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Advanced Launcher Technology Maturation Supported by EU-Aeronautic Research Projects

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The Aeronautics and Air Transport section of the EU's FP7 research program includes a topic "Pioneering the air transport of the future" which supports inter alia some high speed aviation concepts. Investigated technologies are similar to advanced space transportation technologies. Two of these currently running FP7 projects with a funding level of several million € each are described in this paper.

The FAST20XX (Future high-Altitude high-Speed Transport 20XX) project is running since the end of 2009 and is managed by ESA-ESTEC. The new project CHATT (Cryogenic Hypersonic Advanced Tank Technologies) is the second project example which is coordinated by DLR-SART.

The paper presents the technologies relevant for future launchers which are maturated within FAST20XX and CHATT. Major research results, as far as available, will be summarized.

Nomenclature

D	Drag	N
H	Total Enthalpy	J
I_{sp}	(mass) specific Impulse	s (N s / kg)
M	Mach-number	-
T	Thrust	N
P_{ND},P_{NL}	parameters defined by Eq.2	
PFA	Projected Frontal Area	m^2
PPA	Projected Planform Area	m^2
s	Streamwise Wetted Area	
WA	Wetted Area	m^2
v	velocity	m/s
α	angle of attack	-
γ	flight path angle	-
ν	Kinematic Viscosity	m^2/s

Subscripts, Abbreviations

CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
DSMC	Direct Simulation Monte Carlo
ELV	Expendable Launch Vehicle
fm	Free Molecular
i	Inviscid
GNC	Guidance, Navigation, Control
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
NGL	Next/New Generation Launcher
NPSP	Net Positive Suction Pressure
RLV	Reusable Launch Vehicle
TRL	Technology Readiness Level
W	wall
0	Reservoir Conditions
∞	Infinity

1 INTRODUCTION

The Seventh Framework Programme (FP7) for Research and Technological Development is the EU's main instrument for funding research in Europe and it runs from 2007-2013. While the Space Call is addressing in a large part applications such as GMES, the Aeronautics and Air Transport section also includes a topic "Pioneering the air transport of the future" which supports inter alia some high speed aviation concepts.

Hypersonic vehicles require technologies which are in a large part similar to advanced space transportation technologies. Two of these currently running FP7 projects with a funding level of several million € each are described in this paper.

The FAST20XX (Future high-Altitude high-Speed Transport 20XX) project is running since the end of 2009 and is managed by ESA-ESTEC. It aims at providing a sound technological foundation for the industrial introduction of advanced high-altitude high-speed transportation in the medium term and in the longer term. No detailed vehicle design is planned in the study but the mastering of technologies required for any later development. The identified critical technologies will be investigated in depth by developing and applying dedicated analytical, numerical and experimental tools.

The work package 3 of FAST20XX is looking at technologies for High-Energy Suborbital Transportation: Mission Definition and System Analysis of the SpaceLiner, advanced active cooling, Flow and Flight Control, Advanced Structures, Low-Density Effects in Suborbital Flight and Flight Dynamics and Safety.

The new project CHATT (Cryogenic Hypersonic Advanced Tank Technologies) is the second project example which is coordinated by DLR-SART. One of its core objectives is to investigate Carbon Fiber

Reinforced Plastic (CFRP) cryogenic pressure tanks containing propellants like liquid hydrogen, liquid methane and possibly liquid oxygen.

The proposed research in CHATT will increase the knowledge within Europe to a practical cryogenic tank demonstrator level for future aerospace reusable lightweight composite cryogenic structures. The advantages and disadvantages of using liner/linerless tank designs will be investigated as well as issues related to the realization of more complex geometrical tank shapes. Four different subscale CFRP-tanks are planned to be designed, manufactured, and tested under mechanical and thermal loads. Other technologies related to cryogenic propulsion are additionally addressed. A central, steering role is applied to system requirements of advanced passenger airplanes, the development, test and implementation of engineering methods and tools.

2 FAST20XX

The multinational collaborative research project FAST20XX aims at providing a sound technological foundation for the industrial introduction of advanced high-altitude high-speed transportation in the medium term and in the longer term [1]. Note that no detailed vehicle design is planned in the study but the mastering of technologies required for any later development. The identified critical technologies are investigated in depth by developing and applying dedicated analytical, numerical and experimental tools, while the legal or regulatory issues are discussed with government- or international authorities.

FAST20XX is an EC co-funded project coordinated by ESA-ESTEC (NL). Overall 17 partners across Europe are involved in the project ranging from small and medium size enterprises as AI (DE), Astos (DE), CENAERO (BE), CFSE (CH), DEIMOS (ES), ORBSPACE (A), industries as Astrium (DE), research institutes as CIRA (IT), DLR (DE), FOI (SE), ONERA (FR), SSC (SE) and VKI (BE) to the Universities in Berlin (TUB, DE), Brussels (ULB, BE) and Leiden (UL, NL). The duration is three years, starting from December 2009. The overall funding is 7.3 M€, whereas the EC contribution is 5.1 M€ [3].

2.1 Research activities

The project is broken down into three main technical activities (Workpackages WP2 to WP4), which interact as shown in Figure 11.

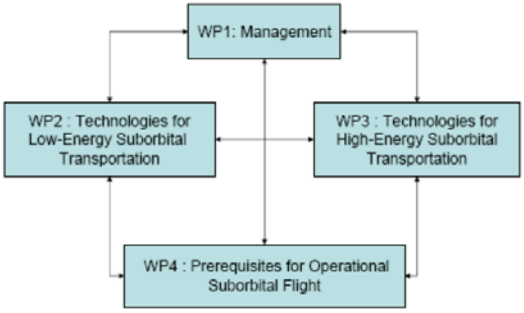

Figure 1: Mutual interaction of workpackages in FAST20XX study [1]

The technology development for low-energy suborbital transportation (with the so called concept ALPHA) directs towards an airplane-launched aircraft for short-range sub-orbital flights using a hybrid propulsion rocket motor. The work package 2 is split into five tasks dealing with: System Design, Aerodynamics, Control, Propulsion and Mechanical Design.

The high-energy concept SpaceLiner is intended to achieve a step change in ultra-fast long-haul passenger and freight transport. Although the basic performance data of the vertically launching and horizontally landing two-stage vehicle using liquid rocket propulsion are undisputable, the eventual commercial realization is facing quite a lot of technical and operational challenges. Some of these challenges characteristic for any high-energy transportation are addressed in the FAST20XX project. The technologies investigated in WP3 are very close to those of launchers and especially to RLV.

Work Package 3 is organized in five different top-level lines, each one addressing a different technology to be developed and/or assessed: Mission Definition and System Analysis of the SpaceLiner, active cooling and Flow Control, Advanced Structures, Low-Density Effects in Suborbital Flight and Flight Dynamics and Safety

Beside the identification of the technical building blocks for the low and high energy suborbital trajectory vehicles the WP4 looks at the pre-requisites that are needed for these types of vehicles. This includes ground and flight operation, safety, the infrastructure needed, medical aspects, legal aspects and certification. Further on, the environmental impact of suborbital flight is investigated.

2.2 Launcher Related Technology Research Results

2.2.1 System Aspects SpaceLiner

Different configurations in terms of propellant combinations, staging, aerodynamic shapes, and structural architectures have been analyzed. A subsequent configuration numbering has been established for all those types investigated in sufficient level of detail. The genealogy of the different SpaceLiner versions is shown in Figure 2. The box is marking the configuration trade-offs performed in FAST20XX.

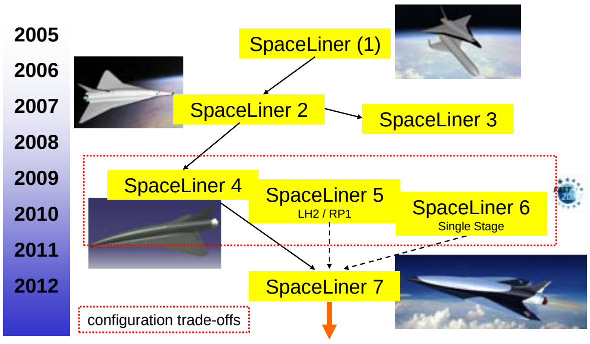

Figure 2: Evolution of the SpaceLiner concept with FAST20XX trade-offs highlighted

The system analyses work package in FAST20XX has been addressing the following subjects:

- Definition of the mission requirements for an ultrafast passenger transport
- Establishment of a preliminary aerodynamic database of the passenger stage
- Analysis of the flight profile and nominal flight trajectories for an ultrafast passenger transport
- Sensitivity of vehicle and trajectory
- Assessment of safeguard issues, crew safety aspects, including abort mission scenarios and associated requirements
- A system of load cases has been generated and a first set of resp. loads for nominal and off-nominal conditions documented
- Concept trade-off studies: Different vehicle concepts have been studied (e.g. different geometries have been investigated, to see the effect of geometry on aerodynamic heating, maximum obtainable range, weight, etc.) Also, apart from the LOX-Hydrogen rocket engines, LOX-Kerosene engines for application on the booster stage have been investigated. An overview description on the achieved results has been published in [11].
- Preliminary definition of SpaceLiner subsystems like:
    - Rescue subsystem
    - Passenger cabin subsystem
    - Propulsion and propellant supply subsystem
    - Active cooling subsystem and passive TPS
- CAD model establishment.
- Calculation of SpaceLiner masses and centre-of-gravity. After integration of the subsystems, the new COG of the vehicle is calculated and it is checked if the vehicle is trimable in nominal and off-nominal flight conditions.

2.2.2 Staged Combustion Cycle Propulsion System

Staged combustion cycle rocket engines with a moderate 16 MPa chamber pressure have been selected as the baseline propulsion system of the SpaceLiner. The engine performance data are not overly ambitious and have already been exceeded by existing engines like SSME or RD-0120. However, the ambitious goal of a passenger rocket is to considerably enhance reliability and reusability of the engines beyond the current state of the art.

Two types of staged combustion cycles (one full-flow and the other fuel-rich) have been considered for the SpaceLiner Main Engine (SLME) and have been traded by numerical cycle analyses in FAST20XX [12]. A Full-Flow Staged Combustion Cycle with a fuel-rich preburner gas turbine driving the LH2-pump and an oxidizer-rich preburner gas turbine driving the LOX-pump is a preferred design solution for the SpaceLiner. This approach should allow avoiding the complexity and cost of additional inert gases like Helium for sealing.

In a Full-Flow Staged Combustion Cycle (FFSC), two preburners whose mixture ratios are strongly different from each other generate turbine gas for the two turbo pumps. All of the fuel and oxidizer, except for the flow rates of the tank pressurisation, is fed to the fuel-rich preburner (FPB) and the oxidizer-rich preburner (OPB) after being pressurised by each turbo pump. After the turbine gas created in each preburner work on each turbine they are all injected in hot gaseous condition into the main combustion chamber (MCC) [12].

The mixture ratios of FPB and OPB are controlled to be 0.7 and 130 so that TET is restricted to around 770 K. at each turbine a bypass line is foreseen for which the flow should be controlled by a hot gas valve in order to allow engine operation in the mixture ratio range from 5.5 to 6.5 without changing TET or excessively raising pre-burner pressures. The limitation of the nominal characteristic conditions should enable an engine lifetime of up to 25 flights. Further, this approach gives some margin to significantly raise engine power in case of emergency by increasing TET beyond the limitation [12].

Reference 10 gives an overview about latest calculated SLME engine operation data for the nominal MR-range as obtained by cycle analyses and some early pre-sizing of the turbomachinery.

2.2.3 Analysis of Low-Density Effects in Suborbital Flight

In the present section the SpaceLiner aerodatabase at high altitude is presented. Referring to the reference re-entry trajectory [13] the altitude of 75 km, corresponding to Kn=0(10^{-4}), was valuated as the altitude for which rarefactions effects were important in prediction of aerodynamic efficiency [4]. The range of SpaceLiner altitudes in which rarefactions effects are expected is 75÷85 km; however the analysis will be conducted consequently in the range 60÷85 km. The vehicle in the higher part of the trajectory will not perform a ballistic re-entry but a guided flight, therefore a correct prediction of its aerodynamic performance is necessary [4].

The study of transitional/rarefied flow regime presents different theoretical and numerical difficulties. It is well known that the Navier-Stokes equations fail in rarefied flow regime, and a molecular approach such as the Direct Simulation Monte Carlo method (DSMC) is necessary. However, DSMC is a very CPU-consuming method and, therefore, engineering methods are usually employed for design issues. To this aim, bridging functions proposed by Potter [6] have been implemented and verified with the most suitable computational approach, i.e. DSMC, for some control points of the reference trajectory. Once the numerical methodologies have been validated also by means of dedicated experiments in DLR-V2G vacuum facility [5], the trajectory point for which rarefaction effects become not negligible have been evaluated by comparing the aerodynamic performance results provided by rarefied tools (i.e., DSMC and bridging functions, once verified) and continuum CFD code.

Hereinafter, a brief description of the Potter's bridging functions is reported. Potter [6] described the correlation of normalized aerodynamic coefficients with a simulation parameter which is designed to account for the principal flow phenomena that cause the aerodynamic coefficients to vary.

Potter used the high number of experimental results and flight data to build his formulae that "bridge" free molecular regime to the well-known inviscid hypersonic limit, i.e., zero Re (Kn tends to infinity). Potter [6] defined the normalized Drag and Lift coefficients as follows:

$$\overline{C_D} = \left(C_D - C_{Di}\right)/\left(C_{Dfm} - C_{Di}\right)$$
$$\overline{C_L} = \left(C_L - C_{Li}\right)/\left(C_{Lfm} - C_{Li}\right) \qquad (1)$$

The coefficients are correlated with simulation parameters:

$$P_{ND} = \left[\frac{V_\infty}{\nu_\infty} s\left(PFA/WA\right)^{1/2}\left(H_\infty/\left(0.2H_0 + 0.5H_w\right)\right)^{0.63}\right]^{1/2}$$
$$P_{NL} = P_{ND}\left(PPA/PFA\right)^{1/4} \qquad (2)$$

$P_{ND/NL}$ are coefficients depending from vehicle geometric data and free stream parameters (i.e., altitude and velocity), where C_{Li}, C_{Di} are, respectively, Lift and Drag coefficients in hypersonic inviscid conditions, C_{Lfm}, C_{Dfm} are, respectively, the Lift and Drag coefficients in free molecular conditions. Each bridging function is related to a constant value of angle of attack (α).

The higher SpaceLiner trajectory point (see Table 1) has been simulated by means of the DSMC code. The scope of the present simulation is to provide the aerodynamic data and aerothermal load for the higher altitude point.

Table 1: SpaceLiner Higher Altitude point data

Velocity (km/s)	**Altitude (km)**	**Mach Number (-)**	**Angle of Attack (°)**	**Kn_∞ (-)**
4.37	84.3	16.4	10	1.6e-4

Details about mesh generations and computational settings are reported in [7], while Figure 3 shows the flow speed contours in the SpaceLiner symmetry plane, in which the strong bow shock appears. The not negligible maximum surface heat flux at the nose region is equal to 1.23 MW/m^2, while the aerodynamic coefficients are: C_L = 0.117 and C_D = 0.04843, with the aerodynamic efficiency of about 2.4.

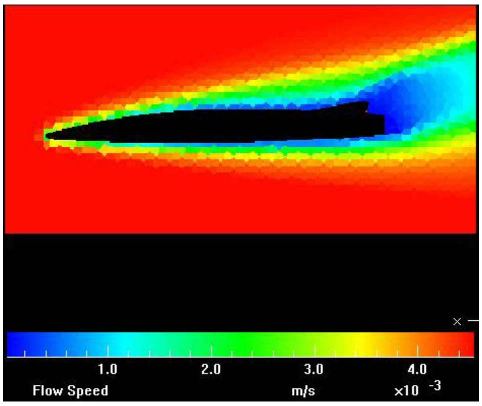

Figure 3: Flow speed contours – symmetry plane; altitude= 84.3 km

Bridging functions have been developed using inviscid data (C_{Li} and C_{Di}, see equation 1) of the DLR continuum aerodatabase [7]. The free molecular input (C_{Lfm} and C_{Dfm}, see equation 1) has been generated by simulating the free molecular condition with the DSMC code.

The validation of bridging functions has been performed at α =10° since this value is the reference one for the higher altitude point. In order to confirm the bridging functions an additional DSMC simulation has been performed at 110 km even though this altitude does not belong to the SpaceLiner reference trajectory. The used free stream velocity and angle of attack are the same of the 84.3 km case.

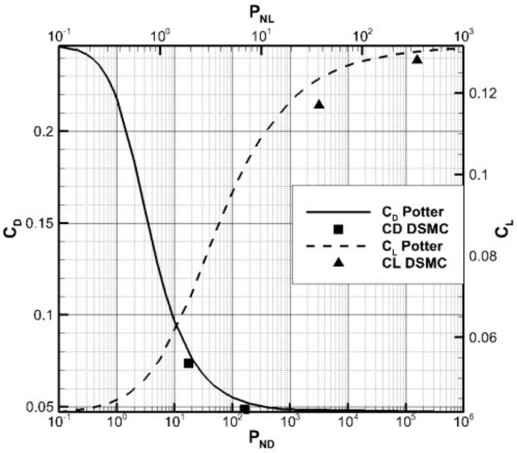

Figure 4: C_L and C_D vs. dimensionless Potter parameters

The Figure 4 shows the behavior of Lift and Drag as function of the dimensionless parameters proposed by Potters (P_{ND} and P_{NL} that can be read as the inverse of altitude). Good agreement with DSMC calculations and bridging functions can be recognized; therefore the reliability of the bridging formulas has been demonstrated. For high values of $P_{NL/D}$ (i.e., at low altitudes) high values of C_L and low values of C_D occur and, consequently, a high value of aerodynamic efficiency close, of course, to the continuum results. For high altitudes (i.e., low value of $P_{NL/ND}$) a decrease of aerodynamic performance occurs (low C_L, high C_D). Once the validation of the bridging functions has been performed the aerodatabase at high altitude (65÷85 km) has been setup for different angles of attack, and the main results are reported hereinafter.

In order to evaluate the effect of rarefaction on global aerodynamics, a comparison between the longitudinal aerodynamic coefficients computed by continuum methods and the bridging functions along the considered range of altitudes for α =10° has been performed. Figure 5 shows that the maximum variation of C_L, C_D and E (not reported in the figure) is, respectively, 7%, 23% and 18% and not negligible for the considered range of altitudes.

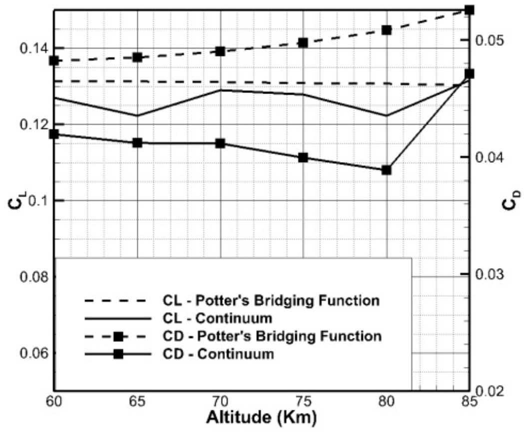

Figure 5: Effects of rarefaction on C_L and C_D

Figure 6 and Figure 7 depict, respectively, the behavior of lift and drag aerodynamic coefficients versus the angle of attack for three altitudes (65, 75 and 85 km). Lift coefficient shows a similar behavior and values for each altitude. Drag coefficient (Figure 7) exhibits a similar behavior for each curve but the effect of the altitude is evident. In particular, as expected, an increase of C_D with the altitude is predicted. Finally, the analysis of Figure 8 confirms the negative effect of altitude on aerodynamic efficiency. In particular, the effect is stronger at high values of the angle of attack, conditions corresponding to the flight conditions at high altitudes of the reference trajectory. The importance to take into account the effect of the rarefaction in prediction of SpaceLiner global aerodynamics in the transitional flow regime is then demonstrated.

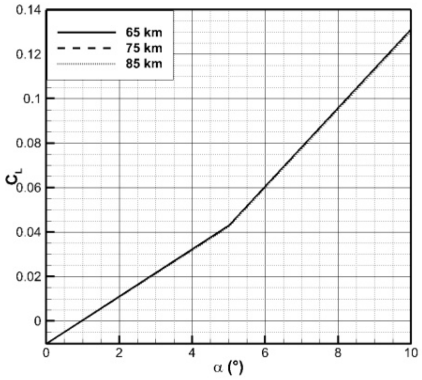

Figure 6: Lift Coefficient C_L vs α

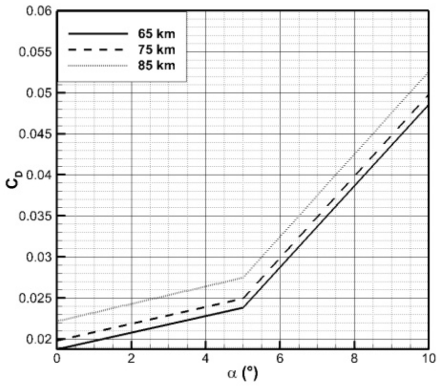

Figure 7: Drag Coefficient C_D vs α

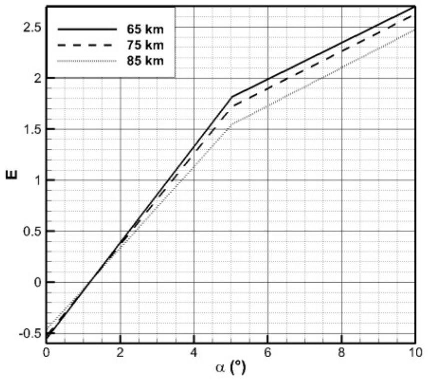

Figure 8: Aerodynamic Efficiency E vs α

2.2.4 Re-entry GNC

The GNC objective in FAST20XX is the evaluation of the flight mechanics of the suborbital flight for the SpaceLiner and the identification of its GNC requirements. The suborbital flight is characterized by the flight at high speeds and high altitudes during long times similar to RLV atmospheric reentry. At high altitudes, rarefied flow effects due to the low density have a considerable impact on the performance of the vehicle. The main requirements from a mission analysis point of view are stability limits, path constraints (heat flux, dynamic pressure, load factor…), and layout restrictions and desired performances [1].

The activity includes the verification of the aerodynamic dataset and the evaluation of the Flying Qualities, which includes the identification of the angle of attack corridor, the optimization of the nominal angle of attack profile and of the control surfaces deflection, both compatible with the constraints. The performances of the mission and the guidance capability of the vehicle are evaluated in case of uncertainties and dispersions in the environment, vehicle characteristics, sensors and actuators, navigation. It provides the sensitivity of the system to different levels of uncertainties and hence it can be used to validate or modify the preliminary specification of the subsystems, in particular the GNC [1].

The flight mechanics of the SpaceLiner concept has been analyzed by Deimos Space to provide requirements in terms of flying qualities, layout (centre of gravity location), angle of attack corridor and entry corridor during the flight. Trajectory control capability is assessed through guidance assessments. An adaptive guidance technique has been laid out to assess the trajectory control margins and expected guidance performance. Alternative flight trajectories have been proposed to ensure margins for trajectory control while preserving the main vehicle and mission constraints [14].

According to the Space Vehicles classification for flying qualities (FQ) proposed in Ref. 15, the SpaceLiner vehicle is of Class III, winged space plane, which generate aerodynamic lift through its body and wings and whose maneuverability exceeds that of lifting bodies (Class II) and capsules (Class I). The SpaceLiner flight covers a broad regime like RLV: hypersonic entry flight, descent and approach and landing into a runway. This process provides the range for the design of the nominal angle of attack (AoA) profile during the entry and identifies the available entry corridor for trajectory design [14].

A Monte-Carlo campaign of 1000 shots for the Flying Qualities has been run with these uncertainties and the 99% rage of variability of the main stability and control indicators has been evaluated. No trim problems are foreseen and deflections remain within a moderate range. The FQ analyses for the SpaceLiner4 concept show that a flyable corridor exists, but stability margins are reduced or even non-existing in some regions of the flight envelope. Therefore, more detailed CoG location analyses together with the system analyses are suggested to derive a vehicle configuration leading to a feasible flight mechanics concept as well as a revisit of the wing shape and its location [14].

For the SpaceLiner4 reference mission, a free-profile guidance technique is implemented in order to match the reference trajectory profiles coming from optimization. Moreover, in case of on-board replanning needs, a direct design of the flyable trajectory within the entry corridor using a fixed shape technique is preferred. The proposed algorithm is a drag-tracking scheme that considers both trajectory generation (on-board trajectory planning) and trajectory control (trajectory tracking). The commanded values are the bank angle and the angle of attack. This guidance algorithm has been selected because of easy adaptability to the vehicles, no restriction regarding to the reference trajectory shape, adaptive control, high order dynamics, energy based onboard trajectory re-planning, and an analytical form that ensures a low CPU loading of the on-board GNC computer. The trajectory in controlled mainly though bank modulation in order to keep the angle of attack under strict limits in the hypersonic phase, where thermal loads are relevant and any AoA excursion can lead to a collapse of the system.
An AoA modulation with more authority is suggested for the low supersonic flight during the heading alignment phase [14].

A Monte-Carlo campaign has been performed using detailed environment models (atmosphere, winds, gravitational harmonics…) and uncertainties into the initial state, the vehicle (aerodynamics and mass properties) and environment (atmosphere and winds). Figure 9 shows that the guidance scheme is able to keep the trajectories within the entry corridor and good tracking performances are achieved [14].

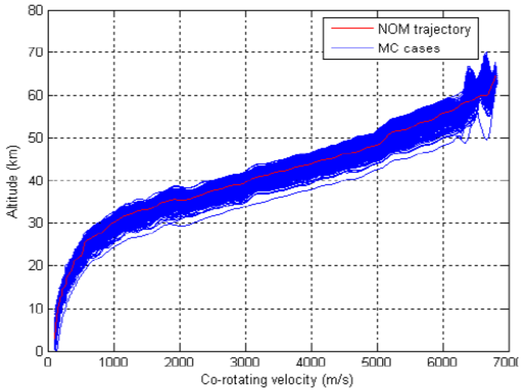

Figure 9: Monte-Carlo campaign: guided trajectories in the altitude – velocity plane [14]

Adequate margins both in terms of angle of attack and bank angle are required for a gliding vehicle in which entry corridor control and range control is performed through drag adjustments. The proposed reference trajectory does not provide enough margins to ensure right longitudinal and lateral targeting of the TAEM conditions in subsonics. An alternative feasible entry trajectory has been identified providing margins for the trajectory control function and leading to performances compliant with the requirements. The guidance assessments have shown the compatibility of the concept with guidance concepts typical for re-entry vehicles based on drag tracking and bank modulation [14].

3 CHATT

In future aviation and particularly in hypersonic systems new propellants will be used, such as liquid hydrogen, liquid methane and possibly liquid oxygen. Some studies in Europe investigate advanced vehicles with these fuels for passenger transport. The question of cryogenic propellant storage inside an airliner – although of critical importance but by far not yet mastered – has not been addressed up to now in comparable detail. Cryogenic propellants are operational since quite some time for launchers. Progress achieved under the harsh requirements of civil aviation, probably will also help in the maturation of launcher tanks.

The project CHATT is part of the European Commission’s Seventh Framework Programme and run on behalf of the Commission by DLR-SART in a multinational collaboration. One of the core objectives is to investigate Carbon Fiber Reinforced Plastic (CFRP) cryogenic pressure tanks also of high interest in future RLV launcher applications. Four different subscale CFRP-tanks are planned to be designed, manufactured, and tested.

The organizational breakdown of the CHATT project is very balanced according to the type of the partners and is as follows [8]:

- SME: 5 (ORB, ECM, CENAERO, GDL, ALE)
- Research institutes: 3 (DLR, FOI, SICOMP)
- Universities: 3 (ULB, ELTE, TUD)

The total budget is exceeding 4.2 M€ with an EU contribution of almost 3.3 M€ [2]. Large industrial companies are not involved in CHATT. All partners receive a 75 % funding by the EU-commission for their research activities. 25 % are funded by internal contribution of each partner. The financial breakdown per country is shown in Figure 10.

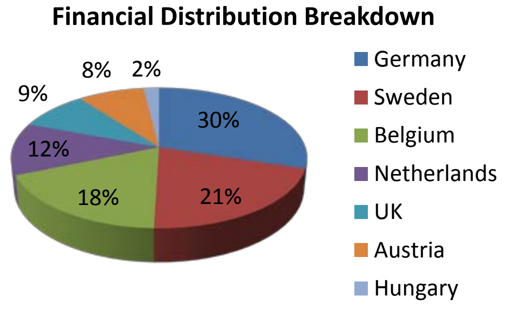

Figure 10: Financial Distribution Breakdown in CHATT per country [8]

3.1 Research activities

The proposed research in CHATT will increase the knowledge within Europe to a practical cryogenic tank demonstrator level for future aerospace reusable lightweight composite cryogenic structures. The advantages and disadvantages of using liner/linerless tank designs will be investigated as well as issues related to the realization of more complex geometrical tank shapes.

The project is broken down into three main technical activities (Workpackages WP2 to WP4), which have a close interaction as shown in Figure 11.

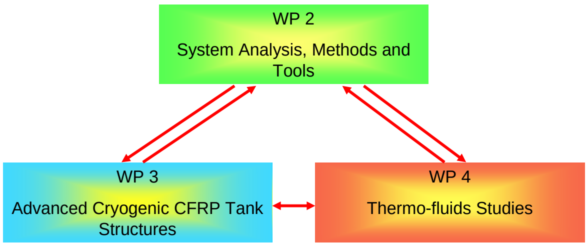

Figure 11: Interaction of different workpackages in CHATT study [2]

A central, steering role is applied to WP2 focusing on system requirements of advanced passenger airplanes, the development, test and implementation of engineering methods and tools. The two remaining workpackages WP3 and WP4 are dedicated to fundamental research with special focus on manufacturing and testing of fully integrated subscale hardware samples. Both WPs are serving as modules supporting the vehicle design and the verification of fast engineering methods.

Four different subscale CFRP-tanks are planned to be designed, manufactured, and tested under mechanical and thermal loads within the scope of the CHATT project. The challenge in developing a cryogenic CFRP tank is finding a solution for the problems caused by differences in thermal expansion coefficients (CTE) on a microscopic scale. If a liner is required, there is also the challenge to overcome the differences in CTE of the liner with respect to the structural shell.

All advanced cryogenic tank technologies to be investigated within CHATT are driven by system demands of future hypersonic passenger configurations. Such vehicles are under study in other EU-funded cooperative projects LAPCAT and FAST20XX: LAPCAT A2, LAPCAT M8, and the SpaceLiner. Thus, the vehicles have already reached a certain level of maturity in their respective propulsion demands and overall size. However, the cryogenic tank systems have not been studied in any detail and major challenges concerning tank weight, sloshing, and insulation have not yet been addressed.

Propellant management is imperative to achieve reliable and efficient vehicle operation. It is therefore the third pillar of the CHATT study and covers tank pressurization, fuel location/retention, and sloshing in horizontal tanks.

Apart from thermal aspects, sloshing of cryogenic fluids within the tanks can have a significant impact on flight operation as the liquid excited through vehicle movements may travel distances of considerable lengths compared to the overall size of the aircraft. The vehicle may consequently experience a noticeable shift in its center of gravity and hence its controllability is put into question.

Counter-measures such as anti-sloshing devices and tank design are susceptible to reduce these effects but will come at the cost of increased mass and production effort. As a consequence a trade-off between hardware design and flight control development in order to minimize the impact of propellant sloshing is an important step in the design phase of a hypersonic vehicle. The CHATT study will focus on establishing engineering models for sloshing verified by numerical calculations and experiments. These models will then be applied to flight control simulations of the reference vehicle concepts allowing an evaluation of their overall feasibility.

The propellant cross-feed between the two rocket-powered stages of the SpaceLiner enables a significant performance improvement. However, cross-feed between operational stages is highly innovative and has never been demonstrated in flight. A simulation of the steady and transient behavior in the propellant feed-system will be performed along the powered flight, performance and critical points will be evaluated, and recommendations will be derived.

Heat-exchangers are one of the most essential elements of a tank pressurization system. Two different types of ceramic heat-exchangers will therefore be looked at in CHATT. In addition to fuel tank pressurization, also oxygen tank pressurization will receive a strong focus, because it is required by systems which partially or fully rely on rocket propulsion like the SpaceLiner.

The air-conditioning system for the hypersonic vehicles investigated in CHATT will be based on a system in which bleed air from the intake exhaust is cooled using cryogenic fuel and then compressed to achieve the conditions required for the cabin air supply. Power for the compressor and other cabin sources is provided by a Rankine cycle on the cryogenic fuel. The ultimate objective is to develop a Rankine cycle cabin air-conditioning system, utilizing a cryogenic working fluid. The absorbed heat will be used to generate electrical and mechanical power. A detailed design will be developed and a small scale (15 kW) prototype turbine will be constructed and tested.

3.2 Early Launcher Related Technology Research Results

3.2.1 CFRP tanks

Fibre reinforced materials are structurally the most efficient material for pressure vessels because there is the possibility to direct the right amount of fibers according to the orientation and the magnitude of the principal stresses, which makes it an iso-tensoid structure. Carbon fibers are currently known to have the highest specific strength and stiffness which makes it the material of choice when it comes to aerospace structures. For advanced tank wall materials the high specific strength at cryogenic temperatures is one of the most essential parameters. Fracture toughness and stiffness are also important properties. Depending on the type of application, different designs may be favorable and tanks may thus be built as single-, double-wall or sandwich structures.

A linerless tank has the advantage over a tank with liner that mass, cost and production time can be reduced. This however means that both the load carrying task, as well as the task of holding the propellant inside the tank should be done by only the composite shell [8] The X-33 demonstrator tank consisted of a multilobed and linerless configuration with integrally bonded, woven composite joints. However, that tank failed in 1999 during ground testing due to polymer matrix micro-cracking and leakage into the sandwich core material causing delamination between the core and the inner composite skin. The tank showed leakage with subsequent damage, so-called “cryopumping”.

Northrop Grumman and NASA later completed within the NGLT project a nine-month test series to demonstrate a cylindrical composite cryogenic tank representative of a future launcher application. The problems that brought the X-33 to a halt were proven to be solved in 40 load cycles performed without failure. The integral tank, utilizing an impermeable barrier film between the inner tank wall and the honeycomb [8] was filled with LH2 and pressurized. The program highlighted the need to improve the permeation resistance with liner materials.

The advantage of a tank with liner is that the task of holding the propellant inside the tank and the task of carrying the loads are done by two different parts. The liner can be designed to prevent permeation and to be chemical compatible with the propellant without worrying about carrying the loads. The composite can be designed to only hold the load, without worrying about permeation. The disadvantages of the liner tank concept are the increased mass, cost and fabrication time. Moreover a mismatch between the CTEs of the liner and the composite can result in separation of the liner and interlaminar debonding in case inappropriate glue is used in an inappropriate way. For low temperature applications the increasing brittleness of the liner has to be considered to ensure gas-tightness. For typical carbon epoxy composites the vessel structure itself is not critical under cryogenic boundary conditions.

Four different subscale tank concepts will be designed, manufactured and tested within CHATT:

- Cylindrical tank with liner by DLR
- Dry wound cylindrical tank with liner by ALE
- Cylindrical tank without liner by FOI/SCICOMP
- Complex shape tank by TU Delft

At DLR-Braunschweig three different tank design variants have been analyzed in pre-production runs. One of those has two caps with a cylindrical part. Here, the tank is cut after winding in half and coated. Thereafter the tank is stuck together by a bandage (Figure 12).

The test tank of the first option was built with a body made of Polystyrene, a soluble material, with good results. The tank was then cut in the middle and afterwards glued together with a bandage (Figure 12). The flange connection will be worked out in detail, specifically the connection of the flange to the tank. Other next steps are the specification of the PE liner and checking the manufacturability.

Figure 12: Tank with bandage in test production run at DLR [8]

3.2.2 Propellant crossfeed

Crossfeeding is the propellant transfer from one tank to another tank or stage during flight. The fundamental challenge of all launch vehicles with reaction engines is their high mass and hence thrust requirement at lift-off and their relatively low mass and lower thrust requirement at burn out. Throttling of the engines is a technical solution, however, related to some drawbacks: Its realization is relatively complicated and, even worse, a large number of engines results in a high vehicle burn-out mass reducing the achievable Δ-v. Parallel staging reduces engine requirements but would result in partially empty tanks at staging. Crossfeeding of the propellant from the first to the second stage during mated flight allows for better performance of the whole vehicle and is therefore used for the SpaceLiner.

The potential crossfeeding architectures are line-to-line and tank-to-tank. Both options are investigated for the propellant cross-feed between the two SpaceLiner stages. The overall feed line architecture has been defined and is simulated in steady flow behavior. Figure 13 shows the tank and propellant feed system arrangement with the booster in the lower part and the passenger stage or orbiter in the upper section. The aft end of the configuration with the engine propellant distribution manifolds is at left.

The preliminary technical selection on the LOX-side is the tank to tank connection which allows feeding the orbiter engines always from the orbiter tank. This approach minimizes any disturbances at stage separation. Due to a significant height difference of the two LOX-tanks, gravity and acceleration will automatically push the liquid oxygen from the booster to the orbiter. On the LH2-side a line to line crossfeed is the likely selection. As can be seen from Figure 13 some height is available from the booster’s LH2 tank to the orbiter’s engines and a large cross section line is selected to minimize losses. Depending on the actual pressure losses, the engine NPSP requirement might be fulfilled. The need of check-valves or additional feedline pumps is still to be investigated. Future work will also include transient simulations of the crossfeeding process taking into account throttling, the engine shut-down, and the crossfeed valve closure prior to separation.

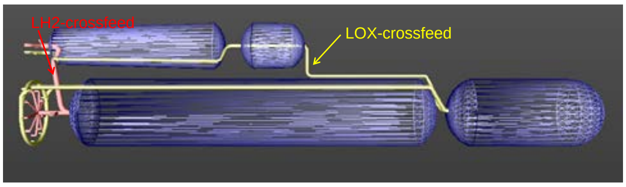

Figure 13: SpaceLiner 7 propellant feed system

3.2.3 Aerogels for insulation

An appropriate thermal insulation system is critical for LH2 storage tanks, particularly for long-duration applications. Thermal insulation of cryogenic tanks is more demanding for hypersonic aviation than in launcher applications because typical operation times are hours instead of minutes (compare [8]). An efficient and lightweight insulation system will minimize the boiloff of LH2 while adding minimum mass to the overall tank structure. This technology, however, is also very relevant for long duration storage required in transfer stage applications of deep space missions which are currently limited to so-called storable, non-cryogenic, however, less performing propellants.

The aerogel is an open-celled, nanoporous, solid foam that is composed of a continuous 3-D network and the pores of the network are filled up by air. The aerogel exhibits a high porosity of more than 50%. The nanostructure (nanopores and nanoparticles) provide the aerogel with outstanding properties. The 3-D solid backbone of the aerogels may be inorganic glass or ceramic, polymer (carbon), and hybrid materials. The aerogels contain particles and pores ranging from 2 to 50 nm in diameter.

One of the aims in CHATT is the assessment and comparison of the insulation materials, which are capable of insulating space objects. The other task is to investigate the temperature range of aerogel`s application. The samples are commercial aerogels (e.g. ”Cabot”, “Spaceloft”) and aerogels prepared at Budapest Technical University ELTE. The high temperature limit has been determined by thermo analysis and scanning electron microscope (SEM). The silica aerogels can be generally applied up to 600-650ºC, while the aluminosilicate aerogels up to 700-750ºC. For the determination of the low temperature limit, the samples are frozen by LN$_2$. After freezing, the structures are checked by small and wide angle X-ray scattering (SAXS and WAXS). The freezing at -130ºC did not affect any structural changes in the aerogel samples.

The Budapest Technical University ELTE synthesized various porous materials, which are capable to insulating aerospace objects. Earlier ELTE had already produced aluminosilicate aerogels (specific surface area of 800-1000 m^2 g^{-1}). Currently, alumina cryogels are prepared because of the cheap initial materials and drying method. Moreover, the alumina possesses excellent chemical and heat resistances. Aluminum oxide even as a compact monolith is a good thermal insulator and is applied usually in the industry. The alumina aerogel is well known and published in several papers. But its procedure is expensive owing to the high price of precursors, Al-alkoxide and the time- and cost-consuming drying method. A new cheap and uncomplicated sol-gel method for alumina gel synthesis is developed at ELTE using only two initial materials, an inorganic Al salt and an alcoholic solvent. The cryogels can be characterized by macro- as well as micro-pores (Figure 14). The size of the macro-pores is about 100-200 μm, the diameter of the micro-pores is approximately 20 nm.

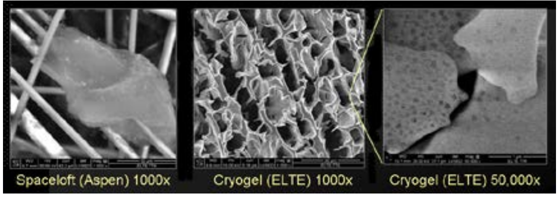

Figure 14: SEM images of aluminum oxide cryogel produced at ELTE and for comparison Spaceloft silica aerogel composite

4 CONCLUSION

This paper describes two European Union funded aviation research projects investigating technologies also interesting for future launcher applications.

The project FAST20XX aims at providing a sound technological foundation for the industrial introduction of advanced high-altitude high-speed transportation in the medium term and in the longer term. The identified critical technologies are investigated in depth by developing and applying dedicated analytical, numerical and experimental tools. FAST20XX is an EC co-funded project coordinated by ESA-ESTEC. The duration is three years, starting from December 2009 with overall funding of 7.3 M€.

Interesting launcher related research results of FAST20XX include system aspects of winged RLV, staged combustion cycle rocket engine pre-design, low-density effects on the aerodynamics of high altitude flight, and reentry flight GNC.

The project CHATT is part of the European Commission’s Seventh Framework Programme and run by DLR-SART in a multinational collaboration. The project started in January 2012 and is running for 42 months with a scheduled end in June 2015. The objectives of this effort with a total budget exceeding 4.2 M€ are to investigate different CFRP cryogenic pressure tanks, propellant crossfeed systems, advanced thermal insulation materials, and ceramic heat-exchangers. Four different subscale CFRP-tanks are planned to be designed, manufactured, and tested.

After approximately eight months some results from the research work are already available. The vehicle reference design loads and conditions have been defined for three reference vehicles representing three different concepts of hypersonic transportation vehicles. A literature review of CFRP tank design concepts and materials helped in the pre-selection of promising design options and materials for the demonstrator tanks. The aerogel is an open-celled, nanoporous, solid foam which could become an attractive insulation material for cryogenic tanks in the future. Supported by CHATT, a cost efficient production process is developed for alumina cryogels.

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Further information on FAST20XX can be found on http://www.esa.int/fast20xx.

Part of this work was performed within the '**C**ryogenic **H**ypersonic **A**dvanced **T**ank **T**echnologies' project investigating tank technologies for high-speed transport. CHATT, coordinated by DLR-SART, is supported by the EU within the 7th Framework Programme Theme 7 Transport, Contract no.: ACP1-GA-2011-285117. Further information on CHATT can be found on http://www.chatt.aero

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