HiSST: International Conference on High-Speed Vehicle Science Technology

26–29 November 2018, Moscow, Russia

Technical Progress of Multiple-Mission Reusable Launch Vehicle SpaceLiner

Martin Sippel, Sven Stappert, Leonid Bussler, Sholto Forbes-Spyratos
Space Launcher Systems Analysis (SART), DLR, 28359 Bremen, Germany

Abstract

The SpaceLiner ultra-high-speed rocket-propelled passenger transport is in Phase A conceptual design after successful completion of the MRR. The ongoing concept evolution is addressing system aspects of the next configuration release 8. The space transportation role of the SpaceLiner concept as a TSTO-launcher is further refined and suitable precursor steps are investigated.

The critical separation of the passenger cabin and rescue capsule and its subsystems are one topic of the paper. The separation process is critically investigated taking into account multi-body dynamics and advanced CFD-simulations.

Potential intercontinental flight routes, considering range-safety and sonic boom constraints as well as good reachability from major business centers, are evaluated Extensions to this trajectory model are implemented to investigate the attitude dynamics and related controllability issues of the asymmetric launcher configuration.

Keywords: *SpaceLiner, RLV, SLME, multi body simulation, trajectory simulation*

Nomenclature / Acronyms

CAD	computer aided design
CFD	Computational Fluid Dynamics
GLOW	Gross Lift-Off Mass
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MRR	Mission Requirements Review
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
SLC	SpaceLiner Cabin
SLME	SpaceLiner Main Engine
SSME	Space Shuttle Main Engine
TAEM	Terminal Area Energy Management
TPS	Thermal Protection System
TSTO	Two-Stage-To-Orbit
TVC	Thrust Vector Control

1. Introduction

The key premise behind the original concept inception is that the SpaceLiner ultimately has the potential to enable sustainable low-cost space transportation to orbit while at the same time revolutionizing ultra-long distance travel between different points on Earth. The number of launches per year should be strongly raised and hence manufacturing and operating cost of launcher hardware should dramatically shrink.

DLR's SpaceLiner concept is similar in certain aspects to the idea of multiple-mission reusable launch vehicles. These concepts are understood to serve quite diverse missions by the same or at least a similar vehicle. Another typical example in this category is the SpaceX BFR [1, 2]. While in its primary role conceived as an ultrafast intercontinental passenger transport, in its second role the SpaceLiner is intended as an RLV capable of delivering heavy payloads into orbit. Simulations proof that the SpaceLiner orbital version stays within the load constraints of the PAX-version which confirms feasibility of the multiple mission intention.

First proposed in 2005 [3], the SpaceLiner is under constant development and descriptions of some major updates have been published since then [4, 7, 13, 14]. The European Union's 7th Research Framework Programme has supported several important aspects of multidisciplinary and multinational cooperation in the projects FAST20XX, CHATT, HIKARI, and HYPMOCES. In the EU's Horizon 2020 program a new project FALCon will be funded which addresses an advanced return mode of the reusable booster stage [18].

An important milestone has been reached in 2016 with the successful completion of the Mission Requirements Review (MRR) which allows the concept to mature from research to structured development [13]. The Mission Requirements Document (MRD) is the baseline and starting point for all technical and programmatic follow-on activities of the SpaceLiner Program.

Figure 1: Rendering of SpaceLiner 7-3 upper stage in final landing approach

2. SpaceLiner 7 Architecture and Geometry

The current arrangement of the two SpaceLiner stages, the reusable booster and the orbiter or passenger stage, at lift-off is presented in Figure 2. All LOX-feedlines and the LH2-crossfeed connection are attached on the booster's top outer side, thus, subjected to flow in the relatively cold wake region. The feedlines of the upper stage are completely internal and ducted underneath the TPS. An adapted feedline and crossfeed system is needed for the LOX-tank of the TSTO orbiter stage bypassing the satellite cargo-bay (Figure 2, top).

The main dimensions of the 7-3 booster configuration are listed in Table 1 while major geometry data of the SpaceLiner 7-3 passenger or orbiter stage are summarized in Table 2.

Table 1: Geometrical data of SpaceLiner 7-3 booster stage

length [m]	span [m]	height [m]	fuselage diameter [m]	wing leading edge angles [deg]	wing pitch angle [deg]	wing dihedral angle [deg]
82.3	36.0	8.7	8.6	82/61/43	3.5	0

Table 2: Geometrical data of SpaceLiner 7-3 passenger / orbiter stage

length [m]	span [m]	height [m]	fuselage diameter [m]	wing leading edge angle [deg]	wing pitch angle [deg]	wing dihedral angle [deg]
65.6	33.0	12.1	6.4	70	0.4	2.65

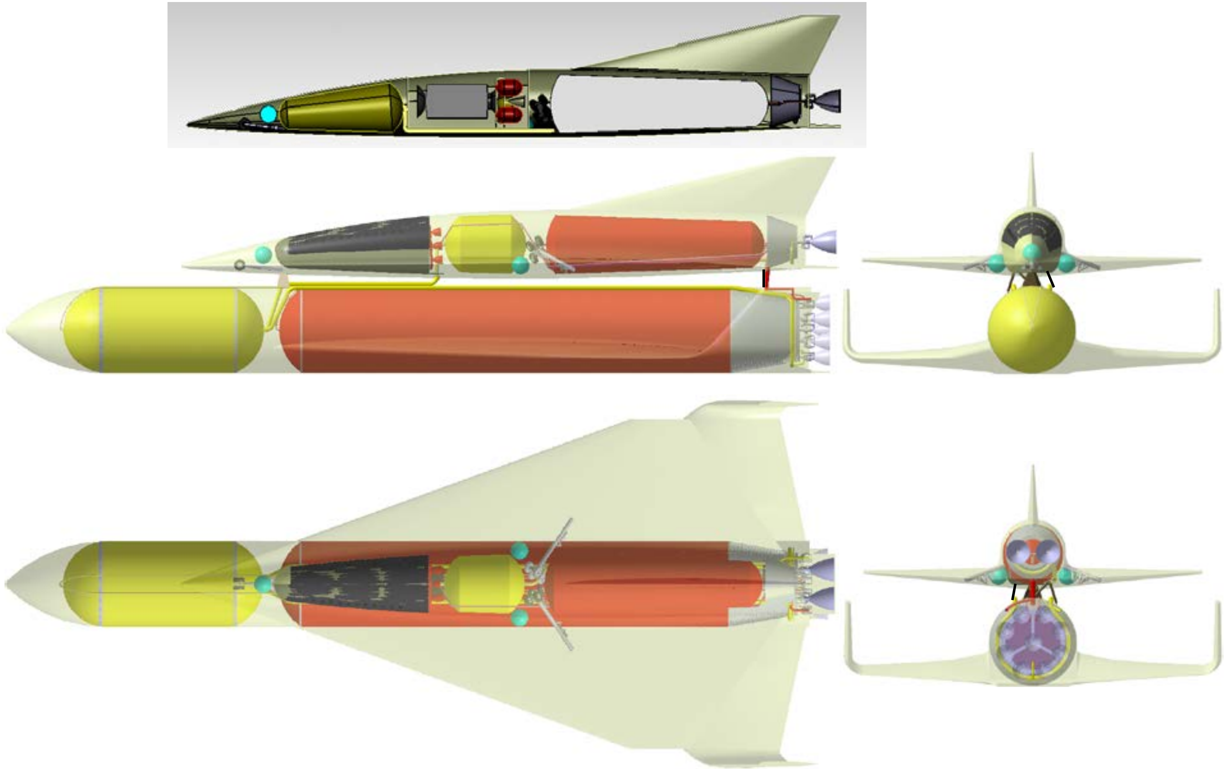

Figure 2: Sketch of SpaceLiner 7-3 launch configuration with passenger version (SLP) with its booster stage at bottom position and orbital stage of SLO in insert at top

2.1. Reusable booster stage

The SpaceLiner 7 booster geometry is relatively conventional with two large integral tanks with separate bulkheads for LOX and LH2 which resembles the Space Shuttle External tank (ET) lay-out (Figure 3). The overall size of the booster is reaching significant dimensions of more than 80 m in length. The major additions to the ET are an ogive nose for aerodynamic reasons and for housing subsystems, the propulsion system, and the wing structure with landing gear. The two tanks are part of the load carrying structure. The structure of the wing follows aircraft convention with ribs to make up the shape of the wing profile and spars to carry the main bending load [14]. Both tanks with an external structural diameter of 8.5 m carry all major loads. The interface thrust to the upper stage is going through the intertank structure right in front of the very large LH2 tank with a total internal volume of 2577 m^3. Engine thrust and the ground support loads at the launch pad are directed through the conical thrust frame which is connected to the aft-Y-ring of the hydrogen tank. The baseline structural design utilizes integrally stringer/frame stiffened aluminum lithium (Al-Li) 2195 skins for the "fuselage" (LOX & LH2 tanks, nose cone, inter-tank-structure, aft skirt), and 2195 honeycomb sandwich panels for the wings. The current configuration of the booster has been defined based on extensive analyses of the propellant crossfeed system [16, 17].

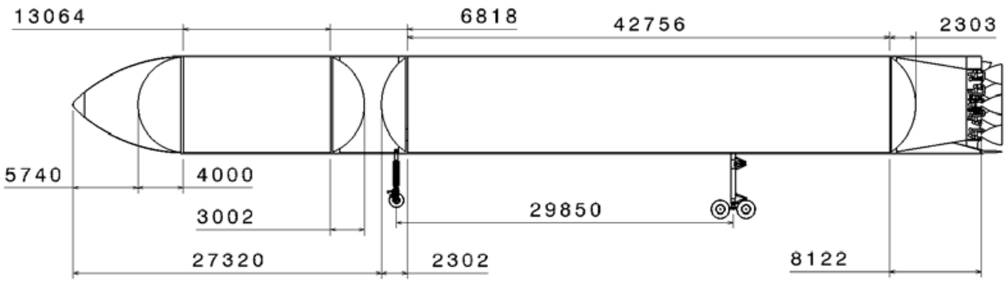

Figure 3: Sketch of SpaceLiner 7 booster stage

The booster wing (and winglet) airfoils have been selected as modified NPL-EC/ECH cut at trailing edge thickness of 75 mm [8]. The relative backward position of maximum chord thickness is beneficial for drag reduction in the supersonic and hypersonic flow (thus improved L/D) and at the same time allows for good structural efficiency where the largest amount of the aerodynamic lift forces are introduced.

2.2. Reusable upper stage

The SpaceLiner7 aerodynamic shape is a result of a trade-off between the optima of three reference trajectory points and showed considerable improvements in glide ratio and heat loads compared with previous designs and pointed out the clear advantages of a single delta wing [8, 9]. Major geometry data of the SpaceLiner 7-3 passenger and orbiter stage are summarized in Table 2. The SpaceLiner passenger stage's shape is shown in Figure 4. The SpaceLiner 7-3 configuration passenger stage wing airfoils keep a finite minimum thickness at the trailing edges of 50 mm constant thickness. At the wing's root a modified NACA 66-003.5 is implemented which is cut when the trailing edge thickness reaches 50 mm.

Figure 4: SpaceLiner 7-3 passenger stage

The SpaceLiner 7 passenger stage achieves without flap deflection an excellent hypersonic L/D of 3.5 up to M=14 assuming a fully turbulent boundary layer. The laminar-turbulent transition is assumed occurring at an altitude of 58 km which is around Mach 18 [8].

Experiments of the 7-3-configuration are planned in the windtunnels TMK and H2K at DLR-Cologne. A model in scale 1:158 with different wingflap (+/- 20°) and bodyflap (10°) deflections has been manufactured. The model is shown in Figure 5 in an early run in hypersonic flow condition.

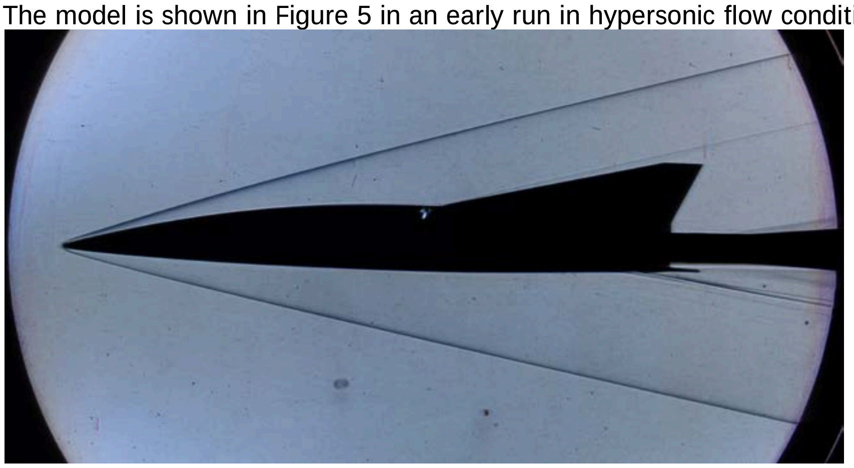

Figure 5: Schlieren image of the SpaceLiner 7-3 passenger stage model in DLR hypersonic windtunnel H2K (M= 5.3, α= 2°, Re= $16 \cdot 10^6$ m^{-1})

In some areas of the SpaceLiner passenger stage (leading edge and nose) the heatflux and temperatures exceed those values acceptable by CMC used in the passive TPS [7, 13]. Already early in the project, transpiration cooling using liquid water has been foreseen as a potential option for solving the problem [4, 10]. In the EU-funded project FAST20XX this innovative method has been experimentally tested in DLR's arc heated facility in Cologne using subscale probes of different porous ceramic materials [11]. Test results have been scaled to full-size by heat transfer correlations and numerical assessment of the complete SpaceLiner trajectory [10]. Based on these data, a water storage tank system, a feedline manifold including control and check-valves and some bypass and redundancy lines were preliminarily sized for accommodation inside the SpaceLiner volume for which an early mass estimation was obtained [12].

Besides the overall promising results also some technical challenges of the active transpiration cooling system have been detected in the FAST20XX-investigations. Precise controllability of the water flow through the porous ceramic media has been found difficult. The experiments sometimes were running into over or under supply of water which could not be recovered within the same experimental run. A more sophisticated supply system would be needed in a flight vehicle. Another concern is the fact that the gas flow from the coolant might trigger early boundary-layer transition. As a consequence, some areas of the passive TPS might need to be reinforced. Therefore, the active transpiration cooling of leading edges and nose is still the reference design option but could once be replaced by other means of active cooling [12].

The passenger stage's design has been adapted for its secondary role as an unmanned satellite launcher. The passenger cabin (see separate section 4 below!) is no longer needed and is to be replaced by a large internal payload bay [13].

Key geometrical constraints and requirements are set that the SpaceLiner 7 passenger stage's outer mold line and aerodynamic configuration including all flaps should be kept unchanged. The internal arrangement of the vehicle could be adapted; however, maximum commonality of internal components (e.g. structure, tanks, gear position, propulsion and feed system) to the passenger version is preferred because of cost reflections. Further, the payload bay should provide sufficient volume for the accommodation of a large satellite and its orbital transfer stage.

The stage's propellant loading has been reduced by 24 Mg to 190 Mg with a smaller LOX-tank to allow for a payload bay length of 12.1 m and at least 4.75 m diameter [13]. These dimensions are close to the Space Shuttle (18.3 m x 5.18 m x 3.96 m) and should accommodate even super-heavy GTO satellites of more than 8 m in length and their respective storable upper stage (Figure 6). Large doors open on the upper side to enable easy and fast release of the satellite payload in orbit.

The orbiter stage mass has been estimated based on the SpaceLiner 7-3 passenger stage budget (see Table 5 on p. 7). Adaptations include the complete removal of all cabin related masses. Instead a mass provision for the payload bay and its mechanisms including doors, the mounting structure, and also a radiator system for on-orbit heat-control is added. The resulting orbiter dry mass is about 102 Mg and the budget is listed in Table 6.

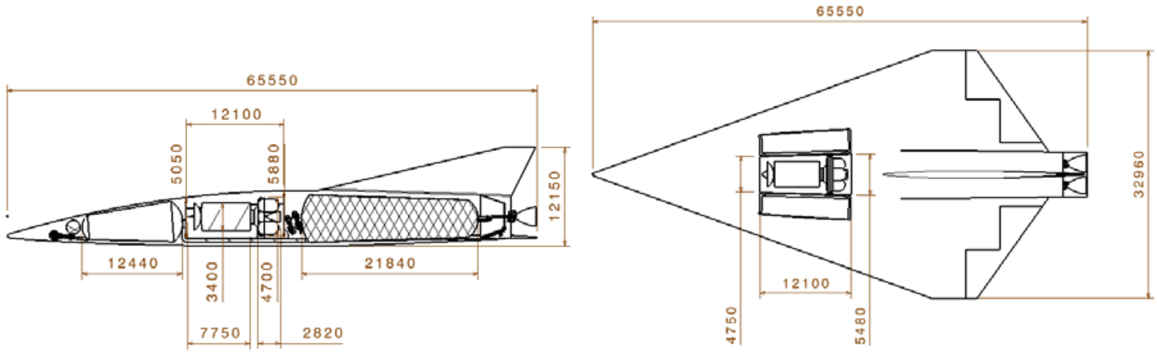

Figure 6: Sketch of SpaceLiner 7 as orbital space transportation with internal cargo bay for satellites

The aerodynamic trimming of the satellite transport stage with the existing trailing edge flaps and the bodyflap has been preliminarily checked in numerical simulation under hypersonic flow conditions of atmospheric reentry and is found feasible within the constraints of the present lay-out [13]. This promising outcome is a result of the robust SpaceLiner design philosophy which is also taking into account off-nominal abort flights. The calculated maximum L/D is reduced approximately 15% by the significant flap deflections compared to the L/D achievable for the nominal passenger mission with almost no deflection. Pre-trimmed aerodynamic data sets have been generated and were used for reentry trajectory simulations of the orbiter.

2.3. Main propulsion system

Staged combustion cycle rocket engines with a moderate 16 MPa chamber pressure have been selected as the baseline propulsion system right at the beginning of the project [3]. 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 the preferred design solution for the SpaceLiner Main Engine (SLME).

The expansion ratios of the booster and passenger stage/ orbiter engines are adapted to their respective optimums; while the mass flow, turbo-machinery, and combustion chamber are assumed to remain identical in the baseline configuration.

The SpaceLiner 7 has the requirement of vacuum thrust up to 2350 kN and sea-level thrust of 2100 kN for the booster engine and 2400 kN, 2000 kN respectively for the passenger stage. All these values are given at a mixture ratio of 6.5 with a nominal operational MR-range requirement from 6.5 to 5.5. Table 3 gives an overview about major SLME engine operation data for the nominal MR-range as obtained by cycle analyses. The full pre-defined operational domain of the SLME is shown in [16].

Table 3: SpaceLiner Main Engine (SLME) technical data [16, 17]

	Booster			Passenger Stage		
Mixture ratio [-]	5.5	6.0	6.5	5.5	6.0	6.5
Chamber pressure [MPa]	15.1	16.0	16.9	15.1	16.0	16.9
Mass flow per engine [kg/s]	481	517	555	481	518	555
Expansion ratio [-]	33	33	33	59	59	59
Specific impulse in vacuum [s]	439	437	435	451	449	448
Specific impulse at sea level [s]	387	389	390	357	363	367
Thrust in vacuum per engine [kN]	2061	2206	2356	2116	2268	2425
Thrust at sea level per engine [kN]	1817	1961	2111	1678	1830	1986

Subcomponent sizing and definition is progressing at Phase A conceptual design level. Refinements are focusing on the turbomachinery designed as an integrated power-head and a suitable regeneratively cooled thrust-chamber lay-out. The key-objective is a light-weight, long-life, low-maintenance architecture. The SLME thrustchamber and regenerative cooling circuit has been preliminarily defined for the booster engine with expansion ratio 33 [16]. Supercritical H2 of the HPFTP discharge at around 30 MPa is split into two separate passes both induced in the supersonic section at expansion 4.5. One counter flow pass (approximately 2/3 of total flow) chills the chamber including the throat area and the other pass chills the nozzle area downstream up to expansion of 16.6 [16]. Beyond that section a combination of small bleed and radiation is used for cooling. Fuel for film cooling is supplied from the side of the injector plate further chilling the chamber wall. In the upper stage version of the SLME with expansion ratio 59 the nozzle extension beyond expansion ratio of 33 should be film and radiation cooled [16].

An Integrated Power Head (Pre-burner + Turbine + Impeller pump) as it has been used on the SSME is also the preferred design solution for the SLME. The reduced length of high pressure hot gas lines should enable significant mass saving and a compact and clean lay-out [16, 17]. Both preburners' external walls are actively cooled by their respective predominant fluids. The cooling fluid is heated up and subsequently used as pressurization gas for the tanks [16].

The SLME engine controls and actuation system is intended to be designed fully electric for maximum safety and manufacturing cost reduction. A FADEC system as in modern aircraft engines centralizes all HM-information and has a redundant data link to the vehicle's flight control and data management and data handling [16].

The size of the SLME in the smaller booster configuration is a maximum diameter of 1800 mm and overall length of 2981 mm. The larger passenger stage SLME has a maximum diameter of 2370 mm and overall length of 3893 mm. The engine masses are estimated at 3375 kg with the large nozzle for the passenger stage and at 3096 kg for the booster stage [16, 17].

2.4. System masses

Based on available subsystem sizing and empirical mass estimation relationships, the stage masses have been derived as listed in Table 4 through Table 6. In case of the passenger stage (Table 5), the total fluid and propellant mass includes all ascent, residual, and RCS propellants and the water needed for the active leading edge cooling [4, 7, 12, 13]. The stages' MECO mass is approximately 151.1 Mg. The SpaceLiner 7-3's GLOW reaches about 1832 Mg (Table 7) for the reference mission Australia – Europe while the TSTO is at 1807 Mg (Table 8) still below that of the Space Shuttle STS of more than 2000 Mg.

Table 4: Mass data of SpaceLiner 7-3 booster stage

Structure [Mg]	Propulsion [Mg]	Subsystem [Mg]	TPS [Mg]	Total dry [Mg]	Total propellant loading [Mg]	GLOW [Mg]
123.5	36.9	18.9	19.1	198.4	1272	1467

Table 5: Mass data of SpaceLiner 7-3 passenger stage

Structure [Mg]	Propulsion [Mg]	Subsystems including cabin [Mg]	TPS [Mg]	Total dry [Mg]	Total fluid & propellant loading [Mg]	GLOW incl. passengers & payload [Mg]
55.3	9.7	43.5	22.3	129	232.1	366

Table 6: Mass data of SpaceLiner 7 Orbiter stage (GTO mission)

Structure [Mg]	Propulsion [Mg]	Subsystems [Mg]	TPS [Mg]	Total dry [Mg]	Total fluid & propellant loading [Mg]	GLOW incl. kick-stage & payload [Mg]
60.1	9.9	9.8	22.3	102	207	309.1

Table 7: Mass data of SpaceLiner 7-3 passenger launch configuration

Total dry [Mg]	Total propellant loading [Mg]	GLOW incl. passengers & payload [Mg]
327.4	1502	1832.2

Table 8: Mass data of SpaceLiner 7-3 TSTO launch configuration

Total dry [Mg]	Total propellant loading [Mg]	GLOW incl. kick-stage & payload [Mg]
300.6	1467	1807

3. Preliminary studies for SpaceLiner 8 Booster

3.1. SLB7 shortcomings

The biplane architecture of the mated launch configuration (Figure 2) is problematic because of complex high-speed flow interactions of the two stages during ascent flight. A 6DOF-simulation based on simplified aerodynamics assuming perturbations and engine-out conditions indicates that the situation could probably be mastered by TVC [26]. Nevertheless, a less interacting, less complicated flow around the geometry of the ascent vehicle is desirable not least to avoid potential damage to surface insulation and coatings.

ESA has been calculating the SpaceLiner 7-3 booster stage with Euler CFD [13, 14] for its reentry conditions. The booster separation Mach number of the passenger version's reference mission Australia to Europe is approximately 12.5. After a short ballistic phase the SLB enters the denser atmosphere and decelerates, reaching the maximum heatload around Mach 10 in 50 km. Figure 7 shows the atmospheric entry condition of the booster stage after separation close to its maximum load condition. A critical shock-shock interaction at the outboard leading edge (highlighted by white circle in Figure 7) has been revealed. The situation needs improvement of the SpaceLiner booster aerodynamic design of future variants.

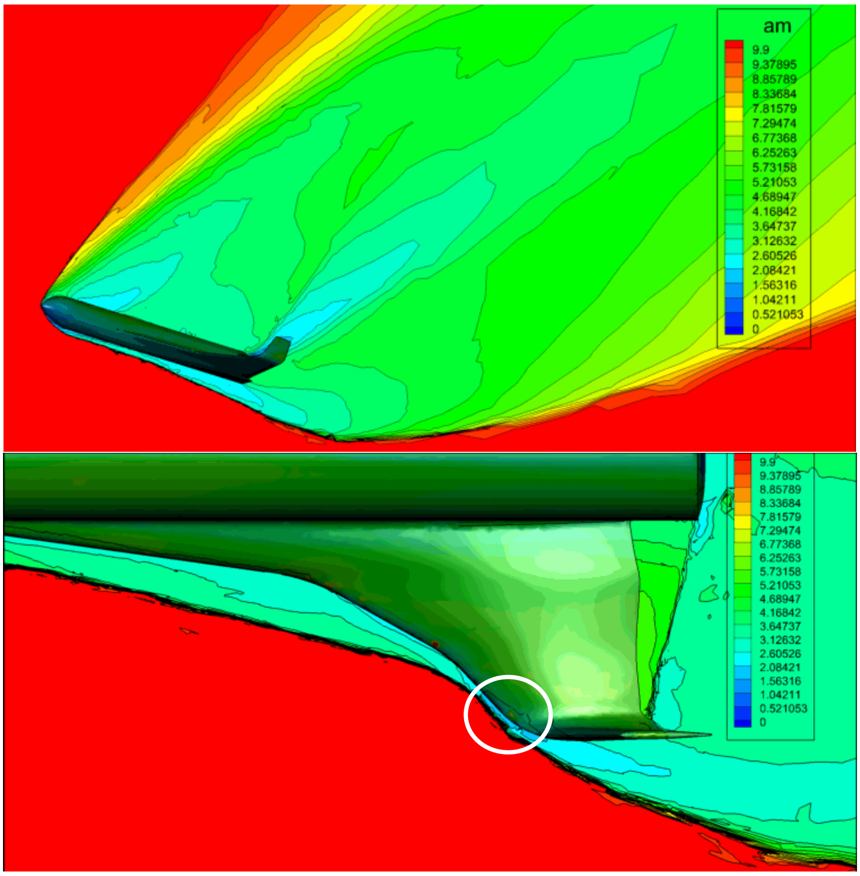

Figure 7: Mach contours of SpaceLiner 7-3 booster stage at M= 10, α= 35° from ESA-ESTEC Euler CFD- calculation showing shock-shock interaction

Both, the complicated flow of the launch configuration and the shock-shock interaction during booster reentry, motivate the investigation of potential geometry changes and improvements to the SpaceLiner booster wing geometry. Currently, the study for the next SpaceLiner 8 design is ongoing without any downselection performed. However, some results of the research are already available.

3.2. SLB8 with small wing

In order to reduce biplane flow interactions during ascent and to avoid the shock-shock-interaction on the outboard leading edge, a drastically reduced size of the SLB wing has been investigated. A first proposal for the SL 8 Booster, called SLB8V2, looks like the configuration presented in Figure 8.

Fuselage length and diameter of the first concept has been kept unchanged to the previous SLB7 (Table 1). The wing span, however, is drastically reduced from the former 36 m to 20 m. The nose bow-shock would no longer interfere with the wing leading edge.

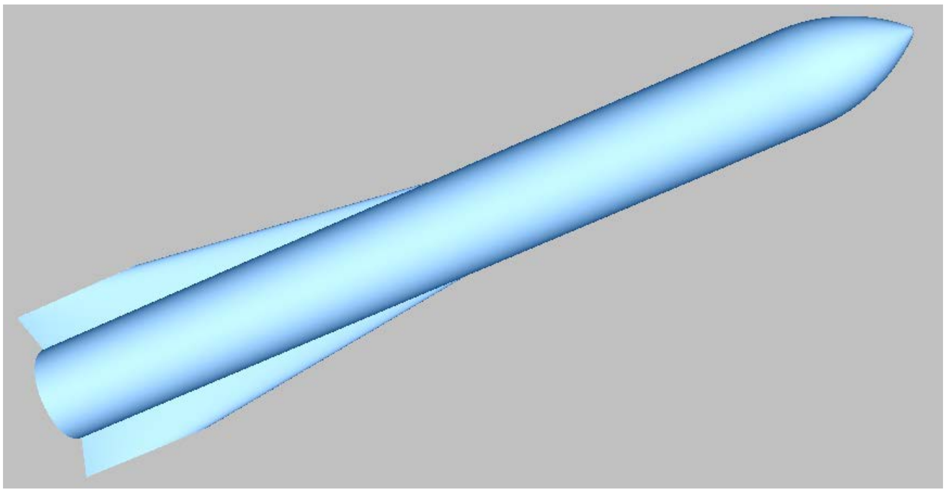

Figure 8: Investigated geometry for SpaceLiner 8 booster variant SLB8V2

On the downside, such a small wing will not be sufficient for horizontal landing of the RLV-stage with its more than 180 Mg of dry mass. L/D is also not satisfactory to allow the tow-back using the “in-air-capturing”-technique. Consequently, the SLB8V2 would need to be designed for vertical downrange landing on a sea-going ship. The reentry could be somehow similar to Blue Origin’s planned New Glenn launcher or to SpaceX’ Falcon9. However, one major difference is the fact that the SLB8 with its separation Mach number above 12 will require a nose first reentry in order to protect the rocket engines in the aft bay. After gliding deceleration to low speed and low altitude, the vehicle should rotate its attitude by 180 deg. and eventually some of the rocket engines are reignited for final slowing down to a vertical landing.

The feasibility check of the SLB8V2 includes analyses of the aerodynamic trimmability for pitch in a wide operational range of Mach-number and AoA. Flaps at the remaining trailing edge with deflection from +20° to -20° enable a trimmed pitch up to α of 50°. In supersonics below 20° the configuration would become unstable for its current calculated CoG-position. Untrimmed maximum L/D in the hypersonic regime is calculated to reach up to 2.4.

The relatively small wing of the SLB8V2 turns out to be fully sufficient for a smooth reentry avoiding extreme heatloads. The configuration is aerodynamically decelerated to 110 m/s in 2.86 km altitude where the turn maneuver should be initiated. A plot from a 3DOF-simulation is presented in Figure 9.

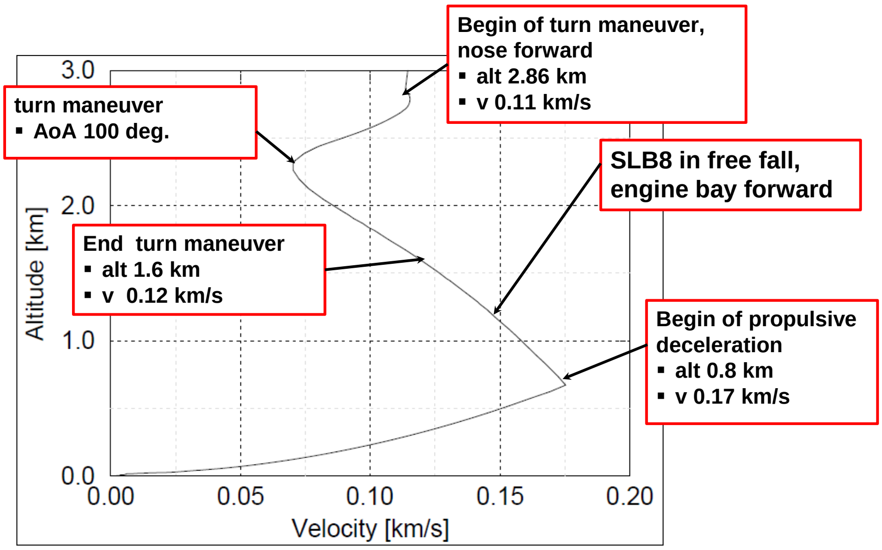

Figure 9: Simulated final vertical landing approach of SpaceLiner 8 booster SLB8V2

The sharp increase in AoA generates lift and further reduces flight speed to approximately 70 m/s. Afterwards the vehicle is further turning so that the aft bay is in the forward position facing the flow. The complete turn maneuver is realized in the simulation within an altitude range of 2000 m. The propulsive deceleration for vertical landing is initiated 800 m above sea-level at 170 m/s.

Using 3 out of 9 SLME engines on the SLB would require approximately 14 tons of propellant for landing including margins. Actual feasibility of the turning maneuver is the most critical part of the return mission and is not yet proven by the 3DOF-simulation results as shown in Figure 9. Without performing a 6DOF-simulation, at least simplified subsonic aerodynamic data sets with 360° angle of attack range have been crosschecked. Extremely high pitching moments are to be expected with a sudden change in the algebraic sign at AoA of 90° and again 270°. This behavior is not surprising for a naturally stable configuration. A controlled turn maneuver of the 80 m SLB8V2 at dynamic pressure of approximately 10 kPa would hence require mastering rapid changes in the aerodynamic pitch moment of around 100 MNm. Aerodynamic control surfaces generating such moments are not considered and propulsive forces would reach far beyond typical RCS-thrusters. If the vehicle would be designed with indifferent pitch stability the necessary moments for its turning would be reduced. However, in the major part of the trajectory this behavior is strongly disadvantageous.

Further, in the first assessment of the SLB8V2 the vertical stabilizer has been disregarded as well as a mass contingency for any dedicated powerful RCS to perform the turn maneuver. Taking these masses and the landing propellant into account, the overall performance of the SLB8 variant shows no improvement potential compared to the current SLB7 despite major savings in wing and TPS mass. As the technical feasibility of the vehicle turn is questionable under the constraint of acceptable mass impact and development and operational risk, design work on the SLB8V2 is discontinued.

3.3. SLB8 next steps

As the vertical landing SLB8V2 turned out to be not very promising, alternative designs are to be explored. The next step of an SLB8 concept will maintain the promising hypersonic aerodynamic configuration with small wings somehow similar to the shape shown in Figure 8. In order to allow again the stage to use “in-air-capturing” and horizontal landing, deployable wing options are checked on integration and mass impact. Design work on this configuration is ongoing.

Another critical aspect for RLVs like the SpaceLiner is the selection of reusable cryogenic tank insulation which works under multiple environmental conditions. Independent of weather conditions (e.g. temperature, humidity) effective insulation needs to be ensured and icing on the vehicle external surface is to be avoided. DLR is currently performing systematic research on promising combinations of insulation and reentry TPS [15] for which the SLB serves as the system reference concept. The expected experimental and numerical results will influence the selection of the SLB8 tank insulation concept which will also impact the external diameter.

4. SpaceLiner Cabin and Rescue System

The passenger cabin of the SpaceLiner has a double role. Providing first a comfortable pressurized travel compartment which allows for horizontal entrance of the passengers, the cabin in its second role serves as a reliable rescue system in case of catastrophic events. Thus, the primary requirements of the cabin are the possibility of being firmly attached late in the launch preparation process and fast and safely separated in case of an emergency.

The capsule should be able to fly autonomously back to Earth’s surface in all separation cases. The abort trajectories are primarily influenced by the mass of the capsule and the aerodynamic performance with the most important subsystems being the separation motors, the thermal protection system (TPS), and the structure. These three subsystems have been investigated and sized for function, performance, and mass.

4.1. SLC design

Overall length of the capsule for 50 passengers (without separation motors) is 15.6 m and its maximum external height is 5.6 m. The estimated masses of the capsule are about 25.5 tons for the dry capsule, about 7600 kg for the passengers, crew and luggage, and 3800 kg for all propellants, separation motor, retro-rockets and RCS [14].

The capsule can be subdivided in a pressurized cabin of conical shape and an outer aerodynamic shell formed by the Thermal Protection System and which provides space for housing several non-pressurized subsystems [7, 13, 23]. The TPS of the SpaceLiner7 capsule is required to withstand several different heat load conditions driven by the different nominal and abort cases it might encounter. During nominal flight the capsule in its baseline design is considered to have its upper part conformal with the topside of the passengers stage (SLP). The SLC lower section is clamped within the SLP without any load carrying structural connection (see e.g. [14]) to allow rapid and safe separation in case of an emergency.

The separation motors attached to the rear end of the SpaceLiner Capsule (SLC) are of crucial importance for the capsule ejection procedure, since they provide the thrust to accelerate the capsule in to safe distance away from the SLP and SLB. Due to severe geometry constraints, it has been decided to utilize a five motor configuration with very short cylindrical section (Figure 10). Each motor has an approximate sea-level thrust of 870 kN and a burn time of almost 2 s. The baseline features classical single-nozzle (ε= 15) solid rocket motors using a mixture of 68% AP, 20% aluminum and 12% HTPB as propellant [22]. The maximum thrust with a chamber pressure of 15 MPa is around 856 kN at sea-level (I_{sp} = 267.8 s) and 908 kN (I_{sp} = 284 s) in vacuum. The total mass per motor is approximately 693 kg leading to a total mass for all motors of 3.47 tons.

Innovative multi-nozzle motors are derived from the single-nozzle type to be operated at the same chamber pressure. Due to the use of multiple nozzles, expansion ratio could be increased to ε= 21 while at the same time the total length and required volume will be decreased (Figure 10). However, the use of multiple nozzles slightly increases the dry mass of the separation motors. It should be noted that the grain shape of the separation motors is significantly different to launcher stages. The high thrust and very short burn time requires a web-like design comparable to those in military missiles. Thus, hot combustion gas should easily reach each of the nozzle entries.

While the baseline motor is underexpanding in all operation conditions, the new multi-nozzle type should operate almost adapted to sea-level conditions with 0.94 bar exit pressure. The I_{sp} in vacuum increases to about 288 s, whereas the calculated sea-level I_{sp} reaches 265.4 s. The optimum nozzle expansion ratio is depending on detailed analyses of several abort scenarios and will be determined after extensive trade-offs to be performed.

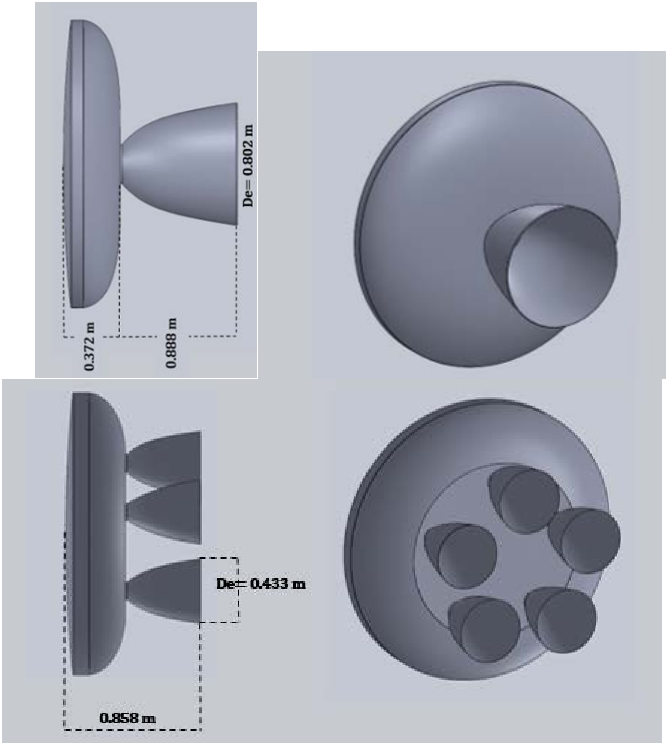

Figure 10: Different SLC separation motor options: single nozzle (top), multiple nozzle (bottom) [22]

A preliminary design for the capsules main subsystems has been elaborated [14, 19]. This includes the body flaps, deployable rudders, the parachute system for transonic stabilization and landing, the electro-mechanical actuators and their batteries, and the reaction control system (RCS). A double bodyflap and two deployable control fins on the upper surface enable flight controllability and stability in a major portion of the required domain. The preferred RCS choice is characterized by 2 clusters of thrusters located in the rear part of the capsule. Each cluster provides a thrust of 3 kN along each of the double axis for a total delivered thrust of 12 kN. This architecture allows performing quick maneuvers and is characterized by sufficient volume available also for implementing larger thrusters. A non-toxic bi-propellant combination is desirable for passengers' safety and ease of handling and this precludes the use of any variant of hydrazine. The combination H_2O_2 (90%) - kerosene is chosen because of its storability for months, potential hypergolic ignition by additives, and its non-toxic behavior. Parachutes are assumed to be deployed and operate in a certain altitude-Mach-box to decelerate the capsule during the final landing phase. The SpaceLiner capsule parachute system is likely a combination of supersonic stabilization chute which allows safe deceleration through the transonics and subsequent subsonic gliding by parafoil [14, 19].

The principal feasibility and flyability of an innovative morphing structure concept on the capsule has been demonstrated by numerical simulations within the HYPMOCES project [20, 21]. In this case the maximum hypersonic L/D-ratio of the capsule is improved by up to 20 % compared to the standard configuration. The additional mass and system complexity is to be justified by significantly improved passenger safety [14].

4.2. SLC integration and separation studies

The current requirement of capsule separation being feasible at any flight condition and attitude is highly challenging from a technical point of view. Analyses revealed some critical issues to be addressed in order to improve the safe functionality of the cabin rescue system. Further investigations have been initiated to find a promising and reliable separation concept and system taking into account multi-body dynamics and CFD-simulations [22].

A preliminary separation process of the baseline SLC has been studied earlier [23] which is shown in Figure 11. The capsule would have first to be slightly pushed forward axially (Frame 1 - 2) to enable the SLC to be tilted upwards without colliding with the SLP tank structure (Frame 3). This maneuver is to be performed by a small solid motor located close to the capsule's nose on its bottom side. Then, the separation motors would be ignited (Frame 4), accelerating the SLC away from the SLP. This preliminary analysis shows that an ejection of the capsule requires jettisoning a forward section of the upper fuselage. The upward motion is to be precisely synchronized with the ignition of the solid motors in a manner that guarantees safe and clean separation in every investigated flight point.

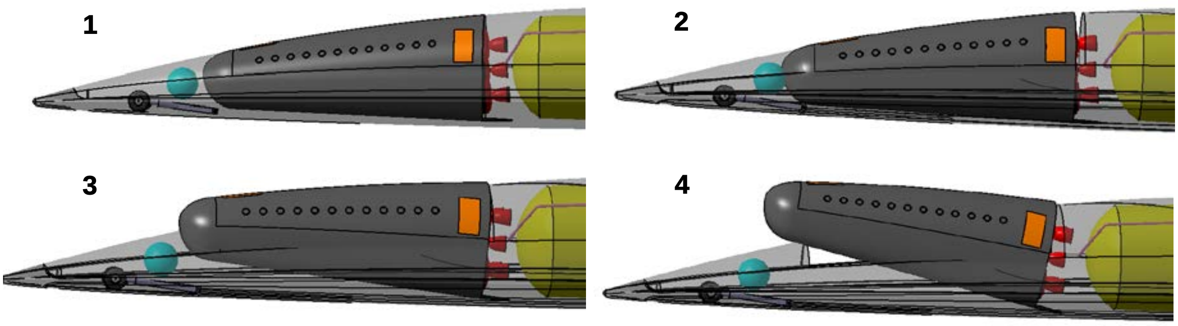

Figure 11: Kinematics of baseline SLC separation process (Concept A) [22, 23]

The relatively complex separation process of the baseline SLC integration is under debate since several years. The high level safety requirement of the MRD indirectly calls for a safe separation from ground launch pad operations through the full flight mission [13]. The realization could become the more challenging when considering hypersonic flow with transient shock-boundary interactions during a significant portion of the trajectory. DLR is in cooperation with ONERA in France for a better understanding of the high-speed separation process by using sophisticated numerical simulation tools.

The baseline integration of Figure 11 (named Concept A) is complemented by two alternative concepts (Concept B and Concept C) which are presented in Figure 12. The Concept B features the

SLC being the complete nose section of the passenger stage. The SLC capsule would then have to accommodate all subsystems that are contained in the nose, such as the front landing gear and the water tank for active cooling. Hence, the SLC mass after separation and the system complexity of the separated capsule would significantly increase. The separation kinematics would be less complex compared to the concept A since acceleration is only necessary in axial direction. However, in contrast to the clamped Concept A load-bearing structures would have to be cut. Technical solutions for a fast and clean cut might exist but require additional pyrotechnic devices to be installed. The other alternative is Concept C with the SLC as the complete upper nose section (marked in green in the sketch of Figure 12). This approach resembles the capsule conception studied for a 2nd generation Space Shuttle (see e.g. [22]) having the advantage of less mass than concept B without necessity of cutting through structure and TPS, and probably simplified separation procedure than the one of concept A. Both Concepts B and C are not compatible with the SpaceLiner 7 upper stage geometry and mass assumptions and will require a completely new design loop leading in the future to an improved SpaceLiner 8 configuration.

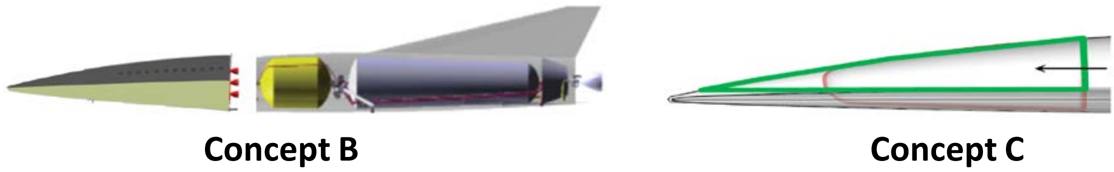

Figure 12: Alternative SLC integration Concepts B and C [22]

4.3. Multibody simulation of SLC ejection

All the challenges of the emergency capsule separation process outlined in the previous section indicate that a sound decision on the best capsule integration concept is not possible based on simple kinematics and assumption of steady or static conditions. Multibody simulations using Simpack have been set up for the analyses of the different SLC concepts. Simpack, formerly developed in DLR but now available as a commercial product, is a general purpose Multibody Simulation (MBS) software used for the dynamic analysis of any mechanical or mechatronic system. Currently, only the Simpack model of the baseline Concept A (see Figure 11) has been set up because a consolidated design with extensive data sets are available [22]. The geometrical model was taken from the respective SpaceLiner CATIA model. Until now only a 6DOF simulation with no collision detection and modelling has been conducted. Hence, the capsule follows a trajectory being dictated by the forces and moments acting upon the SLC but without considering any interaction with other bodies like the remaining part of the passenger stage. This simplification allows already identifying problems or difficulties of the separation procedure without setting up a complicated dynamic model.

The visualization of the simulated separation procedure depicted in Figure 13 shows SLC ejection at the launch pad with zero altitude and zero velocity of the SpaceLiner. The emergency on the launch pad is a separation system design driver because of the requirement to rapidly escape the huge detonation potential of the propellant loading in the completely filled tanks and further reach sufficient altitude for subsequent parachute landing in a safe distance.

After the nose tilt-up, the outboard separation motors are ignited within 0.1 seconds after ignition of the center motor (Figure 13). The solid rockets burn for about 2 seconds and produce a maximum thrust of slightly more than 850 kN each. After burn-out the capsule follows a ballistic trajectory. Note that no aerodynamic forces have yet been implemented in this low-speed simulation. The SLC reaches a distance of about 340 m within 2.9 seconds fulfilling the minimum required distance of 290 m [22]. The absolute acceleration of the SLC is about 11 g almost completely along the x-axis [22], as intended. Medical investigations of NASA had demonstrated in the past that even untrained passengers will endure such elevated acceleration levels for a very short time if pushed back into their seats.

In Figure 13 no reaction forces between the SLP and SLC are observed, since neither a guiding system nor any joint connections at the point of separation motor ignition are modelled in the framework. The capsule collides with the front water tank after around 0.35 seconds while also colliding with the lower part of the SLP fuselage. If such a collision is actually critical for the SLC integrity requires more detailed crash studies. The capsule keeps ejecting through the front part of the nose throughout the first 0.8 seconds. Hence, this separation procedure in reality would need some sort of a guidance mechanism for the front and the rear end of the capsule which might be integrated in form of a fuselage supporting structural frame. Furthermore, a portion of the front upper part of the SLP's fuselage would have to be ejected to minimize the collision risk, if required. In future simulations, such a guiding mechanism as well as the jettisoning of fuselage parts will be simulated.

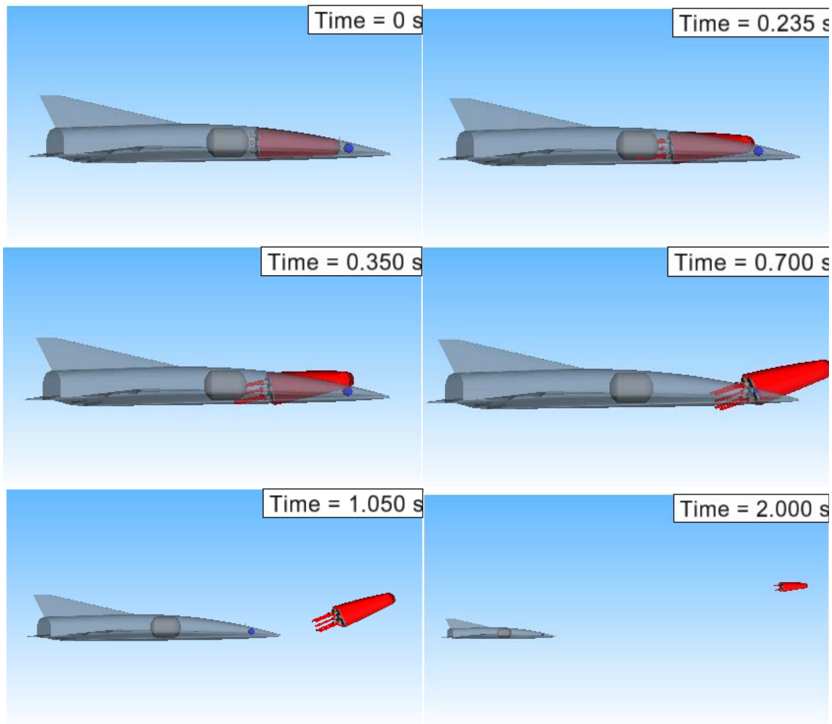

Figure 13: Simulated SLC Concept A separation in case of launch pad emergency [22]

The results presented are based on a preliminary simulation with simplified assumptions. The next steps are to improve the separation sequence, increase the level of simulation complexity and search for feasible solutions. The thrust profile of the separation motors is also subject to optimization and might be adapted within constraints of internal motor ballistics.

The cabin escape system design is a highly interdisciplinary, interdependent and iterative process. At the current point of the SpaceLiner project, the design of the cabin and the ejection system are still open to changes. In the future course of the project, a systems engineering approach shall be used to obtain a feasible and viable solution for the design of the capsule separation system [22]. Functional abilities and constraints shall be derived for the separation process at every point of the mission to determine the dependencies of the cabin design with regards to the different boundary conditions. Subsequently, system requirements shall be derived that will be used to find a feasible solution fulfilling all these requirements. According to the MRD [13], the achievable mission safety levels need to be demonstrated in the ongoing Phase A development.

4.4. SLC hypersonic aerothermodynamic simulations

CFD simulations have been conducted by ONERA within the HYPMOCES project [20] to determine the general aerothermodynamics environment of the SLC after hypersonic emergency separation. In particular the work aimed at performing a global assessment of the aerodynamic coefficients and wall heat fluxes encountered by the rescue cabin, depending on local conditions, as well as to identify the critical flight points from an aerothermodynamics point of view [21].

CFD computations have been conducted for the most extreme aerothermal conditions when the capsule separated close to SpaceLiner MECO subsequently reaching its atmospheric entry peak heat load. Approximately 1000 s in its autonomous flight the capsule arrives at this trajectory point at Mach 20 in 57.8 km [23]. The ONERA unstructured 3D Navier-Stokes solver CHARME (Navier-Stokes solver from the multi-physics CEDRE platform) is used assuming chemical non-equilibrium in the flow with a 5-air species chemical model based on Park's kinetics.

Windward gaps, inserted into the Thermal Protection System material and allowing the deployment of the inflatable system, have a significant influence on the flow topology on the flaps. The gaps begin nearby the nose and drive the streamlines up to the flaps where they induce a significant heterogeneous flow detachment (Figure 14). The temperature of the separation and re-attachment flow can reach almost 5000 K in the stagnation zone (Figure 15).

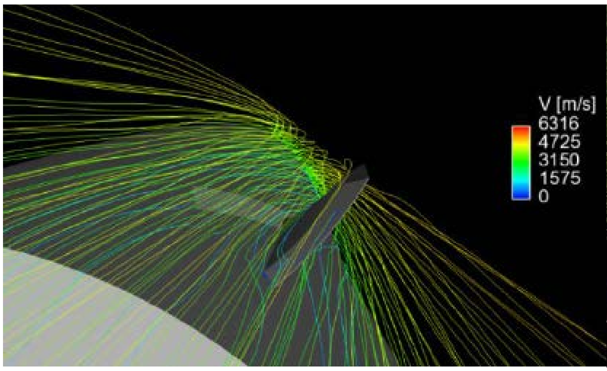

Figure 14: Flow topology around the rudders (with large cavity) on the leeside of the SLC geometry [21]

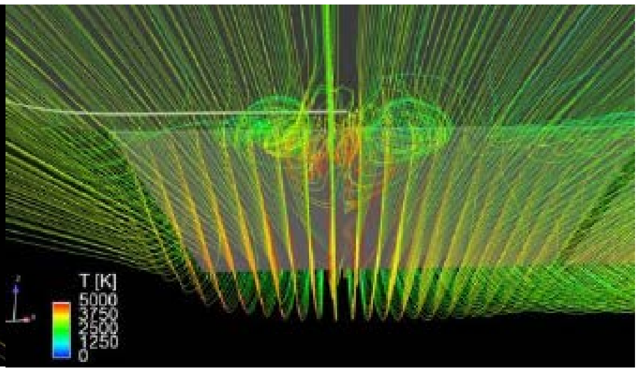

Figure 15: Temperature of the flow (colorized streamlines) in the flaps area on the windward side of the SLC geometry [21]

The wall heat flux and temperature on the flaps are depicted in [21]. The specific flow topology induced by the longitudinal gaps of the HYPMOCES inflatable system [14, 19] has a significant impact on the characteristics of the heat flux distribution on the flaps. The recirculation zone without homogeneous re-attachment zone leads to the presence of longitudinal cooled zones on the flaps. Inside the flaps hinges, a cooling process is active where recirculation zones are developed [21] and thus the heat flux remains lower by 2 kW/m² (Figure 16). However, the radiative heat flux from one wall facing another is not taken into account in this calculation and, if considered, will increase the presented heat flux levels. The thermo-mechanical constraints between the two flaps can be significant. The temperature on the sidewall of the flap can reach 1510 K (Figure 17).

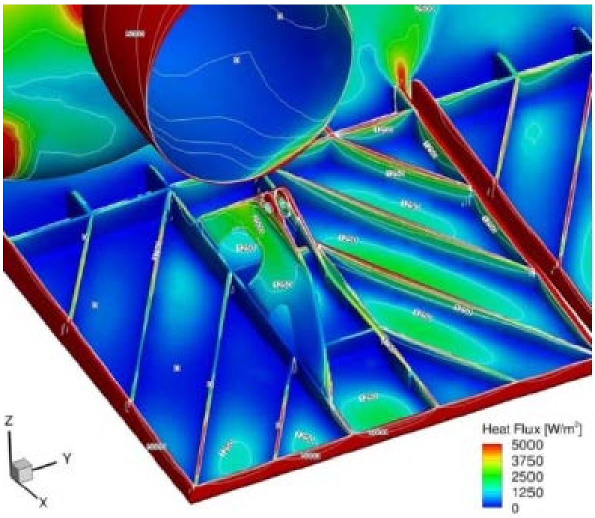

Figure 16: Heat flux distribution on the backside of the SLC flaps with detailed geometry including stiffeners [21]

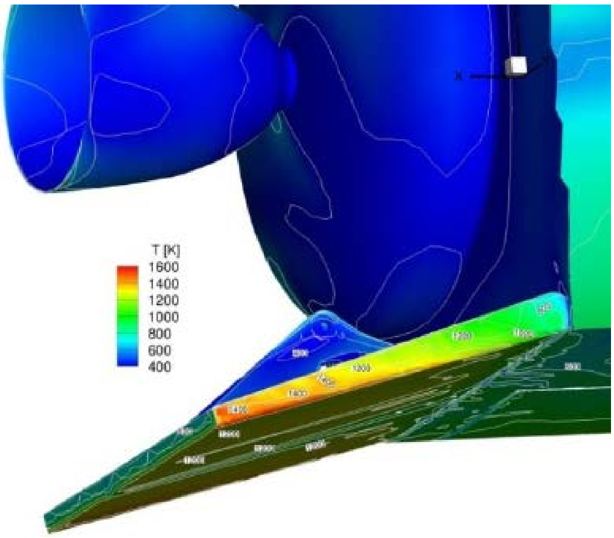

Figure 17: Surface temperature on the sidewall of SLC flaps with detailed geometry [21]

5. Intercontinental passenger flight mission

The ambitious Australia – Europe mission has been used as the reference case since the beginning of the SpaceLiner investigations [4, 5]. This flight distance should be served for 50 passengers on a daily basis in each direction. Several other, shorter intercontinental missions exist, which potentially generate a larger market demand. For this reason a SpaceLiner configuration derivative has been studied, which could transport up to 100 passengers [16]. In order to keep the number of different stage configurations at the lowest possible level, the potentially interesting flight destinations have been divided into three classes:

- Class 1: Reference mission (up to 17000 km) Australia – Europe with 50 passengers orbiter and large reference booster
- Class 2: Mission (up to 12500 km) with increased 100 passengers orbiter and large reference booster
- Class 3: Mission (up to 9200 km) e.g. Trans-Pacific with increased 100 passengers orbiter and reduced size booster

These three mission classes could be flexibly served by a suitable combination of four different vehicles (however with a lot of commonality in subcomponents like engines): 50 and 100 passenger orbiter stage and large and shortened booster.

5.1. SpaceLiner reference mission Australia – Europe

Different trajectory options have been traded in the past mostly for the Australia – Europe reference mission for up to 50 passengers. These were following a standard launch vehicle vertical ascent with an initial azimuth in North-Eastern direction overflying the arctic sea before approaching Europe from the North-Eastern Atlantic. Peak acceleration is constraint at 2.5 g for passenger comfort. The propulsive phase of approximately 8 minutes duration is directly followed by hypersonic gliding succeeded by landing approach after approximately an additional hour and 20 minutes of flight.

Flight path as well as groundtrack constraints and demands for operationally interesting launch and landing sites influence the selection of practical reference trajectories. The launch and ascent noise as well as the sonic boom reaching ground are most critical for a viable SpaceLiner operation in the future. Therefore, operational scenarios of the SpaceLiner are established taking into account realistic launch- and landing sites as well as groundtracks which are acceptable with respect to sonic boom constraints overflying populated areas and fast accessibility to major business centers. Conventional existing airports located close to densely populated areas are not suitable for SpaceLiner operations. Three alternative launch and landing site concepts should fit for almost all potential locations.

The Europe – Australia and return route is the baseline for other investigations. Preliminary and currently non-binding locations have been selected on each continent with the advantage of the complete launch ascent and supersonic gliding approach capable of being performed over the sea while still being relatively close to each continent’s major business centers. These are two key-requirements for successful future SpaceLiner operation. Recently, the East Asia – Europe and the USA – Australia missions have been particularly assessed for these constraints.

Three off-nominal cases have been simulated [14, 24]: Engine I_{sp} degraded by 3 s under all conditions (equivalent to a c*-reduction of 29.4 m/s). In a conservative approach the assumption is that all engines are affected. Further, nominal ascent propellant mass in the booster stage has been reduced by 20 tons while increasing residuals and reserves by the same amount. The third off-nominal case is the impact of one engine inoperative: the entire ascent phase is simulated with only 8 booster engines, instead of 9. Flight times are slightly increased and realized ground tracks are somewhat altered. However, in all investigated cases the mission success has been demonstrated even under significantly degraded off-nominal conditions [14, 24].

Recently, the constraint of acceptable sonic boom on ground has been directly included in the trajectory optimization process. Solving the optimal trajectory problem requires the physical problem to be transcribed into a form which is solvable by a generic optimal control solver [25]. In this case the pseudospectral method of transcribing the optimal control problem is used. The interpolated population density of overflown territories is included in the cost function. The population density cost is scaled by altitude so that the population cost goes to 0 at 80km altitude, and increases linearly as altitude decreases. This drives the optimization to keep the altitude of the SpaceLiner as high as possible over populated areas, if flying over population is unavoidable [25]. Heatflux and load constraints as in standard trajectory optimizations are additionally considered.

The optimized trajectory (Figure 18) is generally similar to the trajectories from previous simulations [24]. The optimized trajectory takes a more northerly trajectory, avoiding a flyover of the Solomon Islands, and flying over a sparsely populated area of Siberia rather than Canada, reducing population flyover. The impact of population flyover on this trajectory is relatively small, allowing significant optimization of the secondary objective; minimization of the integrated heat load.

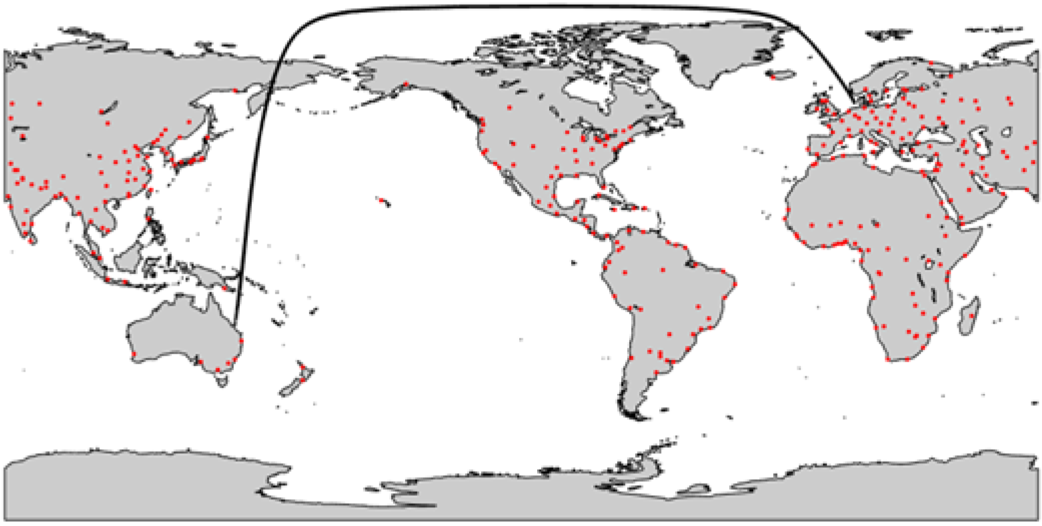

Figure 18: Potential groundtrack of SpaceLiner 7-3 nominal passenger mission Australia - Europe considering population density [25]

5.2. SpaceLiner additional missions

Considering the large market potential an ultrafast mission from East Asia to Europe is highly interesting. However, launching from mainland China or Korea is difficult due to the local geography and large population concentrations complicating the flight path of the SpaceLiner, which must avoid population flyover as much as possible. Assuming the same European launch and landing site it is not easy to find a counterpart in the far eastern region. A potentially feasible option for the site could be in the Japanese Sea from which also the Trans-Pacific route to America could be served (Figure 19). The Europe – East Asia trajectory passes over Kamchatka Krai and the Chukotka region of Russia during descent, producing overpressures between 27.4 - 54.5 Pa on the ground [25]. This overpressure range is high, with the potential for major annoyance in significant portions of the overflown population. However, the overflown region is sparsely populated, with only a handful of small towns potentially affected.

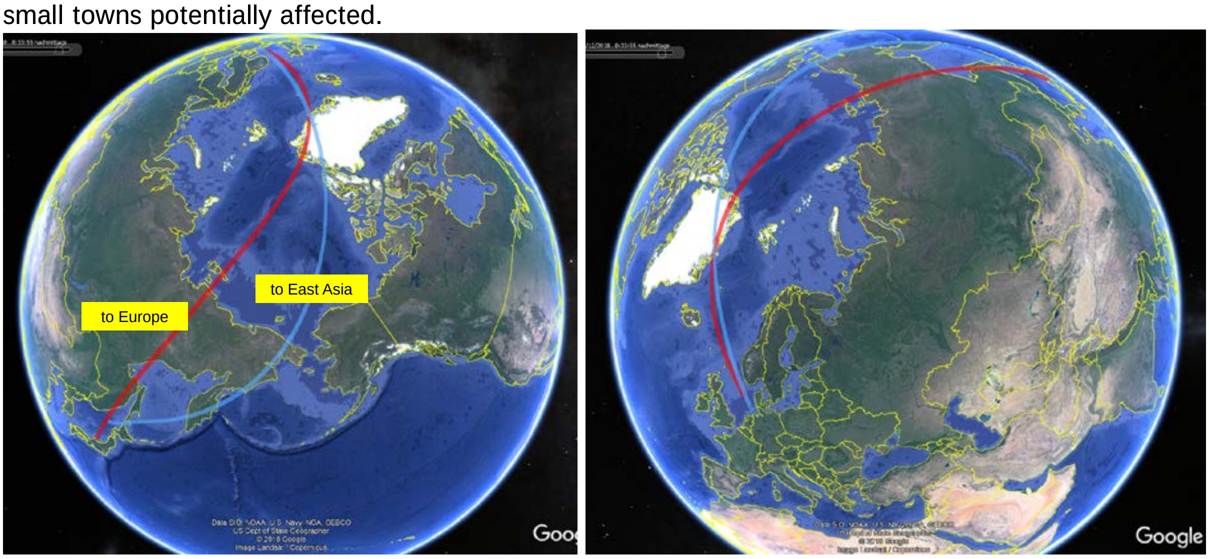

Figure 19: Potential groundtracks of SpaceLiner 7-3 nominal passenger missions Europe to East-Asia

The flight route from Australia to North-East America is found even more difficult and challenging to be achieved under similar constraints. Although it is possible to reach the East Coast of the United States, either approaching from the north or the south, the assumed potential launch sites for return trajectories were not suitable to complete the mission. The proposal for a new launch site on the west coast of Florida seems to be most promising for the North East America – Australia mission. This flight path (blue line in Figure 20) results in overpressures of up to 74.7 Pa over populated regions in Mexico [25]. This level of sonic boom overpressure may produce large levels of annoyance in the overflown population which probably cause this mission to be infeasible as described. The flight time for this mission is 1 hour and 4 minutes. The optimal flight path from Florida to Australia passes over populated areas of southern Texas and northern Mexico (red line in Figure 20). However, the altitude during this flyover in the early phase of the trajectory is high, and the effect of sonic booms on the ground is relatively low. The maximum overpressure produced on the ground during this trajectory is 18.3 Pa [25]. This is within the acceptable range, projected to produce annoyance in 1 to 5 percent of the population. The flight time of this mission is 1 hour and 3 minutes. However, this option might cause problems during the propulsive ascent phase over a highly traffic loaded area (Gulf of Mexico) [13].

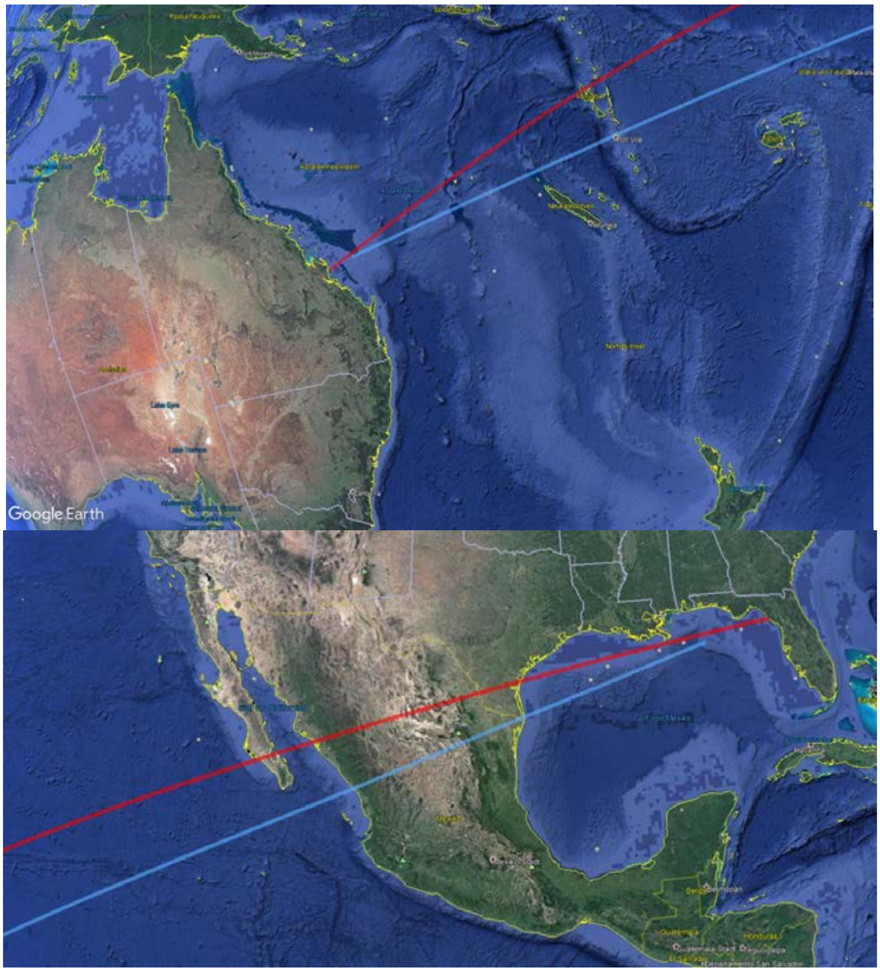

Figure 20: Potential groundtracks of SpaceLiner 7-3 nominal passenger missions Australia – USA (Florida) in both directions

5.3. SpaceLiner ascent flight control

During ascent flight the SpaceLiner trajectory is primarily controlled by the thrust vector control system (TVC). Its main task is to trim the variable position of the CoG as well as the aerodynamic moments by means of gimballing the SpaceLiner Main Engines. Based on the developed SpaceLiner model a simulation study has been concluded investigating the flight dynamics of the SpaceLiner on the reference mission from Australia to Europe. Besides the determination of the undisturbed ascent trajectory, this study considers also simulation cases with atmospheric disturbances. As shown in [14], the maximum vertical deflections are limited to ±2.5° while the lateral deflection angles remain below ±0.6°. Crosswinds are significantly increasing the necessary deflections for roll control, raising the lateral deflection range up to ±1.4° in the disturbed simulation cases. However, these deflection angles are far below the gimbal limit of ±8.5° of typical rocket engines providing good control margins. The positioning accuracy of the SpaceLiner during disturbed ascent flights remains in a similar range as for the nominal case. For the general mission success these accuracies can be considered as non-critical as they are in the same order of magnitude as the vehicle's dimensions [26].

6. Conclusion

The DLR proposed reusable winged rocket SpaceLiner for very high-speed intercontinental passenger transport has successfully completed its Mission Requirements Review (MRR) and is progressing in its conceptual design phase. Research on the vehicle has been performed with support from several EU-funded projects with numerous European partners. 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 passenger rescue capsule, designed to be used in cases of extreme emergencies, has been further elaborated and major subsystems have been defined. Sophisticated CFD-calculations have been performed which allow a better understanding of the challenging aerothermal environment. Multibody simulation models of the emergency capsule separation have been set up and a first set of simulations has been performed. The design of the cabin and the ejection system will be refined in a systems engineering approach to obtain a feasible and viable solution.

The improved design of the capsule integration and separation sequence will lead to the next iteration step, the SpaceLiner 8, in a similar way as the adaptation of the large unmanned booster stage, currently under way.

Potential worldwide flight routes under realistic operational and environmental constraints are under investigation considering advanced optimization, flight control, and guidance methods. Simulated 6DOF ascent trajectories demonstrate the robust behavior of the Thrust Vector Control system showing significant margins even in case of wind and gusts interacting with the winged configuration.

Acknowledgements

The authors gratefully acknowledge the contributions of Ms. Carola Bauer, Ms. Mona Carlsen, Ms. Elena Casali, Ms. Nicole Garbers, Ms. Carina Ludwig, Ms. Sarah Lipp, Ms. Olga Trivailo, Ms. Cecilia Valluchi, Mr. Alexander Kopp, Mr. Ryoma Yamashiro, Mr. Jascha Wilken, Mr. Magni Johannsson, Mr. David Gerson, Mr. Jochen Bütünley, Mr. Sven Krummen and Mr. Tobias Schwanekamp to the analyses and preliminary design of the SpaceLiner.

References

1. Musk, E.: Making Life Multi-Planetary, in *NEW SPACE*, VOL. 6, NO. 1, 2018 DOI: 10.1089/space.2018.29013.emu
2. Sippel, M.; Stappert, S.; Koch, A.: Assessment of Multiple Mission Reusable Launch Vehicles, IAC-18-D2.4.04, 2018
3. Sippel, M., Klevanski, J., Steelant, J.: Comparative Study on Options for High-Speed Intercontinental Passenger Transports: Air-Breathing- vs. Rocket-Propelled, IAC-05-D2.4.09, October 2005
4. Sippel, M., Klevanski, J., van Foreest, A., Gülhan, A., Esser, B., Kuhn, M.: The SpaceLiner Concept and its Aerothermodynamic Challenges, 1st ARA-Days, Arcachon July 2006
5. Sippel, M.: Promising roadmap alternatives for the SpaceLiner, Acta Astronautica, Vol. 66, Iss. 11-12, (2010)
6. Trivailo, O. et.al.: SpaceLiner Mission Requirements Document, SL-MR-SART-00001-1/2, Issue 1, Revision 2, SART TN-005/2016, 11.07.2016
7. Sippel, M.; Schwanekamp, T; Trivailo, O; Kopp, A; Bauer, C; Garbers, N.: SpaceLiner Technical Progress and Mission Definition, AIAA 2015-3582, 20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Glasgow, July 2015
8. Sippel, M.; Schwanekamp, T.: The SpaceLiner Hypersonic System – Aerothermodynamic Requirements and Design Process, 8th European Symposium on Aerothermodynamics for Space Vehicles, Lisbon, March 2015

9. Schwanekamp, T.; Bauer, C.; Kopp, A.: The Development of the SpaceLiner Concept and its Latest Progress, 4TH CSA-IAA CONFERENCE ON ADVANCED SPACE TECHNOLOGY, Shanghai, September 2011
10. Van Foreest, A. , Sippel, M.; Gülhan, A.; Esser, B.; Ambrosius, B.A.C.; Sudmeijer, K.: Transpiration Cooling Using Liquid Water, Journal of Thermophysics and Heat Transfer, Vol. 23, No. 4, October–December 2009
11. Reimer, Th.; Kuhn, M.; Gülhan, A.; Esser, B.; Sippel, M.; van Foreest, A.: Transpiration Cooling Tests of Porous CMC in Hypersonic Flow, AIAA2011-2251, 17th International Space Planes and Hypersonic Systems and Technologies Conference, 2011
12. Schwanekamp, T.; Mayer, F.; Reimer, T.; Petkov, I.; Tröltzsch, A.; Siggel, M.: System Studies on Active Thermal Protection of a Hypersonic Suborbital Passenger Transport Vehicle, AIAA Aviation Conference, AIAA 2014-2372, Atlanta, June 2014
13. Sippel, M., Trivailo, O., Bussler, L., Lipp, S., Kaltenhäuser, S.; Molina, R.: Evolution of the SpaceLiner towards a Reusable TSTO-Launcher, IAC-16-D2.4.03, September 2016
14. Sippel, M.; Bussler, L.; Kopp, A.; Krummen, S.; Valluchi, C.; Wilken, J.; Prévereaud, Y.; Vérant, J.-L.; Laroche, E.; Sourgen, E.; Bonetti, D.: Advanced Simulations of Reusable Hypersonic Rocket-Powered Stages, AIAA 2017-2170, 21st AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 6-9 March 2017, Xiamen, China
15. Kopp, A.; Sippel, M.; Stappert, S.; Darkow, N.; Gerstmann, J.; Krause, S.; Stefaniak, D.; Beerhorst, M.; Thiele, T.; Gülhan, A.; Kronen, R.; Schnepper, K.; Briese, L.E.: FORSCHUNG AN SYSTEMEN UND TECHNOLOGIEN FÜR WIEDERVERWENDBARE RAUMTRANSPORTSYSTEME IM DLR-PROJEKT AKIRA, DLRK 2017 München
16. Sippel, M., Wilken J.: Preliminary Component Definition of Reusable Staged-Combustion Rocket Engine, Space Propulsion 2018, Seville, May 2018
17. Sippel, M.; Schwanekamp, T.; Ortelt, M.: Staged Combustion Cycle Rocket Engine Subsystem Definition for Future Advanced Passenger Transport, Space Propulsion 2014, Cologne, Germany, May 2014
18. Sippel, M.; Bussler, L; Krause, S.; Cain, S.; Stappert, S.: Bringing Highly Efficient RLV-Return Mode "In-Air-Capturing" to Reality, HiSST 2018-1580867, 1st HiSST: International Conference on High-Speed Vehicle Science Technology, Moscow, November 2018
19. Valluchi, C.; Sippel, M.: Hypersonic Morphing for the SpaceLiner Cabin Escape System, 7th European Conference for Aeronautics and Space Sciences (EUCASS), Milan 2017
20. Bonetti, D.; Sippel, M.; Laroche, E.; Gambacciani, G.: From MDO to detailed design of Hypersonic Morphing Cabin Escape Systems, 7th European Conference for Aeronautics and Space Sciences (EUCASS), Milan 2017
21. Laroche, E.; Prévereaud, Y.; Vérant, J.-L.; Sippel, M. ; Bonetti, D.: Micro-Aerothermodynamics Analysis of the SpaceLiner Cabin Escape System along Atmospheric Re-entry, 7th European Conference for Aeronautics and Space Sciences (EUCASS), Milan 2017
22. Stappert, S.; Sippel, M.; Bussler, L.; Wilken, J.; Krummen, S.: SpaceLiner Cabin Escape System Design and Simulation of Emergency Separation from its Winged Stage, AIAA 2018-5255, 22nd AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 17-19 September 2018, Orlando, Florida, USA
23. Bauer, C.; Kopp, A.; Schwanekamp, T.; Clark, V.; Garbers, N.: Passenger Capsule for the SpaceLiner, DLRK-paper, Augsburg 2014
24. Casali, E.; Bussler, L.; Sippel, M.: Investigation of feasible flight trajectories and re-entry atmospheric guidance for SpaceLiner 7, SART-TN014/2015, 2016
25. Wilken, J.: SpaceLiner System Specification Document, SL-SS-SART-00026-1/1, SART TN-003/2018
26. Krummen, S.; Sippel, M.: EFFECTS OF THE ROTATIONAL VEHICLE DYNAMICS ON THE ASCENT FLIGHT TRAJECTORY OF THE SPACELINER CONCEPT, (DOI: 10.1007/s12567-018-0223-7), accepted for publication in CEAS Space Journal, 2018