



Systematic Assessment of SpaceLiner Passenger Cabin Emergency Separation Using Multi-Body Simulations

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Abstract

The SpaceLiner ultra-high-speed rocket-propelled passenger transport is in Phase A conceptual design. 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 with expendable upper stages are investigated.

In the central part of the paper, the separation of the passenger cabin and rescue capsule and its subsystems is systematically investigated for relevant emergency conditions. The separation process is studied taking into account multi-body dynamics of the up to 3 vehicles. A critical assessment of the baseline procedure and potential improvements of components' design and sequences are discussed.

Keywords: *SpaceLiner, RLV, passenger cabin, multi body simulation*

Nomenclature/Acronyms

CAD	computer aided design	SLB	SpaceLiner Booster stage
CFD	Computational Fluid Dynamics	SLC	SpaceLiner Cabin
CRS	Cabin Rescue System	SLME	SpaceLiner Main Engine
DOF	Degrees of Freedom	SLO	SpaceLiner Orbiter stage
GLOW	Gross Lift-Off Mass	SLP	SpaceLiner Passenger stage
LH2	Liquid Hydrogen	SSME	Space Shuttle Main Engine
LOX	Liquid Oxygen	TPS	Thermal Protection System
MRR	Mission Requirements Review	TSTO	Two-Stage-To-Orbit
RCS	Reaction Control System	TVC	Thrust Vector Control
RLV	Reusable Launch Vehicle		

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 rocket 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 Starship&SuperHeavy (formerly called 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 - 10, 16, 17]. 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 the project FALCon addresses the advanced return recovery mode "in-air-capturing" to be used by the reusable booster stage [20, 21]. The way how such hypersonic point-to-point transports like SpaceLiner are to be integrated in future controlled airspace is addressed in the SESAR-project ECHO. The SpaceLiner is one of the reference concepts and feasible intercontinental trajectories are refined in DLR-SART analyses [22].

An important milestone was reached in 2016 with the successful completion of the Mission Requirements Review (MRR) which allows the concept to mature from research to structured development [16]. The Mission Requirements Document (MRD) [6] is the baseline and starting point for all technical and programmatic follow-on activities of the SpaceLiner Program.

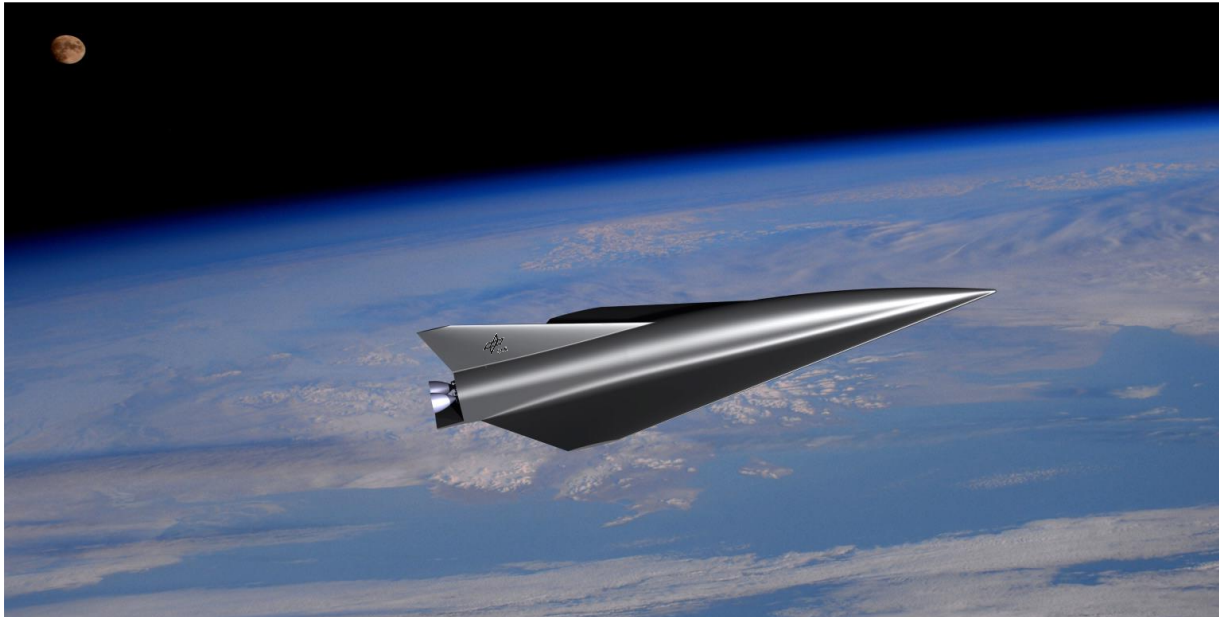


Figure 1: Rendering of SpaceLiner 7-3 upper stage in high altitude gliding flight over Alaska

1.1. Impact of "Corona-Crisis"

Also the SpaceLiner investigation and preliminary subsystem development has been severely hit by the "Corona-Crisis". The last paper exclusively dedicated to the concept was reference [10] and the current paper providing the next updated overview was planned to be published only half a year later in April 2020 at the original date of the 2nd HiSST-conference. Due to the overall pandemic situation with its restrictions, many conferences including HiSST were postponed several times.

The traditional SpaceLiner Design Workshop continuously held each year from 2010 onward (initiated with the FAST20XX-project) until 2019 had to be cancelled in 2020 because of the severe physical-meeting restrictions at DLR. Not only the dedicated workshops but also progress meetings of supporting EC-funded projects were not organized in personal presence. Online meetings as substitute were focusing on the most urgent next project actions and did not allow any fruitful exchange on new ideas or technologies. In November of 2021 the 11th Design Workshop was organized as a short afternoon event with strictly limited participation.

The lack of personal meetings and the necessity to focus resources to other high-priority projects with difficult online conferences have slowed the definition of the SpaceLiner 8 configuration. Nevertheless, remarkable progress can be reported in this paper.

2. SpaceLiner 7 architecture, geometry and main components

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

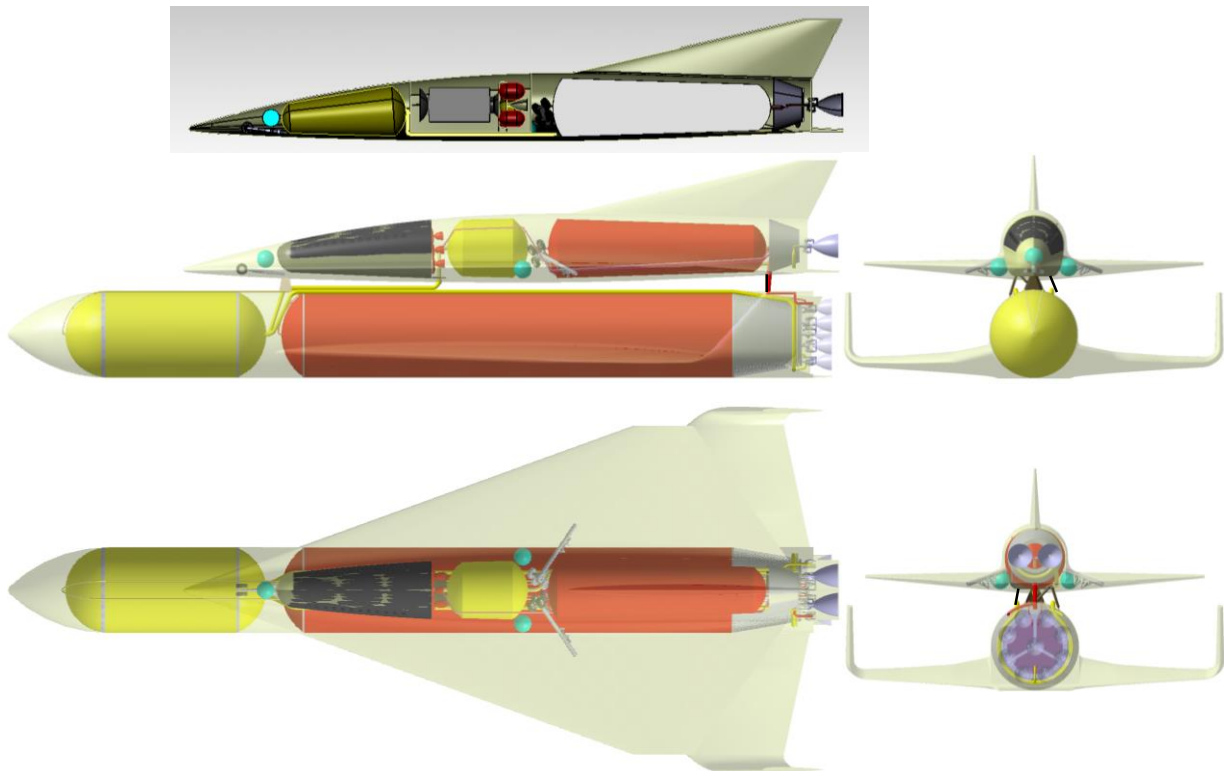


Figure 2: Sketch of SpaceLiner 7-3 launch configuration with passenger version (SLP) with its booster stage at bottom position and orbital stage of SLO in insert at top

2.1. 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). It is interesting to note that the ambitious full-flow cycle is currently developed by SpaceX for its Starship&SuperHeavy with the Raptor-engine [32]. This concept is in some aspects a similar multiple mission reusable launch vehicle as SpaceLiner intends to become [9]. The Raptor engine is influenced by its interplanetary mission and hence is using a different propellant combination LOX-LCH₄ which might one day be produced in-situ on Mars.

The expansion ratios of the booster and passenger stage / orbiter SLME 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 [18].

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. The full pre-defined operational domain of the SLME is shown in [19] including extreme operating points. Table 3 gives an overview about major SLME engine operation data for the nominal MR-range as obtained by latest cycle analyses [19]. Performance data are presented for the two different nozzle expansion ratios of the SpaceLiner: 33 and 59. The latest SLME cycle analyses shows engine performance remaining overall very similar to the data previously published in [8, 18]. Vacuum Isp-data of both tools are very close with relative difference less than 0.5%. At sea-level conditions the largest deviations could reach up to -1.5%.

Table 3: SpaceLiner Main Engine (SLME) technical data from numerical cycle analysis [19]

Operation point	O1		O2		O3	
Mixture ratio [-]	6		6.5		5.5	
Chamber pressure [MPa]	16		16.95		15.1	
Mass flow rate in MCC [kg/s]	513.5		555		477.65	
Expansion ratio [-]	33	59	33	59	33	59
Specific impulse in vacuum [s]	436.9	448.95	433.39	445.97	439	450.56
Specific impulse at sea level [s]	385.9	357.77	386.13	361.5	384.2	352.6
Thrust in vacuum per engine [kN]	2200	2260.68	2358.8	2427.28	2056.7	2110.49
Thrust at sea level per engine [kN]	1943	1801.55	2101.6	1967.32	1800	1651.56

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. 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 [18, 19]. 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 [18]. The combustion in the preburners is a highly complex process involving multiple reaction elements interacting with each other at high pressures and temperatures. In order to preliminarily understand the combustion and those respective interactions, CFD simulations with a very simplified, preliminary 2D geometry of a potential SLME preburner were carried out [19]. The commercial CFD solver ANSYS CFX was used for the first series of numerical analyses.

The commercial AxSTREAM® software tool for turbomachinery analyses has been implemented. AxSTREAM® is a multidisciplinary design, analysis and optimization software platform that provides fully integrated and streamlined solutions, encompassing the complete turbomachinery design process, all in a seamless interactive user interface. The following turbomachinery components have been pre-designed: LPFTP pump and turbine, HPFTP pump and turbine and HPOTP pump and turbine. The thermodynamic parameters used for the turbomachines design correspond to the demanding operational point O2 and the SLME cycle design conditions of 2019, mostly similar to those presented in [18]. Consolidated size, mass, and performance data are available by this analysis and are integrated in the engine model.

Figure 3 shows the integration of all major components of the Integrated Power Head in the upper section of the SLME and their integration with the combustion chamber injector head. The preliminary layout from [16, 18] is maintained but in this consolidated design also considering the preliminary sizing of the regenerative cooling and of the turbopumps. The view of the SLME-33 from above in Figure 3 shows on the left the hydrogen fuel supply and on the right the oxygen flow side.

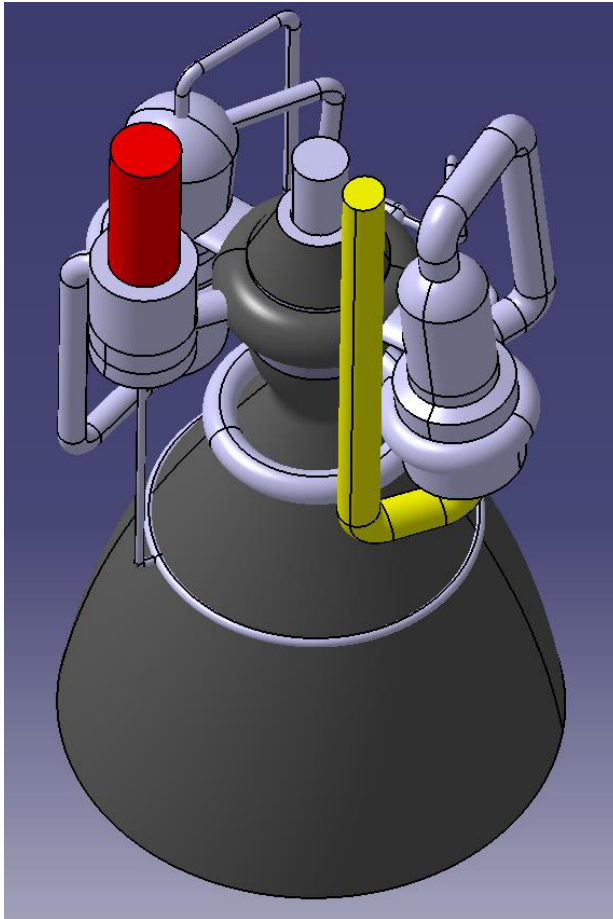


Figure 3: SLME simplified CAD geometry showing arrangement of turbomachinery

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 [18]. The HMS provides input for the engine emergency control and collection of huge operations data sets for maintenance prediction and support. Internal flow conditions, thermal and mechanical load data including vibrations can be used for automated post-flight assessment, implementing machine-learning algorithms. If such an approach is consequently followed already during development testing, a significant improvement in rocket engine reliability and robustness can be expected [19].

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 [18, 19].

2.2. 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 [8]. 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 [17]. 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 m³. 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 [18, 19].

The booster wing (and winglet) airfoils have been selected as modified NPL-EC/ECH cut at trailing edge thickness of 75 mm [11]. 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 aerodynamic lift forces are introduced.

2.3. Reusable upper stage

The SpaceLiner7 aerodynamic shape is a result of a trade-off between the optima fulfilling the requirements of three reference trajectory points. Numerical analyses have pointed out the clear advantages of a single delta wing [11, 12]. 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.

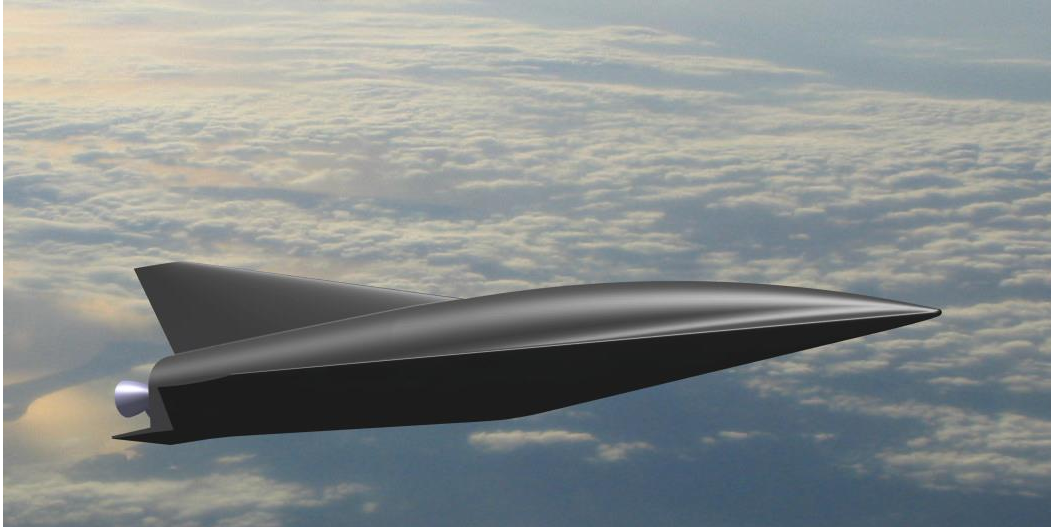


Figure 4: SpaceLiner 7-3 passenger stage

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 [11].

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, 16]. Already early in the project, transpiration cooling using liquid water has been foreseen as a potential option for solving the problem [4, 13]. 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 [14]. Test results have been scaled to full-size by heat transfer correlations and numerical assessment of the complete SpaceLiner trajectory [13]. 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 [15].

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 [15].

The passenger stage's internal design has been adapted for its secondary role as an unmanned satellite launcher. The passenger cabin (see separate section 4 below!) is not needed for this variant and is instead replaced by a large internal payload bay [16]. 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 [8]. For this purpose, 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 [16]. 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. 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.

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 7-3 lay-out [16]. 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. Nevertheless, the once-around-Earth-mission of the orbiter is not compromised as demonstrated by reentry trajectory simulations [16].

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, 15, 16]. 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 and intermediate steps

3.1. SL7 improvement potential

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 [10, 17, 23]. 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.

Both, the complicated flow of the launch configuration and the shock-shock interaction during booster reentry [8, 17] have motivated the investigation of potential geometry changes and improvements to the SpaceLiner booster wing geometry. A refined model of the tank, its cryogenic insulation and external TPS with an overall increased thickness has an impact on the available volume for propellants inside the SLB which is to be addressed to keep the mission margins.

The integration of the passenger rescue system in the nose section of the upper stage and its reliable operation in all flight conditions is another critical aspect. Systematic analyses of the separation process with the SLP7 design have been performed in selected critical flight points. A summary of these results is presented in section 4 which supports a future redesign of the passenger stage.

Currently, the study for the next SpaceLiner 8 design is still ongoing and it is too early to report a consolidated configuration. However, some key results which guide future developments are presented in the following subsections.

3.2. SLB8 with small fixed 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 had been investigated and a sketch of the concept was presented in [8]. The relatively small wing of the so called SLB8V2 turns out to be fully sufficient for a smooth reentry avoiding extreme heatloads. However, 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 even more to SpaceX' Starship. 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 turning maneuver of SLB8V2 before its intended vertical landing, as the procedure was assumed by DLR, has been described in [8]. The large propulsive moment required for a controlled pitch-turn maneuver was evaluated as a critical point for the feasibility of the concept [8].

Meanwhile, SpaceX has performed several flight demonstrations with its Starship prototype at its Boca Chica site, Texas. Five subsequent test vehicles (SN8- SN11 and SN15) were reaching at least 10000 m altitude in ascent flight before performing a controlled "sky-dive" maneuver at very low airspeed. The latter makes the major difference to the SLB8V2 assumption of aerodynamically controlled flight with dynamic pressure of at least 10 kPa. Starship is controlling by changing the dihedral deflection of both canard and main wing before rapidly performing the "belly-flop"-maneuver which brings the vehicle from almost horizontal into vertical orientation for landing. If the dynamic pressure is kept

close to 0 kPa the turn is possible by using TVC of three reignited SpaceX Raptor-engines while this was hardly achievable with realistic interpretation of SLB8V2 simulations [8]. Simulations performed by DLR for the Starship returning from space [32] show that operational dynamic pressure would be rather in the range of 3 to 6 kPa, figures also supported by SpaceX' announcement.

Although, at least the final and successful SN15 flight test of Starship can be understood as a major breakthrough, the innovative "sky-dive"- and "belly-flop"-maneuvers are highly demanding for the wing design and its control as well as the fast rocket engine reignition. Therefore, suitability of this approach also for safe and efficient operation of the SpaceLiner booster is still open for future evaluations.

3.3. SLB8 option with swept wings

As the vertical landing SLB8V2 turned out to be not very promising, alternative designs have been explored [8, 10]. It has been tried to maintain the promising hypersonic aerodynamic configuration with small fixed wings, however, in order to allow the stage to use "in-air-capturing" and horizontal landing, deployable wing options have been checked on integration and mass impact [8, 10]. The challenge of this design is finding a suitable combination of different wing shapes which achieve a sufficiently high trimmed subsonic L/D of around 6, acceptable landing speed but also being fully trimable in hypersonic flight at high-angles of attack. A partially automatic variation of parameters has been implemented in an MDA approach in order to systematically search for feasible and promising lay-outs [10]. The preliminary integration of the outer wing segment inside the inner part with its trailing edge kept open to allow the sweeping part to be stored is shown in [10]. Instead of trailing edge flaps the inner segment has separate spoilers on its lower and upper surface. Structural pre-sizing and mass estimation of the wing and the mechanisms is ongoing.

A 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 has performed systematic research on promising combinations of insulation and reentry TPS for which the SLB7-3 serves as the reference system concept. The booster stage's reusable cryogenic tank insulation has been investigated under consideration of the external TPS by numerical simulation and experiments [29, 30, 31]. The pre-selected design option includes a so-called purge gap creating a distinct gap between the insulation of the cryogenic tank and the external thermal protection system, which has to be resistant to temperatures beyond typical limits of cryo-insulations. This relatively complex combination of external TPS and cryogenic insulation has been selected in order to avoid icing even in humid and relatively cold environment [29]. In the gap a forced flow of pre-heated dry gas is providing a controlled boundary condition at the outer interface of the cryogenic insulation. Results from the DLR projects AKIRA and TRANSIENT demonstrate the reusable insulation concept is functioning, however, a mass impact on the SLB stage is expected [30, 31]. This effect is due to the increased weight per surface area but also by the reduced available volume for propellants inside the SLB because of the enlarged thermal protection thickness compared to the previous assumptions.

At the end of the AKIRA-project such an influence on the reference system has been investigated using the SLB8V3-variant already presented in [10]. Both fuselage diameter and stage length of the initial Iteration 1 were identical to the values of the SLB 7-3 design. Total span in this case is about 45.4 m, while the inner wing segment spans 25.6 m. A so-called Iteration 2 design considers a more detailed definition of the thermal protection system as well as cryogenic insulation based upon AKIRA-investigations. A TPS with external metallic surface (either Inconel or Titanium or Aluminum depending on the expected maximum temperatures) is implemented.

As a consequence, ascent propellant mass, structural mass of the tanks and the structural mass of the wing needed to be increased to maintain the same payload performance to orbit as the previous variant of [10]. The number of SLME on the SLB8 was not adapted. The stage diameter, however, was increased to 8.9 m, the stage length to 83.8 m. Ascent propellant mass increased by 120 Mg and dry mass raised to 222 Mg. Overall this concept was not really attractive.

In contrast to the Iteration 2 design where the enlarged TPS subsystem mass caused an increase of stage mass and ascent propellant mass finally leading to a very low thrust-to-weight ratio of less than 1.2, for the Iteration 3 of the SLB8 design it has been decided to add an additional, 10th rocket engine. Thrust-to-weight ratio significantly improves to approximately 1.4, thus, reduces gravity losses and requires almost no additional ascent propellant mass compared to SLB7-3.

The outer dimensions of the SLB8V3 configuration in Iteration 3 are shown in Figure 5. The fuselage diameter is increased to 8.8 m. As a consequence, the stage length reduces to 79.1 m (without body flap). Aerodynamic performance requirements of the In-Air-Capturing method lead to an increased wing size. The wing is inclined by 2.5° with respect to the fuselage rotational axis. The overall span is at 53.8 m while the mid-chord length increases to 9.9 m. Higher masses for thermal protection, propulsion and structure changes the axial center of gravity position that is calculated at $x = 57.108$ m from the nose of the booster stage in case of the outer wing segment deployed. In case of folded outer wings, the center of gravity position is calculated at $x = 57.243$ m.

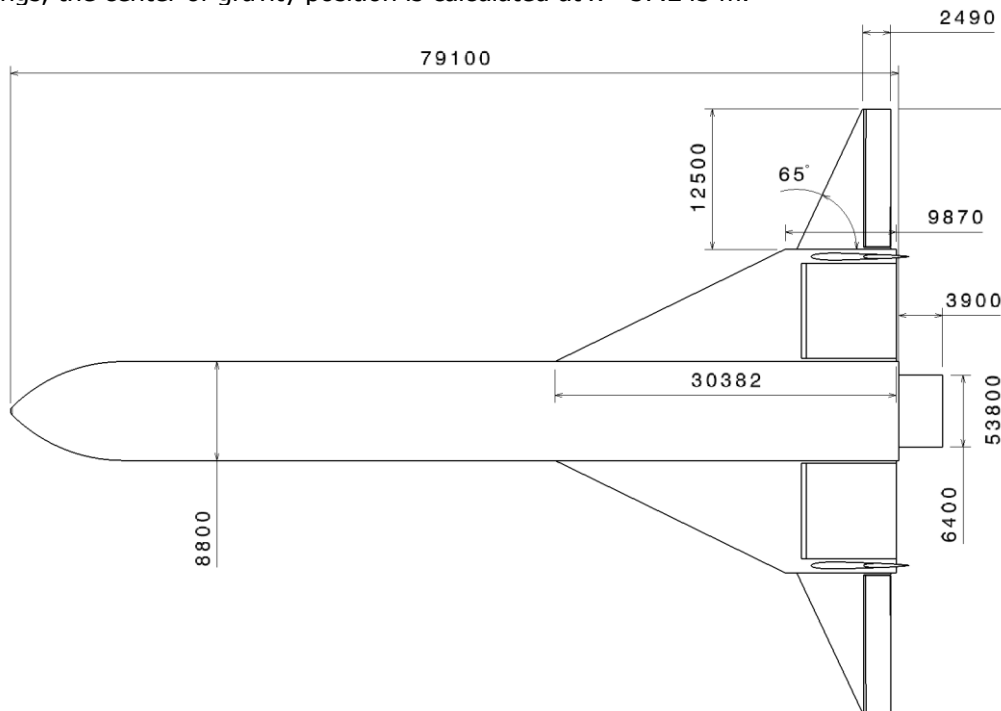


Figure 5: SLB8V3 Iteration 3 – dimensions, deployed outer wing segment

Estimated dry mass of the SLB8V3 Iteration 3 reaches 220 Mg; slightly less than for the Iteration 2. However, its significantly lower GLOW makes Iteration 3 the more robust and more compact design. Despite these advantages, more analyses are needed to define the SpaceLiner 8 booster stage.

A recent systematic numerical assessment on the heatflux peaks originating from the shock-shock interaction show that these are probably less critical for the design of the outer wing leading edge than previously assumed [28] because the estimated nominal peak temperatures are excessively pessimistic. Further, trim capabilities of the large spoilers in hypersonic flow at high angles of attack are compromised by separated flowfields. If a design similar to the one shown in Figure 5 would be chosen, a dedicated study on the spoiler efficiency would have to be performed.

3.4. Intermediate development steps before SpaceLiner

The SpaceLiner defined as a fully-reusable, multiple-mission launch vehicle with advanced rocket engines requires mastering of ambitious technologies. The European expertise of today is limited to expendable launchers with cryogenic propulsion (Ariane 5 and 6). Directly starting the development of the SpaceLiner on such basis is risky, the more as it should also operate as a safe and commercially attractive passenger transport.

During several SpaceLiner Design Workshops potential development roadmaps have been discussed. Gaining expertise with a partially reusable space transportation system in flight operations as pure

cargo carrier would be a major de-risking element before starting the commercial development of the SpaceLiner. An attractive option for such an RLV is a large reusable booster stage accelerating expendable upper stages which could be introduced as a successor to Ariane 6 after 2035.

DLR has started investigation of such launchers with the internal project name RLV-C4 [34, 35]. A systematic variation of design options on propellant choice or aerodynamic configuration has been carried-out. One concept with the SLME as the main engine serves as RLV-reference in the FALCon-project and its architecture is similar to the SLB8V3 (Figure 5), however, with significantly reduced propellant loading (380 Mg) and only four SLME [35].

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.

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 future changes. A systems-engineering approach shall be used to obtain a feasible and viable solution for the design of the capsule separation system. Results from the first step analyses are summarized in the following subsections. 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 [6, 16], the achievable mission safety levels need to be demonstrated in the ongoing Phase A development.

4.1. SLC7 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 [17].

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, 16, 26]. 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 passenger stage (SLP). The SLC lower section is clamped within the SLP without any load carrying structural connection (see e.g. [17]) 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 early to utilize a five-motor configuration with very short cylindrical section. By the use of innovative multi-nozzle motors, expansion ratio could reach $\varepsilon = 21$ while at the same time the total length and required volume decreased compared to earlier single nozzle concepts (Figure 6). Each motor has an approximate sea-level thrust of 870 kN and a burn time of almost 2 s. The solid rocket motors are using a mixture of 68% AP, 20% aluminum and 12% HTPB as propellant [25]. The maximum thrust with a chamber pressure of 15 MPa is around 856 kN at sea-level ($I_{sp} = 267$ s) and

908 kN ($I_{sp} = 290$ s) in vacuum. The total mass per motor is approximately 693 kg leading to a total mass for all motors of 3.47 tons.

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 require a web-like design comparable to those in military missiles. Thus, hot combustion gas should easily reach each of the nozzle entries.

Beyond the separation motors which should accelerate the SLC in case of extreme emergencies away from the SLP vehicle, the current integration in the fuselage requires a short pitch-up maneuver. The pitch motor is preliminarily defined by the separation studies and consideration of acceptable acceleration levels of passengers sitting in the forward section with a thrust of 240 kN operating for approximately 0.4 s [36].

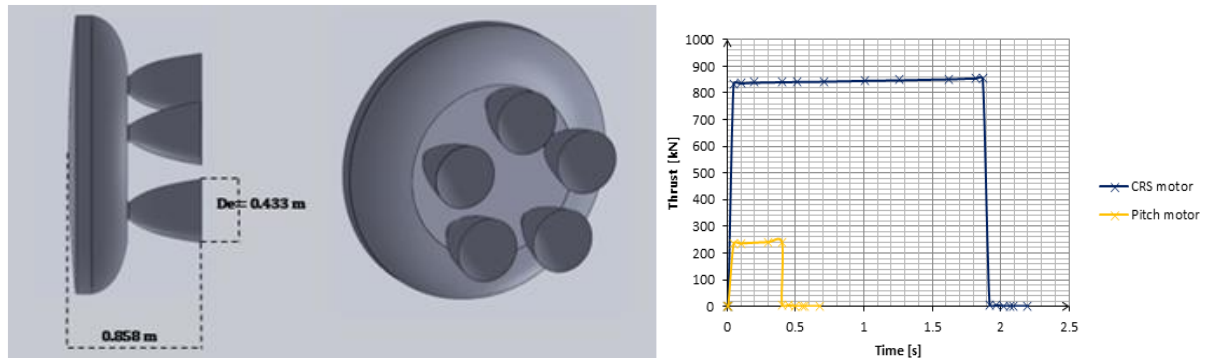


Figure 6: SLC separation motor in multiple nozzle baseline [25] (left), sea-level thrust profiles of SLC motors [36] (right)

A preliminary design for the capsules main subsystems has been elaborated [17, 24]. 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 H₂O₂ (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 [17, 24].

The principal feasibility and flyability of an innovative morphing structure concept on the capsule has been demonstrated by numerical simulations within the HYPMOCES project [8, 17, 24]. 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 are to be justified by significantly improved passenger safety [17].

4.2. SLC7 integration in passenger stage and separation process

The high-level safety requirement of the MRD indirectly calls for a safe separation from ground launch pad operations through the full flight mission [6, 16]. Capsule separation being feasible at any flight condition and attitude is highly challenging from a technical point of view.

A rigid connection of SLC with the passenger stage's forward fuselage is avoided so that cutting of load-carrying structural elements e.g. by pyrotechnic charges is not necessary. Thus, the SLC is supported on its lower and aft surface but is free to expand in forward and upward direction within the stage. Flexible sealings assure that hot gases can't enter during hypersonic flight into the vehicle at the interfaces but having only marginal drag effects during the separation process.

A preliminary separation process of the baseline SLC has been studied already quite early [26]. The capsule would have first to be slightly pushed forward axially to enable the SLC to be tilted upwards without colliding with the SLP tank structure. This maneuver is to be performed by the solid pitch-up motor located close to the capsule's nose on its bottom side. Then, the five separation motors would be ignited accelerating the SLC away from the SLP. This preliminary analysis shows that an ejection of the capsule requires jettisoning a forward cover section of the upper fuselage (called CRS door in Figure 7). 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.

The relatively complex separation process of the baseline SLC integration is under debate since several years. The realization could become the more challenging when considering hypersonic flow with transient shock-boundary layer interactions during a significant portion of the trajectory. Prerequisite for any potential improvement is a good understanding of all the challenges and constraints along the complete mission under all relevant conditions. A systematic assessment of SpaceLiner cabin emergency separations in several critical flight environments provides a good database.

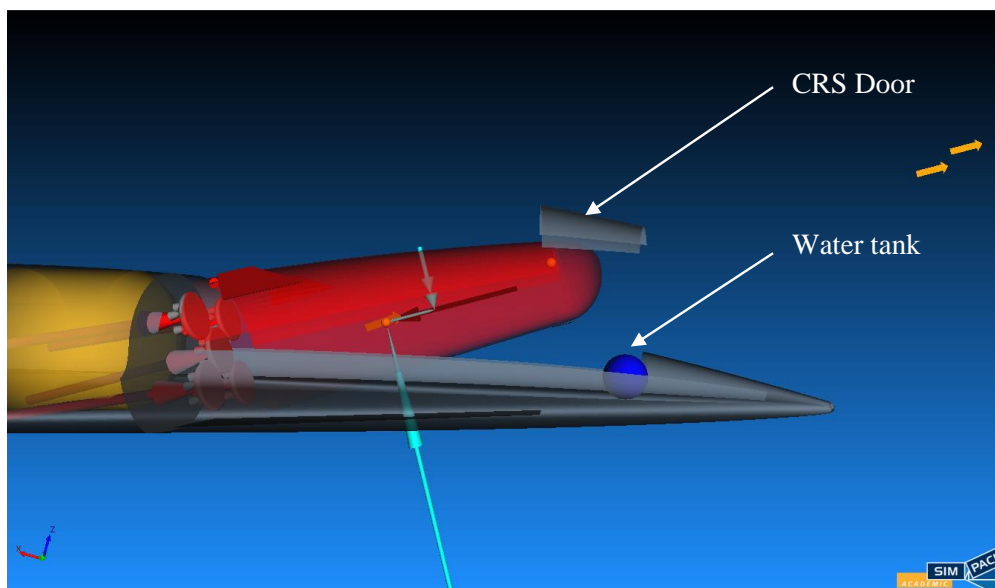


Figure 7: SLC early in separation phase (Concept A) [36]

4.3. Multi-body simulation of SLC separation

Multi-body 6DOF-simulations using Simpack have been set up for the analyses of the baseline SLC integration Concept A as shown in Figure 7 for which a consolidated pre-design with extensive data sets is available [9, 10]. The geometrical model was taken from the respective SpaceLiner CATIA model and is shown in its Simpack simplification in Figure 8. The CRS is colored bright red.

A multi-body simulation is a dynamic model of a real system consisting of several elements. These are simplified to bodies with mass and inertia and connectors without these properties. The six degrees of freedom for a single body can be limited by joints. For the SLC simulation only rigid bodies have been used [36]. The three main or primary bodies SLC, SLP and SLB are not connected by joints to each other to allow free motion and calculate independent trajectories in case of separation. Secondary bodies are connected to their respective primary ones by 0-DOF-joints, not contributing to the multi-body integration. Such bodies like tanks, stabilizers etc. serve for visualization purposes but also to detect structural collisions [36]. The force elements can be divided into contact forces, aerodynamic forces and forces imposed by the separation motors.

The tool Simpack, formerly developed in DLR but now available as a commercial product, is a general-purpose Multi-body Simulation (MBS) software used for the dynamic analysis of any mechanical or mechatronic system.

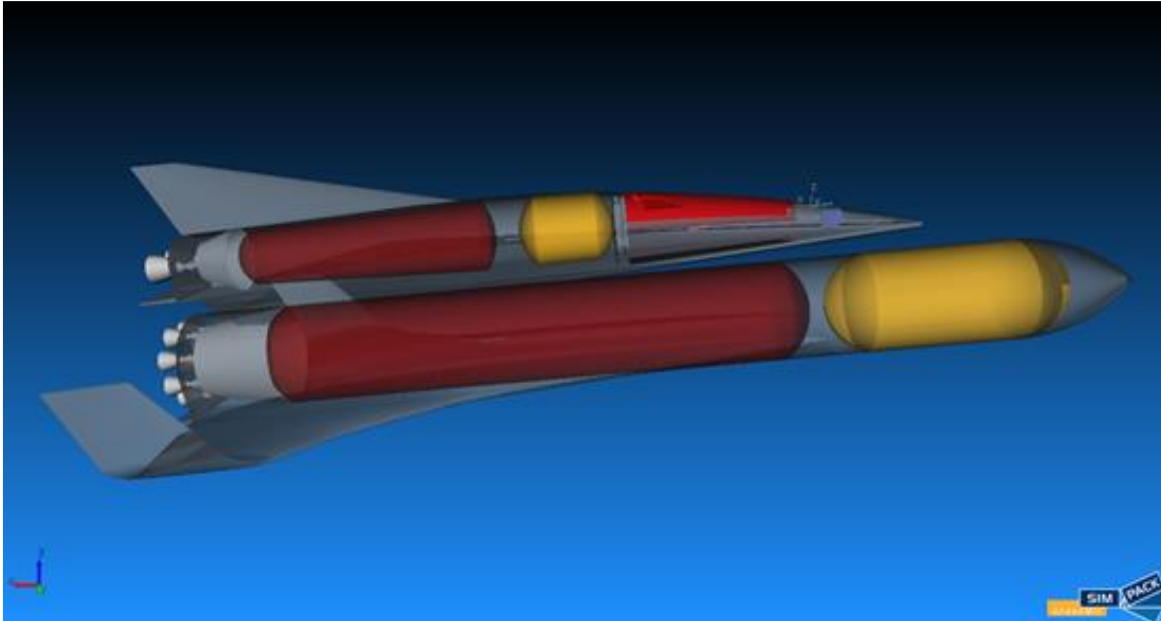


Figure 8: Three-dimensional visualization of the primary and secondary bodies of the multi-body simulation

4.4. Modelling assumptions and simulation constraints

The mass models of the SpaceLiner and all its main components are available not only for dry condition but also including the propellant filling levels along the mission. Therefore, the total or component masses, center of gravity positions, and inertia matrices can be calculated at any flight point at which the separation maneuver should be initiated. However, the Simpack software has one major restriction: any further time-dependent changes of mass or inertia cannot be included within simulations. In most technical systems with dynamic multi-body movement the mass and inertia are constant or changes are very small during the relatively short periods simulated. Differently in rocket propelled systems: the high mass flow of rocket motors (e.g. 3.5 tons ejected in 2 s by the separation motors) cause a major change in mass and inertia of the SLC. Unfortunately, it has not been possible to implement this effect in Simpack. The corresponding shift in CoG-position could be simulated indirectly by the addition of secondary bodies.

External forces from rocket engines like the pitch-up and separation motors (Figure 6) or the RCS thrusters including their actuation times are fully modelled including the thrust vector. The main propulsion system with SLME has been assumed in this first systematic assessment being completely shut-down. This simplification makes sense for this study in order to decouple from the effects of abnormal engine behaviour.

The aerodynamic data sets are complete for all three vehicles SLC, SLP, SLB in the relevant Mach- and in a very large AoA-range. Correct application of the coefficients and subsequent calculation of aerodynamic forces by Simpack has been carefully checked [36]. However, the calculated coefficients are still simplified because produced by fast aerodynamic engineering tools. Further, any flow interference of the three bodies has been completely neglected. This is due to the nature of the engineering tools which are unable to consider such flow interactions. An accurate simulation of the transient flow conditions during the early separation phase is computationally expensive. Therefore, it has been decided to focus initially on trade-offs based on simplified aerodynamic data and identify the critical points to be addressed. Based on this first round of numerical studies, an improved understanding of system requirements can be derived which should allow to study alternative, potentially better design and integration options.

Contact forces between the separate bodies are calculated within Simpack. However, the type of contact and its position on the body is to be specified. The SLC is supported at its rear and at the bottom of the passenger stage SLP. The structural design of the components and material choice is not fixed yet. As simplified assumption, any penetration is excluded and elastic coupling is prohibited.

4.5. Results from multi-body simulations of SLC7 separation

In the first step, five abort cases with SLC ejection along the nominal operational flight have been analyzed with multi-body simulations:

- Launch pad abort prior to lift-off with zero altitude and zero velocity
- Maximum dynamic pressure in transonic flow conditions (29.8 kPa at Mach 1.37 in 10995 m)
- SLB separation (Mach 12.33 in 76774 m)
- MECO of SLP (Mach 25.39 in 76087 m)
- Maximum heat flux re-entry (Mach 13.95 in 54218 m)

Initial conditions are used in all cases from the nominal passenger flight simulations without assuming any degradation in flight path or attitude due to anomalies. Obviously, this is a major simplification of potential emergency situations and is not reflecting a worst-case scenario. However, the latter is not intended and these trade-offs serve in the definition of system requirements in the Phase A analyses and are not to be confused with future CRS qualification or certification.

The emergency ejection on the launch pad is a separation system design driver of the separation motors because of the requirement to rapidly escape the huge detonation potential of the propellant loading in the completely filled tanks and further to reach sufficient altitude for subsequent parachute landing in a safe distance. The visualization of the simulated separation procedure depicted in Figure 9 shows SLC ejection at the launch pad with zero altitude and zero velocity of the SpaceLiner. After the nose tilt-up, the outboard separation motors are ignited within 0.1 seconds after ignition of the center motor. The solid rockets burn until approximately 2.1 s at a distance to the launcher of 170 m. After burn-out the capsule follows a ballistic trajectory stabilized and oriented by RCS.

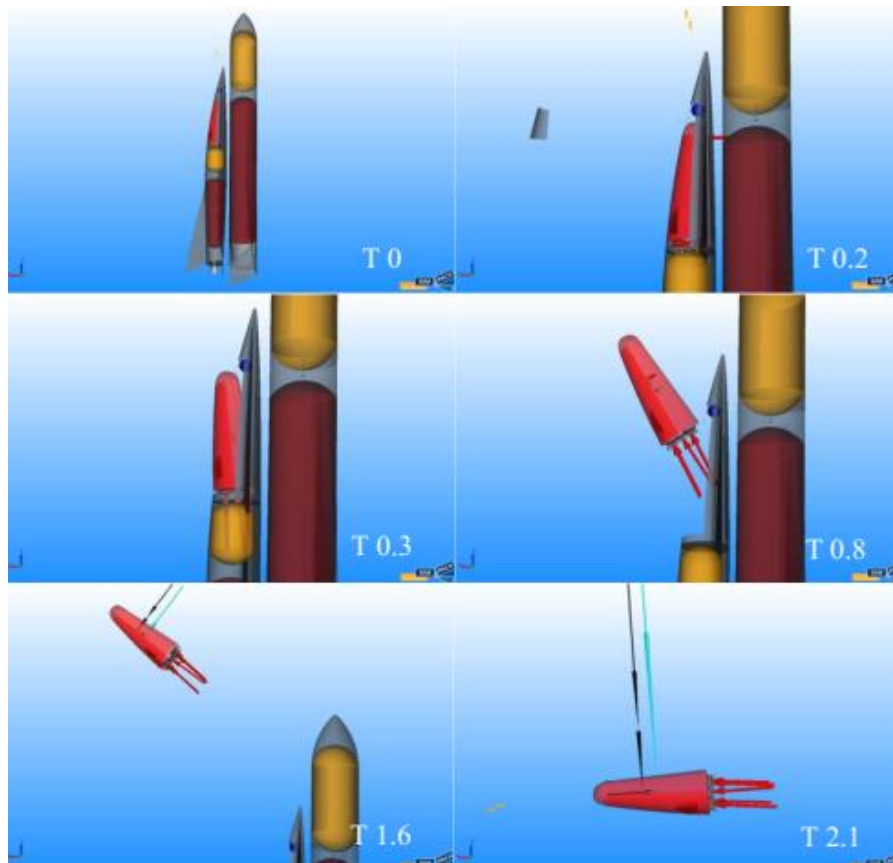


Figure 9: Multi-body simulation of SLC separation at launch pad with time in s after initiation [36]

In the launch pad abort simulations, the SLC is climbing to an apogee slightly above 300 m which is below the requirements and might become challenging for a safe and controlled parachute landing. One of the reasons for this situation is the initial mass of the SLC, incorrectly kept constant due to Simpack modeling restrictions. Further, the drag generated by the rotating cabin is higher than necessary. Nevertheless, this is one of the critical points to be addressed in future SLC refinements.

Separation of the cabin from the passenger stage in hypersonic re-entry gliding flight is shown in Figure 10. The SLC movement is dynamically stable and oscillates with relatively high amplitude. This result is due to the initial pitching moment created by the separation motors producing an unnecessarily high angle of attack for this case. A relatively simple option for improvement would be igniting only part of the solid motors because rapid distancing of the cabin from the stage is no longer required as it was in the early ascent phases due to the now low explosion potential.

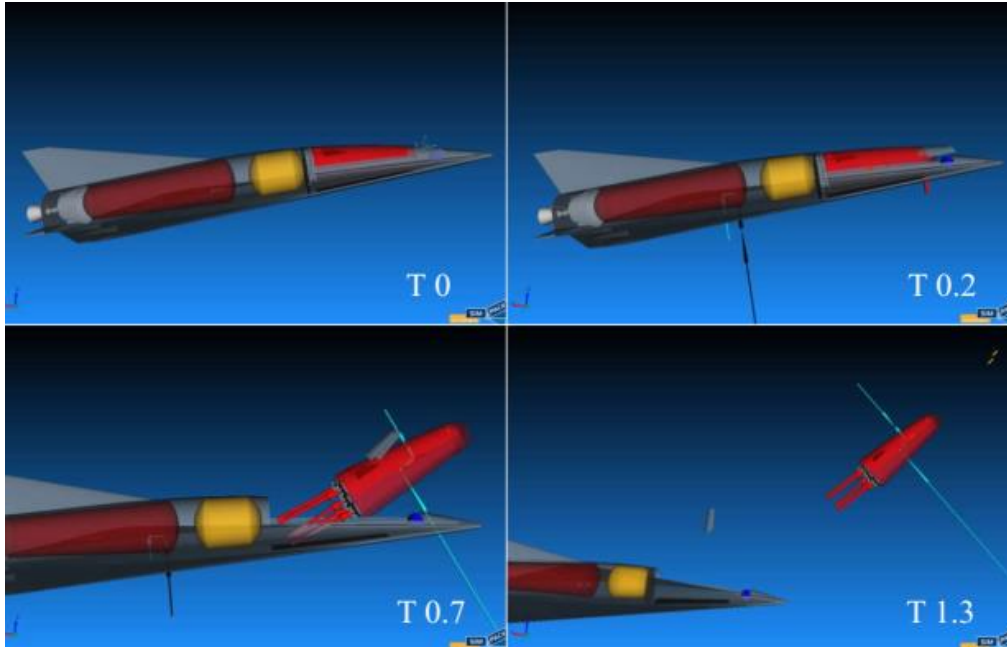


Figure 10: Multi-body simulation of SLC separation at max. heat flux during re-entry with time in s after initiation [36]

Beyond visual animations and videos of the movement or collision of the multiple bodies, Simpack saves the load and trajectory data in tabulated form to be used in further analyses. Of key-interest are the loads acting on the passengers during the emergency separation or immediately afterwards. Figure 11 is presenting the axial accelerations acting on seat rows in the most forward and most aft position of the SLC depending on the separation conditions of the five cases. After the nose tilt-up of about 0.2 s, the outboard separation motors are ignited within 0.1 seconds after ignition of the center motor and burn for about 2 seconds. Around 0.4 s after initiation of the process approximately 12 g are reached with burn duration of 2 s and in case of the aft row, very short peaks even approach up to 14 g. With the motors burn-out the acceleration levels are sharply reduced, nevertheless, in some cases oscillating around $\pm 2g$ due to SLC rotation and the effect of aerodynamic forces. Attitude changes are already damped in the simulations shown in Figure 11 by controlled firing of RCS. Minimization of resulting loads, however, has not been pursued.

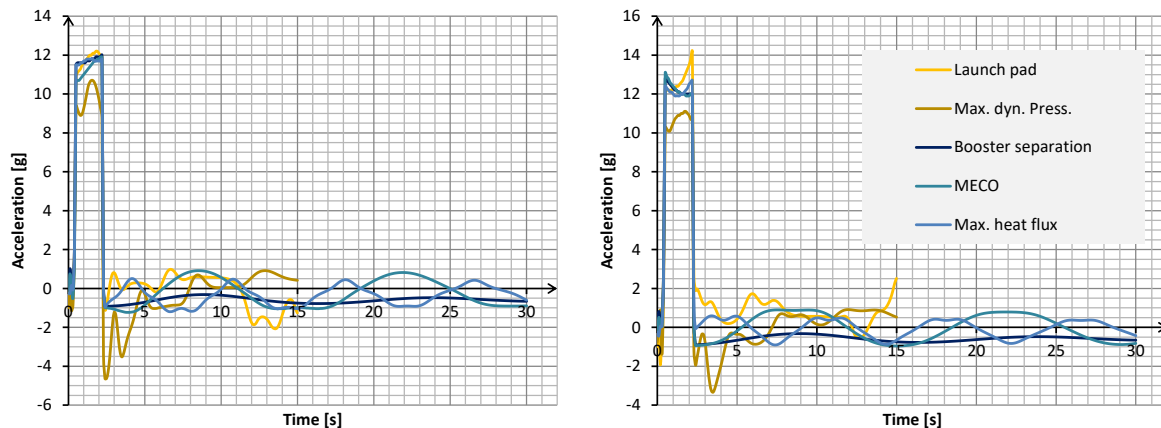


Figure 11: Axial acceleration (n_x) acting on fwd. seat (left) and aft seat (right) obtained by Simpack simulations for different SLC separation cases [36]

Medical investigations of NASA had demonstrated in the past that even untrained passengers will endure such elevated acceleration levels for a short time if pushed back into their seats (“eyeballs in”) and somehow less in the opposite direction (“eyeballs out”) corresponding here to negative n_x .

The human body is more sensitive to normal acceleration levels, pressed downward into the seats, the latter corresponding to negative n_z . While the extreme medical limits were not visible in the axial plots, these limits are included in the normal acceleration plots (Figure 12) as horizontal lines for load durations of 1 or 2 seconds.

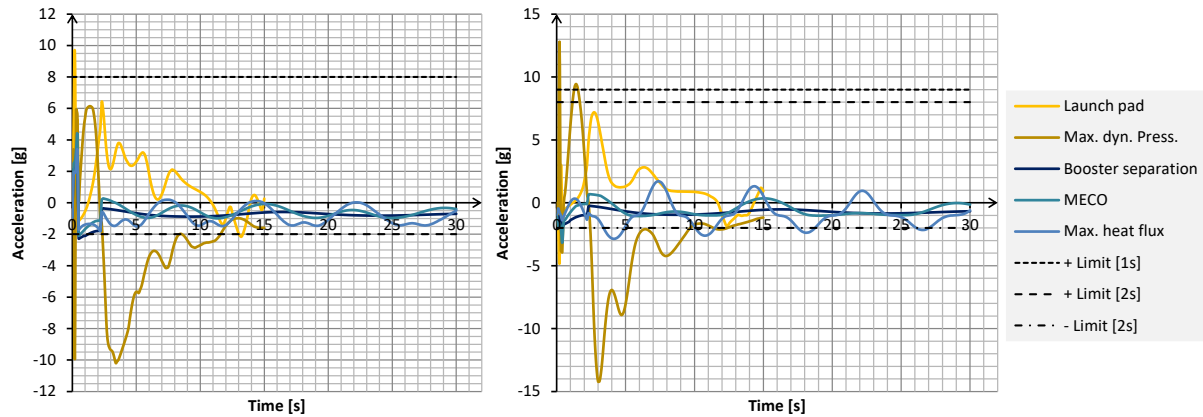


Figure 12: Normal acceleration (n_z) acting on fwd. seat (left) and aft seat (right) obtained by Simpack simulations for different SLC separation cases [36]

Note that four of the simulated cases show overall similar behavior of load histories and these are staying within acceptable limits. A remarkable difference is visible for separation at maximum dynamic pressure. The strong aerodynamic forces are influencing the acceleration profile and severe oscillations with high angular accelerations [36] have been detected due to relatively fast rotation of the capsule. The results clearly indicate that SLC separation at maximum dynamic pressure in transonics during ascent flight is highly critical and is not safely feasible in the current aerodynamic design of SLC7. It has been hoped to find a relatively short period of transonic ascent flight during which the separation sequence should be blocked for safety reasons [10]. However, a preliminary assessment revealed that this blocking would need to be extended for at least 110 s. This is effectively the full section of flight at elevated dynamic pressure and is obviously too long to be compatible with the MRD safety requirement.

4.6. Recommendations from separation studies

The baseline integration of Figure 7 (named Concept A) is complemented by two alternative concepts (Concept B and Concept C) which are presented in Figure 13. The separation sequence of Concept A has been studied in multi-body simulations and the overall feasibility of the process is confirmed. The alternative 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 13). This approach resembles the capsule conception studied for a 2nd generation Space Shuttle (see e.g. [25]) 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.

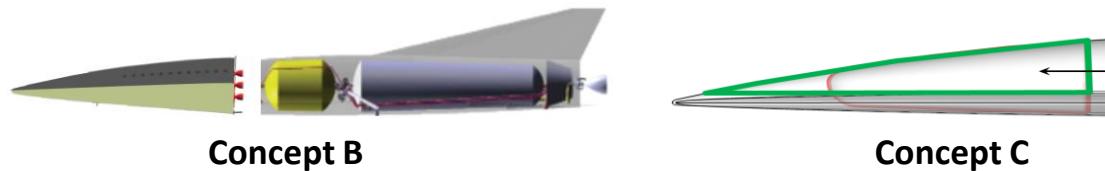


Figure 13: Alternative SLC integration Concepts B and C [25]

In any case, the SLC integration is not the most important challenge to be addressed. The systematic assessment of different critical separation cases revealed that the aerodynamic unstable design of the capsule is creating serious problems. The initial approach of actively controlling by RCS-thrusters turns out to be unfeasible at elevated dynamic pressure levels. Thrusters would have to be upscaled to an excessive size and mass. Instead the SLC needs to be redesigned for SpaceLiner 8 that its shape is rapidly morphing into an aerodynamically stable configuration. Further, the nose section of a future SLC derived of Concept C should include part of the separation motors and thus help improving stability of the separation maneuver.

5. Conclusion

The DLR proposed reusable winged rocket SpaceLiner for very high-speed intercontinental passenger transport is progressing in its conceptual design phase after having successfully completed its Mission Requirements Review (MRR). Research on the vehicle is continuously performed with support from several former and ongoing EC-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. Multi-body simulation models of the emergency capsule separation have been set up and systematic simulations have been performed for five critical flight conditions. The separation sequence has been studied and the overall feasibility of the baseline process is confirmed. Simulation results clearly indicate that SLC separation and safe distancing at elevated dynamic pressure flight is highly critical and is assessed as not feasible in the current aerodynamic shape of the emergency capsule.

The improved design of the capsule requires an aerodynamically stable configuration, simplified integration and further refined separation sequence. This should be integrated in the next iteration step, the SpaceLiner 8.

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