	4.6 m	**4.6 m**
Motor casing length	20.4 m	**24.8 m**
Dry-mass with interstage	38.1 t	**47.2 t**
Total propellant loading	456 t	**596 t**

The cryogenic upper stage including its functional architecture is similar to the "K3" version presented in the previous paragraph 2.4.1, but both tanks with 5.4 m diameter due to the larger amount of propellant (Figure 9). The resulting "F2" 2nd stage concept general features in comparison of first and second loop are:

	Loop 1	**Loop 2**
Total Length	13 m	**14 m**
Stage diameter	5.4 m	**5.4 m**
Total propellant loading	59.2 t	**67.4 t**
Stage dry mass (w/o fairing and VEB)	7260 kg	**6970 kg**

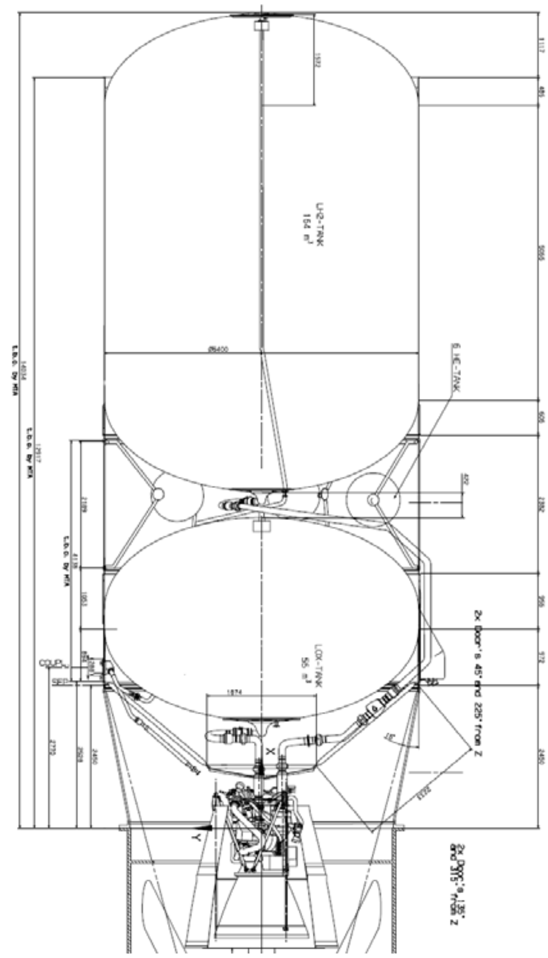

Figure 9: WOTAN "F"2 conceptual architecture of upper stage H68

The structural optimization process has also been successful in case of F2 because the enlarged stage of the second loop comes with a small reduction of approximately 260 kg (- 3.5 %) in dry mass.

2.5 Structural dynamic and controllability analyses

Based on the latest structural lay-out and corresponding weight and stiffness distribution of EADS astrium and MT-Aerospace, SART has performed a preliminary dynamic analyses and controllability assessment of the K3 launcher along its trajectory. The stability and controllability of the ELV should be provided despite of atmospheric disturbances like wind and gusts acting on the launcher during the ascent flight phase.

The characteristics of stability and controllability of the WOTAN K3 launcher from lift-off till fairing separation have been studied for two mission-specific configurations:

- K3 GTO-mission: w/o boosters, short fairing
- K3+ ISS-mission: 6 boosters, long fairing

The artificial stability of heavy launchers with liquid propellant can only be provided by the GNC system with a wide transmission band. The essential problem, especially for a very long launch vehicle like WOTAN K3, is the fact that the elastic structure Eigenfrequencies and the sloshing frequencies of the liquid propellant are low and very close to the frequency of the short-periodic motion. This problem has to be considered already in the preliminary design phase to guarantee the system's feasibility.

2.5.1 Elastic Structure Beam Model and Mass Model

The mathematical model of the launcher follows the beam schematisation [8]. The calculation of the stiffness matrix is based on the material properties and equivalent shell thicknesses of the latest EADS Astrium and MT-Aerospace design.

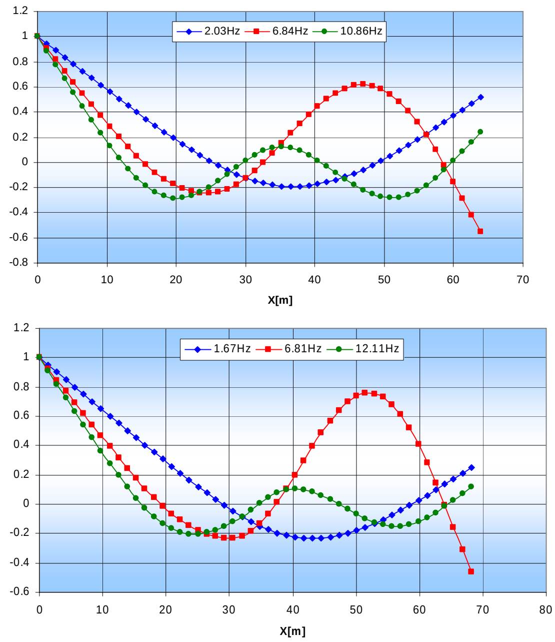

Figure 10: Normalized bending modes of WOTAN K3 at t =59 s, (top: K3-GTO, bottom: K3+ ISS)

The system stiffness matrices combined with the mass distribution matrices are used for calculation of the Eigenfrequencies and principal lateral bending modes, which are presented in Figure 10. The calculated Eigenfrequencies of the lowest three bending modes from lift-off to the fairing separation are presented as a function of flight time in Figure 11.

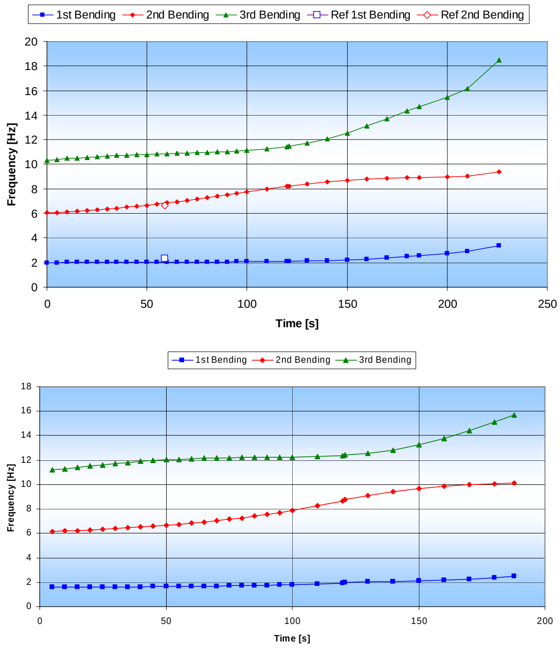

Figure 11: Primary mode frequencies as a function of ascent time (top: K3-GTO, bottom: K3+ ISS)

Wind is modeled according to GRAM-95 mean east-west wind assuming high solar activity. Additionally, an instantaneous, angle of attack augmenting gust of 10 m/s is applied during the ascent flight simulations at the time (t≈ 35 s) corresponding to the maximum product q α.

2.5.2 Flight dynamic Model and Control System

The simulation is done with simplified flight dynamic equations in two dimensions. The differential equations are integrated numerically with a fixed time step of 0.001 s. The closed loop control system follows the optimal ascent trajectory previously calculated in a 3-DOF optimization. The external disturbances as e.g. wind have to be compensated. The principal control algorithm complies with the following law and its control system coefficients:

$$\sigma_{TVC} = K_{\vartheta}(\vartheta - \vartheta_{set}) + K_{\omega}\omega_y$$

The influence of aeroelasticity has been taken into account both on the GNC-sensors functioning and on the efficiency of the thrust deflection system. The sensors of the control system measure the local accelerations, angles and angular velocities at the nodes where they are located, i.e. for example i^{th} node for accelerometer and j^{th} node for gyroscopes:

$$\omega_{y\,j} = \omega_{y\,cog} + \frac{\partial(\dot{z}_j)}{\partial x} \quad \text{and} \quad \vartheta_j = \vartheta_{cog} + \frac{\partial z_j}{\partial x}$$

The control forces and moments (aerodynamic or from TVC - thrust vector control) act onto the local nodes where the actuators are attached. When calculating the control forces and moments, the influence of the nodes' displacements (as a result of structural deformation) is to be taken into consideration. The mathematical model also takes into account the nonlinearity of the actuator characteristic: the insensibility zone, the maximal angular velocity and the deflection limitations.

In a systematic approach, the WOTAN K3 launcher configurations had been analyzed on their sensitivity to atmospheric perturbations. The most critical instant during the ascent flight is identified at about 35 s after lift-off. The maximum obtained deflection of the WOTAN engines takes an extreme value for a wind gust at that time. Nevertheless, the maximum nozzle deflection during the ascent flight stays below 1.5° for the K3-GTO-Mission and below 2.5° for K3+ ISS-Mission (Figure 12). The critical flight time of 35 s is in coherence with expectations based on the evolution of the product of angle of attack times dynamic pressure $(q\ \alpha)_{max}$.

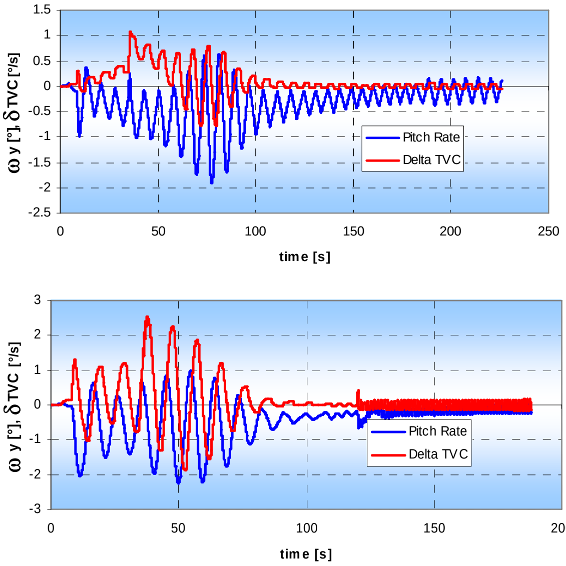

Figure 12: Angular pitch velocity ω_y as function of ascent flight time for WOTAN K3 configurations subject to wind and gust (top: K3-GTO, bottom: K3+ ISS)

The maximum amplitude of the angular pitch velocity is reached for K3 and K3+ close to the peaks of their dynamic pressures. Values between -2 and -2.2 deg/s can be detected (Figure 12). The pitching movement is the result of the changing wind profile and the requirement to follow the pitch angle of the optimized ascent trajectory.

The simulation of the control system in a critical gust and wind condition proofs its principal feasibility within typical actuator constraints. The amplification factors of the control algorithms should be adaptable due to the flight configuration.

2.6 Performance Synthesis

The performance calculations of the WOTAN K3 and F2 TSTO launchers are based on the final configurations as described in paragraphs 2.3 and 2.4. Note that the presented separated payload masses are theoretical maximum performances, not taking into account any additional upper-stage fuel for de-orbiting. The TSTOs are not constrained by their lower-stage impact points, if launched from Kourou.

The WOTAN data obtained at the end of phase 3 are no longer subject to a resizing process and therefore differ from the original payload requirements. The second iteration loop including a resizing of the stages and a structural optimization was quite successful insofar as the reference values are now well beyond the initial goal. Figure 13 shows that GTO payloads of K3 and F2 still come quite close, with a performance edge for F2+ due its more powerful upper stage.

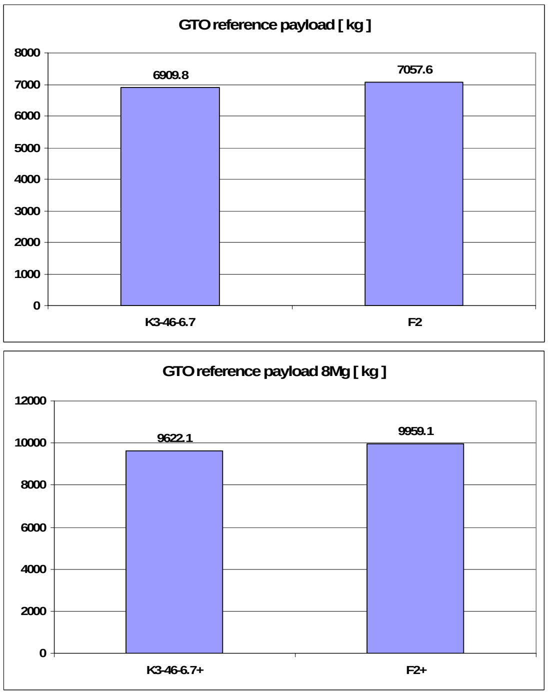

Figure 13: Separated payload mass of WOTAN launchers for GTO mission

Further, it is interesting to compare the required GLOW presented in Figure 14 which is approximately twice for F2 due to its lower average I_{sp}.

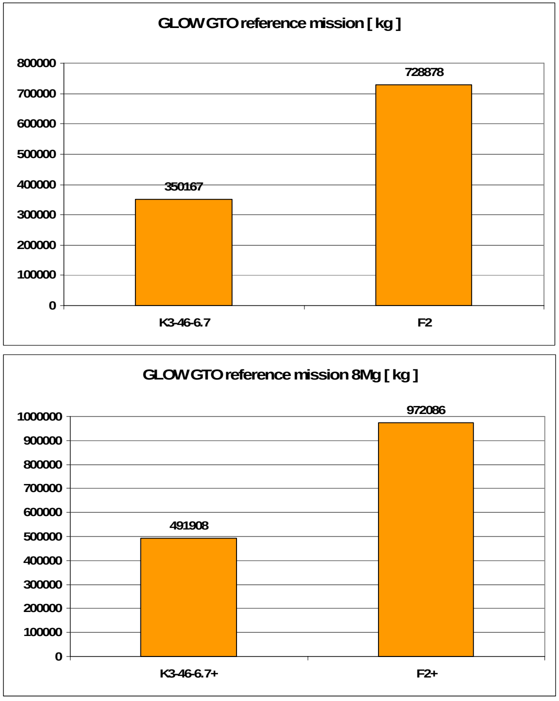

Figure 14: GLOW of WOTAN launchers for GTO missions (bottom with strap-on boosters)

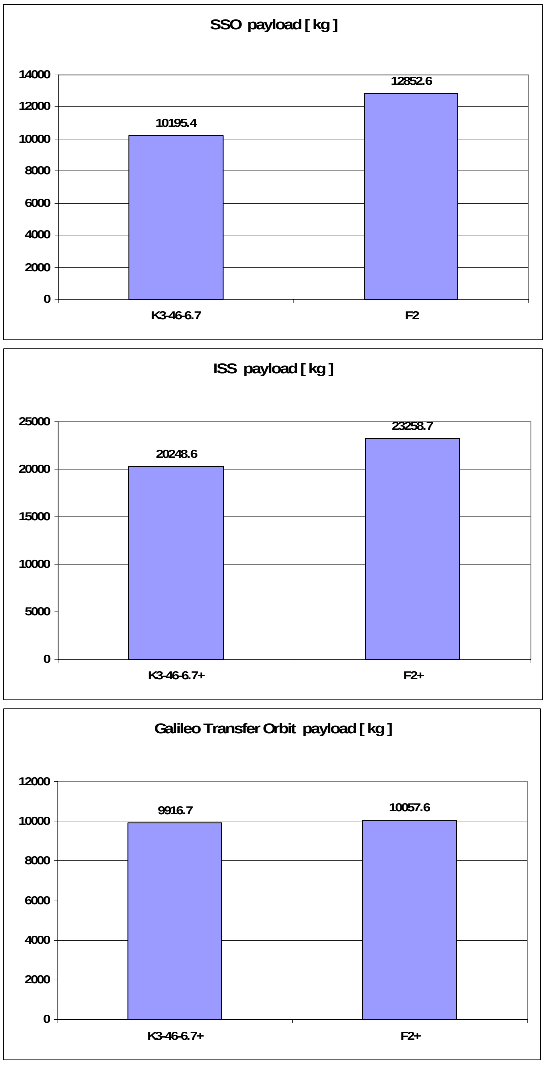

Figure 15: Separated payload mass of WOTAN launchers for secondary SSO, ISS and Galileo missions

Regarding the secondary missions, F2 shows notably better performance in a comparison of achieved payloads in the LEO-missions for ISS re-supply and to polar SSO then K3 (see Figure 15), while the high-energy Galileo orbit payload is almost the same. All investigated types are able to deliver heavy platforms into SSO without strap-on boosters. The resized K3 and F2 are both able to at least match the current Ariane 5 ES performance in case of the flight to the ISS.

3 VENUS: SMALL LAUNCHER EVOLUTION OPTIONS

Currently, a small launcher with an advanced solid propellant first stage, P80, is under development in Europe. This VEGA called vehicle should become operational within the next few years. VEGA consists of three solid rocket motors and a small liquid propulsion module for precise orbit injection called AVUM. Germany is not participating state in this launcher development project.

However, the need for a performance upgrade of VEGA in the next decade has already been identified. A simplification of the overall lay-out combined with a reduction in the total number of stages and the introduction of a larger liquid propellant upper stage could be an interesting configuration. Several options of different propellant combinations and engines are currently under assessment in the German VENUS study. This work is another joint DLR-SART EADS astrium effort.

3.1 Study Logic, Constraints, and Margin Policy

The VENUS study has been initiated in mid 2007 and is running in 3 phases until the end of this year. The approach is quite different to WOTAN because upper stages should be adapted for VEGA's already existing lower composite instead of starting a blank sheet of paper design. In the first step SART analyzed 6 different liquid engine options and found the optimum performance for each stage into the VEGA polar reference orbit. Based on these data, astrium established a preliminary upper stage architecture including mass balance for some of the most promising configurations. Recent results are presented in section 3.2.

Early in the VENUS study it became clear that a potential new liquid upper stage would probably not be mounted on the already qualified P80 and Z23 but on newly upgraded stages P100 and Z40 as proposed in the VEGA Evolution Program. The remaining work is therefore focused on two promising configurations from the previous VENUS investigations. However, the changes on the lower composites' performance required a new liquid stage propellant loading optimization. Available data for these analyses are described in the paragraph 3.3.

Further, development plans for the storable and cryogenic engines and stages as well as cost estimation will be performed.

Trajectory and performance analysis for all the upper stage configurations is made, targeting the VEGA reference mission, a final circular orbit with an altitude of 700 km and an inclination of 90°. After injection in a transfer orbit and succeeding ballistic phase an apogee circularization maneuver takes place.

In the trajectory analyses, an additional margin of 5 s on the specific impulse is taken into account for the cryogenic Vinci and 4 s for AESTUS 2.

3.2 Configurations with P80 (+ Z23)

The different upper stages investigated differ in propellant type and engine. Below all the versions initially investigated are listed. For each version the potential propellant loading to reach maximum payload capacity to the reference orbit is determined. Further the performance for typical LEO and GTO missions is calculated. The following short paragraphs for each configuration focus on new results; complementary data on e.g. the engines is found in [5].

3.2.1 VENUS version "A"

Version "A" intends replacing the current Vega Z9 solid 3rd stage and the AVUM 4th stage by a single new storable propellant stage equipped with Ariane 5's

AESTUS engine. The configuration is severely restricted by the low 27.8 kN thrust of the AESTUS. Payload capacity could be up to 1340 kg, considerably below that expected for VEGA. Thus, this configuration is not interesting as VEGA's future upgrade and is no longer considered for more detailed investigations.

3.2.2 VENUS version "B"

Version "B" intends replacing the current Vega Z9 solid 3rd stage and the AVUM 4th stage by a single new storable propellant stage equipped with a potential future AESTUS-2 engine (see section 3.3.1 and Table 4 below).

Upper stage propellant loading optimization results in an optimum fuel mass of around 8000 kg [5]. On this basis the stage architecture has been defined by EADS astrium. The nominal engine mixture ration is assumed at 1.9. A slightly increased mixture ratio would deliver better I_{sp} performance but 1.9 is still the AESTUS 2 baseline because the Pathfinder thrust chamber tests had been performed with a corresponding mixture ratio [12]. The theoretical optimum performance is expected for an engine mixture ratio of about 2.2. The calculated tank volume needed for the N_2O_4 tank is 4.4 m^3 and for the MMH tank 3.85 m^3. The design choice of the tank configuration is a common bulkhead with the N_2O_4 in the forward position. The thermal insulation should be foam insulation removable from the stage outer structure on ground.

The pressurization system could be re-used from the Ariane 5 EPS stage. The helium vessels might be off-the-shelf products with an MEOP of 349 bar storing a helium mass of 15 kg. The thrust vector control could also be re-used from the EPS stage, while the reaction control system should be re-used from AVUM.

The VENUS so called "B80" or L8 conceptual architecture is shown in Figure 16. The L8 is the only detailed stage architecture designed in VENUS for the P80 first stage. Mass estimation values including propellant residuals and hence performance data are thus expected to be the most reliable. Payload capacity is limited to 1610 kg; a slight improvement compared to VEGA. However, using the current VEGA lower composite does not seem to be very promising. Therefore the storable stage with AESTUS 2 engine will now be investigated as an upper stage on top of to be developed more powerful P100 and Z40 solid motors. (See paragraph 3.3!)

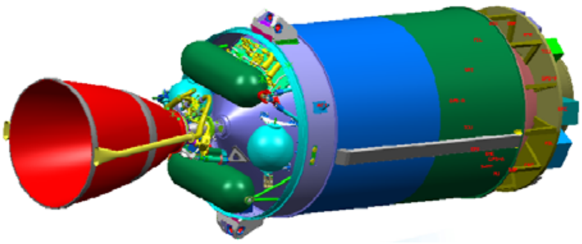

Figure 16: VENUS "B80" conceptual architecture of upper stage L8 by EADS astrium

3.2.3 VENUS version "C"

Version "C" intends replacing the current Vega Z9 solid 3rd stage and the AVUM 4th stage by a single new cryogenic (LOX/LH2) propellant stage equipped with the 180 kN Vinci engine (Table 2). Analyses show that the optimum loading is around 16000 kg fuel. Payload might reach an impressive 3560 kg [5]. However, the large upper stage propellant mass and low density of LH2 causes the size of the upper stage and therefore total launcher length to become very long. This could lead to problems regarding high bending moments. In addition the upper stage diameter is larger than the diameter of the Z23 2nd stage. This is unavoidable because of the large nozzle diameter of the Vinci engine. Potential problems of such a configuration could be aerodynamic buffeting, vehicle control and difficult stage integration [5].

Thus, VENUS C is reoriented towards an upper stage with shortened Vinci nozzle mounted on an increased diameter Z40 motor. (See paragraph 3.3!)

3.2.4 VENUS version "D"

Version "D" intends replacing the current Vega Z9 solid 3rd stage and the AVUM 4th stage by a single new cryogenic (LOX/LH2) propellant stage equipped with adapted expander-cycle cryogenic engines: 100 kN and 60 kN vacuum thrust [5]. The expansion ratios are limited to 200, to fit in any case within the diameter of the Z23 second stage.

The VENUS D 60 kN version has a payload maximum of 2760 kg, whereas the 100 kN version has a capacity of about 3200 kg [5]. In these two cases the launcher again becomes quite long and this could lead to problems regarding high bending moments or control issues. Another problem of VENUS D is that a complete new thrust chamber would have to be developed, making this option less attractive and investigations on the D version are not continued.

3.2.5 VENUS version "E"

Version "E" intends replacing the current Vega Z9 solid 3rd stage and the AVUM 4th stage by a single new LOX/CH4 (Methane) propellant stage equipped with an optimized expander-cycle cryogenic engine. The methane engine has been assumed with some similar parameters as the 100 kN LH2 engine [5].

The E version has a payload maximum of about 2440 kg; more than the storable AESTUS 2 variant. Compared to its quite similar 100 kN LOX/LH2 counterpart, performance is clearly much lower. Even the 60 kN LOX/LH2 powered upper stage achieves a higher payload. The length of the VENUS E launcher is only marginally shorter, and therefore does not offer a significant benefit [5]. Investigations on this type have been stopped.

3.2.6 VENUS version "F"

Version "F" intends replacing the current Vega Z23 solid 2nd stage, Vega Z9 solid 3rd stage, and the AVUM 4th stage by a single new cryogenic (LOX/LH2) propellant stage equipped with a 180 kN Vinci engine (Table 2). For the VENUS F TSTO version, the optimum upper stage fuel mass has been found around 16000 kg. The F version has a relatively low lift off mass of below 120 tons, requiring an adjustment of the P80 end burn profile in order not to exceed 6 g axial acceleration. Such a tailored profile should be in full compliance with the technology required for the

WOTAN solid first stages. Payload capacity could reach almost 2600 kg [5].

The VENUS F TSTO launcher shows very interesting performance. The small TSTO has the additional advantage of being very compact and having the shortest length of all versions [5]. More detailed investigations are intended in the future, also taking into account more powerful first stages like P100.

3.2.7 Performance overview

A comparison of the payload into VEGA's polar reference orbit for the different versions with P80 first stage motor can be seen in Figure 17. Note that for all VENUS configurations the amount of fuel needed for stage deorbiting is not included, which might reduce the actual payload mass.

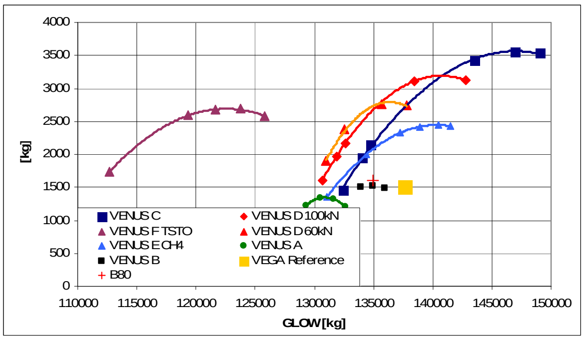

Figure 17: Payload to VEGA polar reference orbit vs. Gross Lift-Off weight for all VENUS configurations

DLR-SART has also calculated the "off-design"-performance of VENUS A through D for application orbits like SSO, ISS and GTO [9]. SSO comes very close to the reference orbit and payload to ISS is between 2000 kg and 4500 kg (VENUS C). The storable propellant upper stages A and B have a negligible GTO performance while the cryogenic versions might reach slightly more than 1000 kg.

3.3 New configurations with P100 + Z40

A future increase in the size of VEGA's first and second stages P80 and Z23 is already under discussion before its inaugural flight. The propellant loadings, as they have been calculated but not yet tested, could reach almost 100 tons (P100) for the first stage and almost 40 tons (Z40) for the second stage motor. The primary intention of this change is to assure a payload capability of at least 2000 kg in a polar orbit. The VENUS study has been reoriented checking the performance of the B and C versions with the new potential lower composite of P100 and Z40.

3.3.1 Upper stage engines

The AESTUS 2 engine is a proposed upgrade of the AESTUS engine with turbopumps and multiple ignition capability. The turbopumps allow for a higher chamber pressure and mass flow and therefore an increase in specific impulse and thrust. Some engine data are not yet fixed, providing some uncertainty for this engine in Table 4. A new European power pack and gas generator is still to be developed for the AESTUS 2.

The full size VINCI-engine is found geometrically too large for VENUS C. An interesting option could be the removal of one or two of VINCI's three nozzle segments A, B, C without changing the turbomachinery or the thrust chamber. Performance data of engine variants when only segment A or A+B are left can be found in Table 4. A new shorter B segment with intermediate performance could be another alternative.

Table 4: Characteristic performance data of small launcher upper stage engine options (calculated)

		AESTUS 2	VINCI A	VINCI A+B
vacuum thrust	kN	54.5	175	178.4
vacuum spec. impulse	s	339	452	460.8
ENGINE SIZE ESTIMATION				
total engine length	m	2.313	2.13	3.16
nozzle exit diameter	m	1.361	1.31	1.81
nozzle expansion ratio	-	280	90	175

3.3.2 Upper stages B100, C100

The optimum upper stage propellant loadings of the so called B100 and C100 stages have been found by SART in combination of mass estimation and trajectory simulation. A payload beyond 2000 kg is now achievable for the storable stage with AESTUS 2. However, the proposed thrust law of the Z40 motor has to be considerably adapted because currently the axial acceleration exceeds 6.8 g.

The definition of the upper stage architecture VENUS B100 and C100 is ongoing and will be finished until the end of October 2008.

4 RESEARCH COOPERATION ON ADVANCED CRYOGENIC UPPER-STAGE TECHNOLOGIES

In preparation of the development of new European advanced cryogenic upper stages the need to maturate related technologies has been identified. A German research cooperation involving the German launcher industry, University and DLR research has been initiated to work jointly on various identified key technologies. In focus are the propellant management technology, further extension of a special CFD-Code, the simulation of the propulsion system, advanced structure technology, and avionics. The partners involved are EADS astrium, MT-Aerospace, various DLR-institutes, and the ZARM at the University of Bremen. All research work is coordinated by DLR's new Institute of Space Systems in Bremen.

4.1 Propellant Management Technology

The propellant behavior in cryogenic upper stages demands for specific requirements on the tank system, especially for future upper stages designed for multiple restarts and intermediate long ballistic flight phases.

The main focus of this project is to qualify the well known **P**ropellant **M**anagement **D**evice (PMD) technology for cryogenic tank systems. During the whole mission the engine requires a bubble free and gaseous free supply of propellant. Until now PMD's are successfully used in surface tension tanks for storable liquids in satellites. A study performed by EADS astrium demonstrated that the usage of this technology could increase the performance of future re-ignitable upper stages by major mass and cost savings [10].

A further focal point is the investigation of the coupling of propellant sloshing and heat and mass transfer between the fluids liquid and gaseous states. Propellant sloshing could lead to liquid break up together with bubble and drop generation. In consequence the ullage pressure might change drastically. To understand the interactions of these phenomena, experimental and numerical investigations are intended at ZARM. A further aim is to develop a software tool to simulate the closed loop between the rigid body dynamic and the back-coupling of the sloshing behavior in the propellant tanks of the upper stage. The control tool should be able to compensate the back-coupling of the propellant sloshing and/or the load on the rigid body dynamic of the upper stage with respect to the mission profile and with special emphasis on the reaction control system of re-ignitable upper stages.

4.2 Further Extension of the DLR TAU-Code

The DLR TAU code is an existing code developed by DLR for high Mach numbers and compressible flow. The code has been successfully used by industry in the development of aircrafts, but also for the design of scram jets, calculation of the flow in rocket combustion chambers, for aero-elastic fluid-structure interaction and thermal coupling during the ascent flight of launcher systems [11]. The objective in the current study is the further extension of the TAU code for flow conditions within tank systems and feed lines of cryogenic re-ignitable upper stages. The long-term objective is to have a comprehensive design tool for all fluid mechanical problems of space transportation systems.

4.3 Simulation of the propulsion system

The time dependant simulation of the entire propulsion system with the consideration of all interacting components is of crucial importance for the upper stage optimization.

The aim is the extension of the DLR SART tool Propellant Management Program (PMP) for the needs of re-ignitable upper stages with long ballistic flight phases to calculate the integral dimensioning values and to allow supporting the preliminary upper stage engineering.

The objective is the simulation and prediction of the behavior of the propellants and pressurization gas in the complete feed system along the entire mission. Missing model parameters, with respect to engine re-ignition and optimization of the chill down process, are going to be determined experimentally.

4.4 Composite Fiber Technology

With the exception of the propellant tanks, all primary components of advanced upper stages consist of composite fiber structures. The structure has to withstand high temperature gradients together with high mechanical loads. Four topics are investigated in this project.

The first topic deals with the connection of cold metal components and composite light- weight construction. The problem is in connecting of hybrid structures consisting of different materials posing specific challenges for the designer. The aim is to optimize the connection technology to reduce weight.

The second topic, damage tolerant fiber structures, is driven by the challenge to develop numerical models to calculate the effects of delamination, debonding, and impact on damage growth and the residual strength.

Large carbon fiber connection rings are discussed in the third topic. The aim is to substitute heavy metal interface rings with carbon fiber connection rings to reduce weight. The intention is to investigate alternatives for metal interface rings between two primary structure components.

The fourth topic is the simulation of the production process for buckling analysis of curved composite fiber structures. The aim is to predict the stability behavior with consideration of imperfections, residual stress and forced stress due to mounting constraints.

4.5 Avionics Technology

The core avionics system consists of the on-board-computer, the operating system, as well as the bus system. The core avionics system is the platform for the control software and the infrastructure for the communication with sensors and actuators. This project includes two aspects.

The first aspect deals with the development of a flexible, fault-tolerant and high reliable core avionics system. The main issue is the design of a multi-cast capable, intelligent and flexible middle switch core element.

The second aspect is dedicated to sensor technology. Future cryogenic re-ignitable upper stages enable new mission scenarios. The resulting changes on the sensor system requirements will be identified and the need of new sensors will be specified. The aim is to proof and to verify the feasibility of using off-the-shelf-sensors ful-filling the identified need.

5 CONCLUSION

The paper describes some of the most recent activities in Germany in the technical assessment of future European launcher architecture and in the preparation of cryogenic advanced upper stage technology.

The first part gives an overview on the final results of a joint effort of DLR-SART with German launcher industry (EADS astrium and MT Aerospace) in the definition of a next generation upper-medium class expendable TSTO with an initial operational capability after 2020. This study called WOTAN has investigated fully cryogenic launchers as well as those with a combination of solid and cryogenic stages, fulfilling a requirement of 5000 kg single payload into GTO.

The study's later phases focused on staged combustion cycle propulsion as well as large solid motors in the first stages. Based on detailed analyses including stage pre-dimensioning, mass estimation, and iterative trajectory optimization to several orbital missions the conclusion can be drawn that a significant payload mass can be delivered to GTO by an expendable TSTO. However, mastering of advanced technologies for building very large and high performance solid motors or advanced cycle liquid engines will be essential to stay within acceptable size and hence cost targets for the launcher. The WOTAN design iterations confirmed again that a TSTO with potential strap-on boosters is probably more flexible but also much more sensitive to the availability of advanced technologies than a 2 ½ stage launcher like Ariane 5.

In its second part the paper describes options for new liquid fuel upper stages to be put on the lower composite of the future European small launcher VEGA or some of its proposed advanced derivatives. Versions with storable as well as cryogenic propellants are investigated in the VENUS study and most of them are sized for optimum performance to the VEGA polar reference orbit.

The technical, performance, and cost evaluations of the first round of upper stage investigations, all mounted on the P80 first stage, allow a preliminary down selection. The storable propellant version with existing AESTUS, the LOX/LH2 stage with a new, smaller expander cycle engine, and a variant with a new methane engine are no longer considered in VENUS due to poor performance, high cost or significant technology risk.

Another configuration with storable propellant using the potential AESTUS 2 engine with turbopumps is the only stage for which a preliminary but detailed architecture has been derived so far by EADS. However, this stage needs a more powerful lower composite of to be newly developed P100 and Z40 solid motors before achieving a considerable performance gain compared to VEGA. A new and larger first stage could also benefit cryogenic upper stage variants with VINCI engine, in both a three-stage and a TSTO configuration.

More detailed data on the remaining three upper stage options will be available within the next year allowing a better evaluation of their advantages and drawbacks as a potential VEGA upgrade.

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