System Analyses Driving Improved Aerothermodynamic Lay-out of the SpaceLiner Configuration

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The revolutionary ultrafast passenger transport SpaceLiner is under investigation at DLR since 2005. The two-stage, fully reusable vehicle is powered by rocket engines. The maximum achieved velocity, depending on the configuration or mission type, is beyond 6.5 km/s putting some challenging aerothermal requirements on the vehicle. At the lower end of the speed-range, the SpaceLiner should have the smallest possible flight velocity for landing with an acceptable angle of attack.

The focus of the paper is on all system aspects including the SpaceLiner's flight performance which have an impact on the aerodynamic configuration. A preliminary sizing of both stages's passive TPS is done. At the vehicle's leading edges heat fluxes and hence equilibrium temperatures temporarily reach excessive values requiring advanced active transpiration cooling. An experimental campaign is run at the DLR arc-heated facility to increase the TRL of this promising cooling technology.

An aerodynamic shape optimization taking into account trim drag aspects and latest status of the vehicle design and flight profile is described.

Nomenclature

D	Drag	N
I_{sp}	(mass) specific Impulse	s (N s / kg)
L	Lift	N
M	Mach-number	-
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	-

Subscripts, Abbreviations

AOA	Angle of Attack
CMC	Ceramic Matrix Composites
GLOW	Gross Lift-Off Mass
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MECO	Main Engine Cut Off
PEEK	Poly-ether-ether ketone
RLV	Reusable Launch Vehicle
SSME	Space Shuttle Main Engine
SSTO	Single Stage to Orbit
TPS	Thermal Protection System
TSTO	Two Stage to Orbit
cog	center of gravity
cop	center of pressure

1 INTRODUCTION

A strategic vision has been proposed by DLR in 2005 which ultimately has the potential to enable sustainable low-cost space transportation to orbit (references 1, 2, 3). Ultra long distance travel from one major business center of the world to another major agglomeration on earth is a huge and major market. The ultra fast transportation far in excess of supersonic and even potential hypersonic airplanes is definitely a fundamental new application for launch vehicles.

Such a new kind of 'space tourism' based on a two stage RLV has been proposed by DLR under the name **SpaceLiner** [1]. Ultra long-haul distances like Europe – Australia could be flown in 90 minutes. Another interesting intercontinental destination between Europe and North-West America could be reduced to flight times of about one hour [6].

Figure 1: The SpaceLiner vision of a rocket-propelled intercontinental passenger transport, shown here at stage separation in a video animation, could push spaceflight further than any other credible scenario

2 TECHNICAL EVOLUTION OF THE SPACELINER CONCEPT

Technical progress of the advanced SpaceLiner concept has been achieved in the frame of the EU funded FAST20XX study [5] as well as also by internal funding of DLR. 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 (see Figure 2). These investigations deliver important data for the next reference configuration SpaceLiner7 which is still in its definition process.

Several configuration trade-offs have been performed in order to support the definition of the next reference configuration already dubbed “SpaceLiner7”. The interim research configurations 3, 4, 5, and 6 are at sufficiently high quality because they have been iteratively sized with careful scaling of the reference mass break-down, preliminary aerodynamic sizing and always trajectory optimization. A documentation of all trade-off results can be found in [7, 9].

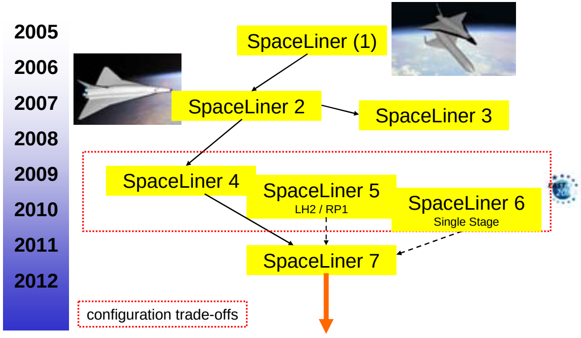

Figure 2: Evolution of the SpaceLiner concept

2.1 Basic Requirements for a Rocket-Propelled Intercontinental Passenger Stage

The very high-speed travel option of the SpaceLiner is most attractive on ultra-long haul distances between the main population and business centers of the world. A reduction in total travel time of up to 80 % seems to be achievable [4]. These centers can be identified at least in Australia, East Asia, Europe, and the Atlantic and Pacific coast of North America (compare ref. 4).

One of the most demanding missions in terms of $\Delta\text{–v}$ is the west-bound flight from south-east Australia to a central European destination which is selected as the reference design case.

The most important requirement for the overall design of the 'SpaceLiner' concept is an acceptable safety record. The specific number of fatalities in its operation should not exceed those of early jet-airliner travel. It has to be realized that such a requirement is a notable technical challenge in itself, far beyond the capability of today's manned spaceflight. The rocket engine powered ‘SpaceLiner’ is based on an advanced but technically conservative approach which does not rely on any exotic technologies. Thus, a two stage, fully reusable vehicle is designed as an “exceedingly reliable” system to overcome the safety deficits of current state-of-the-art launchers.

The rocket engines are intentionally not designed to their technical limits to improve their reliability. Intensive testing and qualification of the propulsion system is further essential. Nevertheless, an engine-out capability during all acceleration flight phases is to be integrated. Despite all effort, tight margins are intrinsic of all launch systems and significantly reduce the achievable safety and reliability. Thus, a passenger rescue system will be indispensable. This could be envisioned as a cabin in the form of a large capsule to be separated from the orbiter in case of an emergency and then safely returning to Earth (see section 3.1).

Although the reusable upper stage with the passenger payload does not reach stable orbital velocity during nominal missions of the reference design, its conditions are so similar to those of an orbiter that the vehicle is also dubbed as 'orbiter' in the following paragraphs.

3 DRIVERS OF THE AEROTHERMODYNAMIC LAY-OUT

3.1 Integration of a passenger rescue capsule

The tight margins intrinsic of all launch systems make a dedicated passenger rescue system indispensable for viable SpaceLiner operation. A straight forward and least exotic form is a cabin designed in the form of a large capsule to be separated from the orbiter in case of an emergency and then safely returning to Earth.

A perliminary design of a passenger rescue capsule (Figure 3) has been performed in a multi-disciplinary, iterative approach [7, 10] taking into account NASA manned system requirements.

A fundamental requirement for the design of the rescue capsule is its integration in the front section of the passenger stage. The capsule should be separated as easily and quickly as possible. Therefore, it is not an integral part of the fuselage structure, however, its upper aft section is conformal with the SpaceLiner’s fuselage while the lower side is fully protected by the fuselage bottom structure. The cabin might be attached late in the launch preparation process when the tanks are already filled.

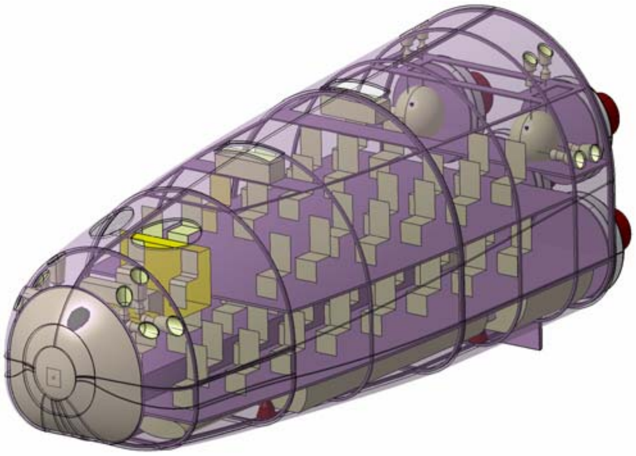

Figure 3: CAD model of rescue capsule variant 2 in isometric view (from front) [10]

The flight of the SpaceLiner has been divided in three phases for the pre-design of the rescue capsule and its subsystems. Different actions have to be performed to guarantee a safe separation, distancing and afterwards a safe landing of the rescue capsule.

During the early **ground** operation and early **lift-off** phase it is important in an emergency to rapidly gain distance but also to gain altitude. If a severe malfunction is noticed during the **ascent**, it is crucial for the capsule to leave the original flight path to avoid being hit by the remains of the SpaceLiner. After passing the highest point the unpowered **descent** phase begins.

A detailed analysis of the Separation Propulsion System and the Thermal Protection System has been made as they are regarded to be the most critical components.

The cabin rescue system of the SpaceLiner concept requires powerful solid separation motors with a very short burn time to enable the capsule reaching a safe distance for passenger evacuation while not being destroyed by the overpressure of a blast wave. The separation system will be placed between the passengers and the tanks of the SpaceLiner. A propellant mixture of HTPB, AP and Al is used and burnt at 150 bar chamber pressure.

The TPS of the capsule is subject to high heat flux and has no need for re-usability. Therefore, an ablative thermal protection is preferred in stagnation and bottom areas with low system complexity, thus guaranteeing high safety. The insulation material on the upper side of the capsule could be similar to the SpaceLiner's fuselage upper side because in some regions it is the same surface. The relatively low heat loads allow for a thin multi-layer insulation as already used for the Space Shuttle orbiter or a metallic TPS (compare section 3.2).

A comparison of round and flat bottom geometry and different sizes and positions of the body flap have been investigated [10] to find the optimum aerodynamic configuration with respect to trim and contollability requirements in hypersonics.

The length of the capsule reaches almost 15 m and its maximum diameter is close to 5.7 m. The total mass of the fully equipped capsule, including the passengers and payload after burn-out of the separation motors, is estimated to be slightly above 29 tons. [10] The overall size of the capsule is challengengly large with its landing mass about three times that of the largest capsules built to date.

An interesting option in the design of SpaceLiner7 could be splitting the passenger and crew cabin into two parts which might also improve the utilization of the long nose section. Several trade-offs are still nessecary to find the optimum configuration.

3.2 Preliminary structural concept of the passenger stage

For the SpaceLiner 7 configuration a relatively detailed structural concept definition has started by DLR with the FAST20XX support of FOI from Sweden and Orbspace from Austria.

A few baseline choices have already been fixed. An aeroshell-like structure for the passenger stage is most promising because of decoupling the maximum thermal gradients between cryogenic tanks and the outside surface. The internal protected structure could be metallic or CFRP. Materials with sufficient strength at elevated temperatures (e.g. 250°C, > 500 K) like Titanium or the polymer PEEK could be interesting for reducing the insulation thickness and hence the TPS mass. Design trade-offs are required to find an optimum technical solution.

For all configurations up to SpaceLiner 6 a double-delta wing has been used while the optimization process (compare section 4.2!) prefers a large single delta. A preliminary structural sizing of such an updated wing has been completed, taking into account the loads and dimensions of the main gear and flap actuator forces and moments. Figure 4 shows the von-Mises stress distribution in the wing for a subsonic load case. In [13] it is concluded that in a future improved structural optimization, a frequency constraint that is based on stability considerations should preferably be added in order to avoid significant weight penalties.

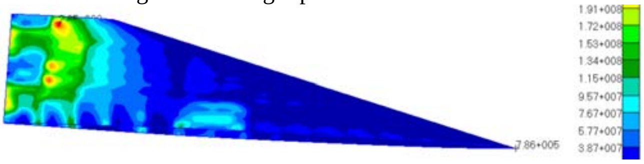

Figure 4: Von-Mises stress distribution in NASTRAN FE-model of wing under flap deflection loads

The wing structures model has been assembled by FOI with models of the fuselage and the fin into a preliminary conceptual global model of the orbiter in order to add a more realistic global boundary condition. The fuselage frame spacing was chosen identical with the distance between the wing-beams (typically 3.1 m) for this first design iteration [13]. The wing is low mounted on the fuselage and the stiffness of the beams being part of the frames in the lower fuselage becomes critical for the rigidity of the wing attachments. The height of the wing-carry through beams is constrained in the center and rear part of the fuselage because liquid fuel-tanks are located this part of the fuselage. It is concluded from the first analyses that bulkheads or truss-structures are to be introduced for preserving the fuselage's cross-section shape and sufficiently raising Eigenfrequencies [13].

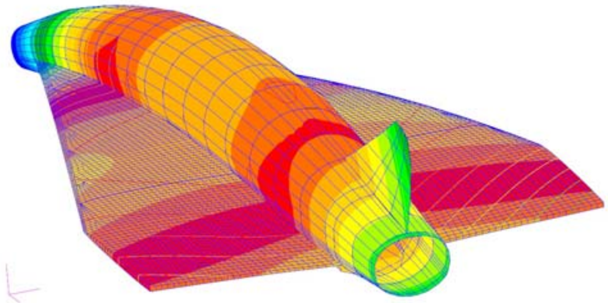

Figure 5: First bending mode of empty orbiter, f= 4.9 Hz

Results of the preliminary structural analyses are now under assessment considering vehicle control requirements, TPS thickness and attachment, and volumetric efficiency. All these aspects will influence the aerodynamic shape definition.

3.3 Preliminary TPS concept of the passenger stage considering an optimized trajectory

A preliminary sizing of the SpaceLiner's TPS has been performed using fast engineering methods which allow investigating the full vehicle surface of the SpaceLiner along different trajectories. A heat flux profile over time has been obtained for the complete vehicle surface.

The original SpaceLiner reference trajectory after MECO was skipping the vehicle on the atmosphere in order to maximize its range [2, 5, 6, 7]. By this approach, the maximum heat flux at the stagnation point is about 2 MW/m^2 but could reach 4 MW/m^2 on the leading edge. The outboard leading edge of the double-delta wing of earlier SpaceLiner configurations was found to be most critical and might be subject to additional shock-shock and shock-boundary layer interaction further raising the heat loads in this region. Although the heat peaks are relatively short transient phenomena of about 100 s, a first estimation reveals that actual wall temperatures on the leading edges and nose reach about 3000 K and 2600 K, respectively [2, 6].

A peak temperature of 3000 K is well beyond the capabilities of any available material. Thus, the need for advanced active cooling processes in a limited leading edge area of the vehicle has been identified early in the SpaceLiner investigations [2, 6]. Promising cooling technologies and their experimental verification are described in the next section 3.4. The passenger stage's TPS is subdivided into a smaller actively cooled part and a large passive, radiatively cooled section. The latest trajectory optimization using the ASTOS tool found a new non-skipping flight with only marginal increase in propellant consumption compared to the original skipping approach which allowed for an estimated stagnation point heat flux reduction of 50 % [5]. The corresponding TPS mass saving clearly outweighs the additional propellant. Therefore, a hypersonic gliding flight without skips is chosen as the new SpaceLiner reference trajectory [5]. Nevertheless, the implementation of both an active and a passive TPS is maintained because thermal loads are still beyond those of the Space Shuttle orbiter at reentry.

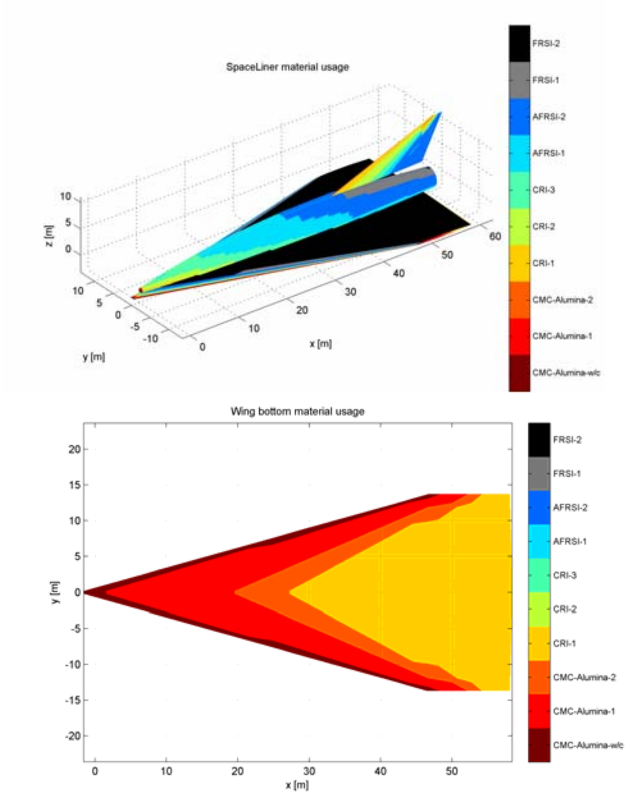

Figure 6: SpaceLiner7 TPS materials distribution, top side (top) and bottom side (bottom)

Figure 6 shows the TPS materials used and their distribution on the surface of a preliminary SpaceLiner 7 geometry assuming the latest non-skipping flight path. In the legend similar materials followed by different numbers indicate regions where the material thickness differs.

The maximum acceptable temperatures for the passive TPS should be limited to approximately 1850 K to be compliant with the reusability requirement. In the high temperature zones ceramic matrix composite (CMC) cover has been selected with insulation material ZIRCAR Alumina mat. For protection of the areas with intermediate temperatures a Conformable Reusable Insulation (CRI) has been selected, which has been used on the X-37 re-entry vehicle. CRI is made of a metal Inconel 617 fabric, a ceramic NEXTEL fabric and flexible ZIRCAR alumina insulation in between. CRI is waterproof and has a comparatively low surface roughness and should be applied to large areas on the leeward side together with Advanced Flexible Reusable Insulation (AFRSI) also used of the Space Shuttle. Felt Reusable Surface Insulation (FRSI) consists of a NOMEX blanket which is coated with a silicon elastomer for waterproofing. FRSI is very lightweight and can be used up to temperatures of 672 K on the wing's top surfaces exposed to lower temperatures. [13]

3.4 Advanced active cooling concepts

Some promising ceramic materials exist which sustain very high temperatures and which are also capable of active transpiration cooling due to their porosity. The principle of transpiration is a promising cooling approach making use of two phenomena: Firstly, the porous structure will be cooled by convection of the coolant flow. Secondly, a thermal blocking coolant layer is built on the outer, hot surface of the porous structure, which reduces heat transfer to the surface. In order to make the cooling system as light as possible, a coolant with high cooling capacity per kg has to be used. For the SpaceLiner it has been proposed early to use liquid water as a coolant, potentially much more effective than gas [2, 6].

Today's knowledge on transpiration cooling efficiency (especially in case of water coolant) and its impact on the hypersonic boundary layer are still limited. Therefore, DLR initiated a fundamental research test campaign on active nose cone cooling in high enthalpy flow. The arc heated facilities LBK at the DLR Cologne site, consisting of two test legs dubbed L2K and L3K have been used (Figure 7). The test facility L2K, with a maximum electrical power of 1.4 MW, is equipped with a Huels type arc heater and allows to achieve cold wall heat flux rates up to 2 MW/m^2 at stagnation pressures up to 150 hPa, with different conical nozzles Mach numbers between 4 and 8 at Reynolds numbers up to 10000/m are provided. [15].

Three different nose cone models were made out of a porous material called Procelit-170. This material consists of 91% Al_2O_3 and 9% SiO_2 [6, 8]. Although the Procelit-170 material is not actually suited for an application in a real size vehicle it is nevertheless attractive to be used in the research of transpiration cooling. The main reasons for this material selection were its high porosity and its ability to withstand temperatures of up to 2000 K.

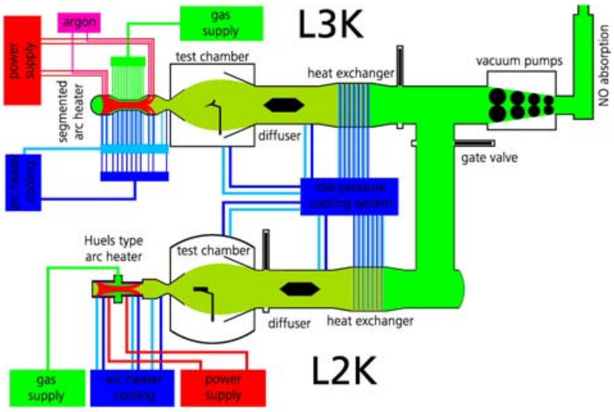

Figure 7: Schematic overview of DLR LBK (L2K and L3K) facility

Performed tests indicate that a water mass flow of approximately 0.2 g/s per nose cone has reduced the temperature in the stagnation point by about 1600 K. References [6, 8] demonstrate that the whole model is cooled to temperatures below 500 K. The infrared camera was not able to measure temperatures lower than this value, but it could reasonably be expected that the wall temperature being equal to the boiling temperature of the water (about 290 K at wind tunnel conditions). Transpiration cooling using liquid water has been proven to be much more efficient compared to gas cooling using the same models and conditions [6, 8].

While the principal feasibility of the active transpiration cooling approach has successfully been demonstrated in experiments, a lot more data are needed for the preliminary sizing of a practical SpaceLiner active leading edge cooling. Note that preliminary estimations of the required cooling water during a mission [6, 8] are still based on the measured nose cooling efficiency, while the same might be different for leading edges. Additional heat flux due to shock-shock and shock-boundary layer interaction is not yet considered. In FAST20XX a more extensive and systematic research, scanning different geometries and materials is run at DLR's arc heated LBK facility.

This time the L3K facility, with a segmented arc heater of 6 MW maximum electrical power is used, allowing to achieve total enthalpies up to 25 MJ/kg at reservoir pressures between 0.15 MPa and 1.8 MPa. The different combinations of nozzles provide Mach numbers between 5 and 10 at Reynolds numbers up to 100000/m. In the stagnation point configuration, cold wall heat flux rates of up to 4 MW/m^2 at pressures up to 350 hPa can be set on models with a diameter of 150 mm.

Ceramic matrix composites are very suitable for transpiration cooling [14]. They further exhibit excellent mechanical, thermomechanical and thermal properties. In contrast to metal foams, they do not fail if local hot spots occur.

The CMC probes to be used in FAST20XX are designed at DLR Stuttgart. Figure 8 shows the three different probes planned for testing: stagnation point, conical nose, and leading edge. Beyond the different geometries, a range of material with three basic types is investigated: C-fibre based: C/C and C/C-SiC and with Oxide fibre / matrix: AVA-Z-P50. A C/C pre-form already has high porosity and permeability, which results from shrinking cracks and small hollow spaces. However, temperature resistance of C/C is not very high in oxidizing atmospheres (approximately 450 °C). Therefore, these C/C pre-forms will be infiltrated with liquid silicon in the so called LSI-process. At the final state, C/C-SiC will be obtained, whereby C/C characterizes the carbon reinforced carbon-fibers and SiC the matrix. This material was intended to be used for the nose cap section of X-38, where surface temperatures of 1750 °C for a phase of 20 minutes during re-entry were expected.

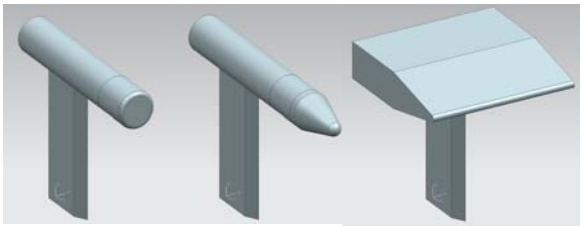

Figure 8: Different probe geometries foreseen in FAST20XX transpiration cooling experiments

The experimental logic has been established and tests with relatively simple "2-D"-axisymmetric stagnation probes (in Figure 8 at left) have already been started. Geometry effects and cooling distribution is investigated. Finally tests of the more complex 3-D leading edge (in Figure 8 at right) will be run.

The pressure losses of the coolant fluid have been estimated, the material's permeabilities are determined, and feasibility tests are completed. The main test campaign of the stagnation probe is running.

3.5 Aerodynamic Flap Selection Driven by Non-Nominal Flight Conditions

Safe controllability of the vehicle in all flight conditions has to be assured including during abort cases. The Mach number range stretches from the hypersonics through the transonic regime to the low speed subsonic landing approach.

To define the wing flaps of the SpaceLiner, knowledge on the most extreme flight maneuvers is needed. This is currently assumed to be an abort scenario starting at the time of booster separation with the passenger stage's propulsion system inoperative. A re-entry trajectory for this case has been simulated for the SpaceLiner4 with the constraint of maximal allowed loads. The results show that high angle of attacks need to be flown in the supersonic regime for a short time. Thus, for designing the size of the wing flaps such angles of attack need to be trimmable and maneuverable.

A non-nominal 2.5g maneuver in subsonics and the nominal final approach before landing are found to be the other two dimensioning cases for the flap design. Angle of attack under these conditions is much smaller (below 20 degrees) but the resulting pitching moment is significantly stronger, requiring larger deflections [5].

The SpaceLiner4's trailing edge flaps have been preliminarily defined as elevons with two flaps on each wing for redundancy in case of blockage. The wing flaps are both sized with a 2.5 m chord and should be able to be deflected 20 degrees up- and 30 degrees downward in subsonic flight [5].

Similar studies are currently run for the refined SpaceLiner 7 geometry and obtained results will have an impact on the selected aerodynamic configuration. (See [16] and section 4.2!) The flap of the vertical stabilizer might be split for the option of symmetrical deflection. This measure has an impact on the pitching moment and might reduce the requirement for the wing flaps in non-nominal high angle of attack conditions.

4 AERODYNAMIC SHAPE REFINEMENT

System studies show a high sensitivity of the orbiter's hypersonic L/D on the achievable range. Dependence is almost linear with a 0.25 improvement in L/D allowing for 1000 km additional range. Since losses by trimming and flight control using flaps are unavoidable, the optimization of the aerodynamic shape is of paramount importance [7].

The SpaceLiner should have natural longitudinal stability in the hypersonic flight regime because the aerodynamic forces at some points of the trajectory might be too low for efficient generation of artificial stability. The Mach number range stretches from the hypersonics through the transonic regime to the low speed subsonic landing approach.

The final outer aerodynamic shape of the SpaceLiner7 is planned to be frozen in 2011 taking into account the results presented in this paragraph, more detailed CFD of low-speed aerodynamics, as well as structural considerations and integration of a passive thermal protection (see previous paragraph 3.2). An extensive study on the different geometrical options for the optimization of the hypersonic aerodynamic and aerothermodynamic characteristics of the SpaceLiner has been recently concluded at DLR [11, 12].

4.1 CFD analyses validating optimization procedure

A numerical optimization of the SpaceLiner's hypersonic characteristics has been performed by calculations with the fast DLR-tool HOTSOSE using the modified Newtonian method. Although acknowledged as a good engineering tool, the program is not able to consider all aerodynamic effects like interferences or shock-shock-interactions. Therefore, a simplified SpaceLiner2 geometry has been analyzed with DLR's TAU code using unstructured grids at several hypersonic flight conditions. In general a good agreement can be noticed between the results of the CFD computations and the approximation methods of HOTSOSE. Especially the wave drag solutions are in excellent agreement [12].

Figure 9 shows that a strong bow shock is formed at the nose of the vehicle which propagates very closely along the fuselage. Due to the small angle of attack of approximately 6°, the shock front is very close to the bottom region of the vehicle whereas in the upper part the fin is embedded inside the bow shock. The nose bow shock (NBS) impinges on the inner part of the double delta wing at around Y=-4 m (see also Figure 10).

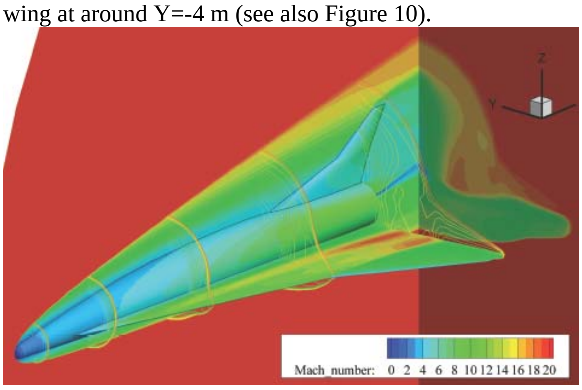

Figure 9: TAU (Euler) flow field of the SpaceLiner2 configuration at M= 19.8, 45.9 km [12]

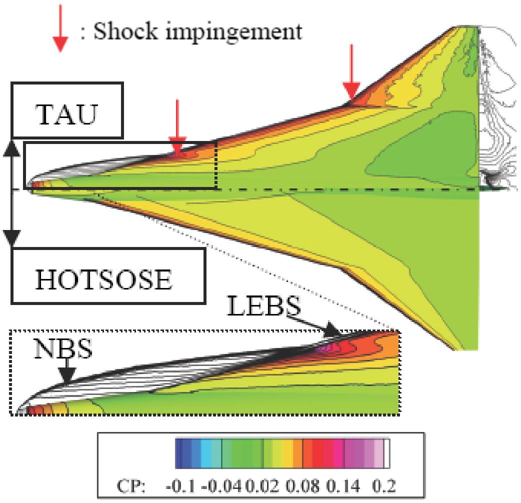

Figure 10: Comparison of cp for TAU (Euler) and HOTSOSE of the SpaceLiner2's lower surface at M= 19.8, 45.9 km [12]

Outside of the NBS, an inner wing leading edge bow shock (LEBS in Figure 10) very close to the leading edge is forming along the wing span. As a consequence of the shock impingement zones, locally high pressure regions exist on the lower wing surface, as can be seen in the pressure coefficient comparison between TAU and HOTSOSE (Figure 10). Besides these regions, an overall reasonably comparable pressure distribution can be noted [12].

4.2 Optimization of L/D considering trimmability in non-nominal case

Studies concerning aerodynamic shape optimization of the SpaceLiner delivered some promising single-delta wing geometry options with increased hypersonic L/D and decreased thermal loads for the orbiter compared to the double-delta winged SpaceLiner2 and 4 [7, 11, 12]. However, aerodynamic trimming under all flight conditions and the impact of the actual thickness of the TPS (not available at that time) on the outboard chord dimensions had not been included in the earlier shape optimization process.

The configurations found in [11, 12] for the SpaceLiner 7 have been slightly adapted and then used as a baseline for further numerical optimizations of L/D. These optimizations take into account some additional constraints:

- Minimum trim drag in the nominal trajectory
- Trimmability in case of flight abort scenario (with α up to 35°)
- Minimum tip chord thickness due to available TPS data (see section 3.2)

To satisfy the need for an efficient TPS including active cooling, the nose radius is limited in the optimizations to a minimum of $R_n = 0.2$ m, the relative thickness of the wing tip NACA66 profile is increased from 3.5% to 5.5% and the wing tip chord length is set to a fixed value of 11.54 m.

The main geometrical design parameters in the new optimization process are the following:

- Nose Radius: R_n [m]
- Offset of the nose in z-direction: $z_{Off,n}$ [m]
- Wing position in x-direction: x_{wing} [m]
- Chord length of the wingflaps: $c_{l,flap}$ [m]
- Flap deflection angle: δ_{flap} [°]

The wing shape itself will again be part of future optimizations.

The numerical optimization process is performed by an iterative loop containing grid generation, CFD calculation by means of approximate engineering methods (e.g. modified Newtonian Method) and optimization by a single objective response surface methodology. Different Mach numbers, altitudes and boundary layer conditions are analyzed taking into account high temperature effects, to ensure optimal performance along the nominal trajectory and feasibility of flight control in case of flight abort scenarios.

The optimizations show that the maximum achievable glide ratio increases with $c_{l,flap}$. Because of structural restrictions $c_{l,flap}$ has been limited to a maximum value of 5.0 m. Furthermore R_n and $z_{Off,n}$ shape up as the main driving parameters for the glide ratio while x_{wing} has a stake in trimmability. Figure 11 shows a newly optimized shape compared to the baseline configuration.

Modification of R_n, $z_{Off,n}$ and x_{wing} in conjunction with the need for an applicable adaptation of wing and fuselage as well as the demand for a minimum amount of space for subsystems lead to an increased nose length ($\Delta l = +3.0$ m). Figure 12 shows the improvement in L/D and C_M of the optimized shape.

The improvement of L/D is Mach dependent while the improvement of C_M is nearly constant. At flight abort ($\alpha = 35°$) aerodynamic trimming is still possible for the optimized configuration with less than the maximum allowed δ_{flap}.

Comparing the latest aerodynamics of Figure 12 with previous data [9] demonstrates somehow reduced performance despite the new optimization. This result is due to the latest flight trajectory, a thicker wing tip, and a more detailed and hence more realistic mesh. The optimized SpaceLiner 7 geometry, nevertheless, comes up to the specified requirements of minimum trim drag with full controllability in nominal conditions with still impressive hypersonic L/D performance. The configuration is planned to be part of further optimization investigations in the future.

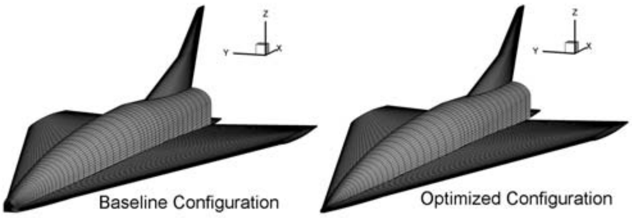

Figure 11: Baseline and optimized configuration of SpaceLiner 7

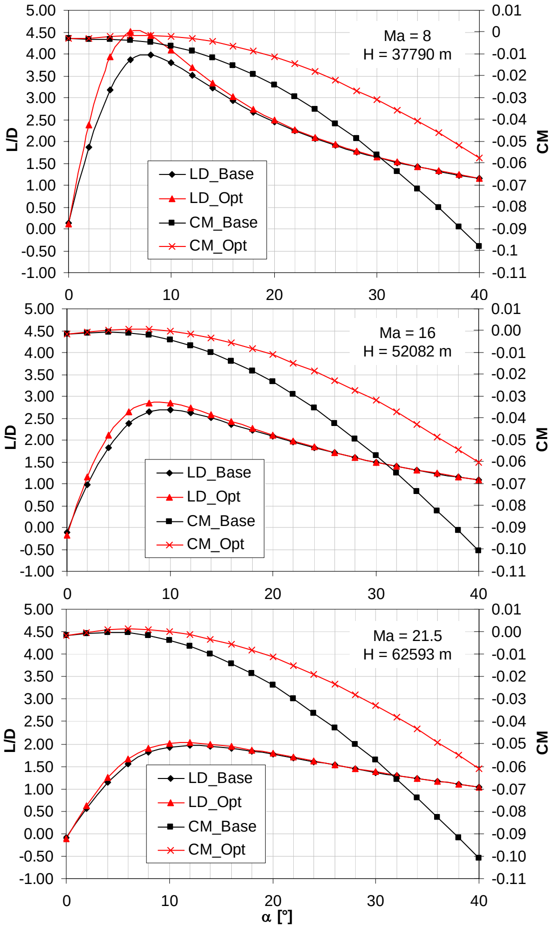

Figure 12: L/D (fully turbulent) and C_M as a function of AoA for baseline and optimized configuration

5 CONCLUSION

A conceptual reusable winged rocket for very high-speed intercontinental passenger transport is proposed by DLR. Research on the vehicle is performed with support from the EU project FAST20XX. Assuming advanced but not exotic technologies, a vertically launched rocket powered two stage space vehicle is able to transport about 50 passengers over distances of up to 17000 km in about 1.5 hours.

The next iteration step of the SpaceLiner concept will be version 7 which will be based on more detailed design of different subsystems and vehicle structures than previous configurations. An integrated interdisciplinary design process of the passenger stage will be necessary based on the ongoing configuration trade-offs. The paper presents the driving factors in the design of major technical aspects.

The aerodynamic shape of the SpaceLiner orbiter is now in an iteration process taking into account requirements of the hypersonic and subsonic flight regimes. Further, flight dynamics and controllability are considered. The structural concept of the passenger stage is defined as an aeroshell concept for which a pre-design is available. A passenger rescue capsule has to be integrated into the fuselage which should allow for a safe landing of the people on board even in case of a launch site explosion of booster and orbiter stage. A passive thermal protection system of the passenger stage has been preliminarily sized delivering mass and dimensions required for further realistic aerodynamic shape optimizations.

The temperatures at leading edge areas during the most severe flight conditions may rise to 3000 K and therefore are to be actively cooled. Transpiration cooling could be an attractive countermeasure and in FAST20XX an experimental research campaign with relevant conditions for the stagnation point and leading edges has started.

6 ACKNOWLEDGEMENTS

Part of this work was performed within the ‘Future High-Altitude High-Speed Transport 20XX’ project investigating high-speed transport. FAST20XX, co-ordinated by ESA-ESTEC, is supported by the EU within the 7th Framework Programme Theme7 Transport, Contract no.: ACP8-GA-2009-233816.
Further information on FAST20XX can be found on http://www.esa.int/fast20xx.

The authors gratefully acknowledge the contributions of Ms. Carola Bauer, Ms. Carina Ludwig, Mr. Josef Klevanski, Mr. Paul-Benjamin Eißmann, Mr. Paul Nizenkov, Mr. Francesco Cremaschi, Mr. Daniel Keller, Mr. Burkard Esser, Mr. Thomas Reimer, and Mr. Bryan Tong Minh to the preliminary design of the SpaceLiner and related investigations.

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