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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 three 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

Abbreviations

CAD	Computer-aided design
CFD	Computational fluid dynamics
CRS	Cabin rescue system
DOF	Degrees of freedom
GLOW	Gross lift-off mass
LH2	Liquid hydrogen
LOX	Liquid oxygen
MRR	Mission requirements review
RCS	Reaction control system
RLV	Reusable launch vehicle
SLB	SpaceLiner booster stage
SLC	SpaceLiner cabin
SLME	SpaceLiner main engine
SLO	SpaceLiner orbiter stage
SLP	SpaceLiner passenger stage
SSME	Space shuttle main engine
TPS	Thermal protection system
TSTO	Two-stage-to-orbit
TVC	Thrust vector control

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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 [4–10]. 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 [11, 12]. 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 [13].

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 [9]. The Mission Requirements Document (MRD) [14] is the baseline and starting point for all technical and programmatic follow-on activities of the SpaceLiner Program (Fig. 1).

## 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 Fig. 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 (Fig. 2, top).

The main dimensions of the 7-3 booster configuration are listed in Table 1 while major geometry data of the

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

Fig. 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
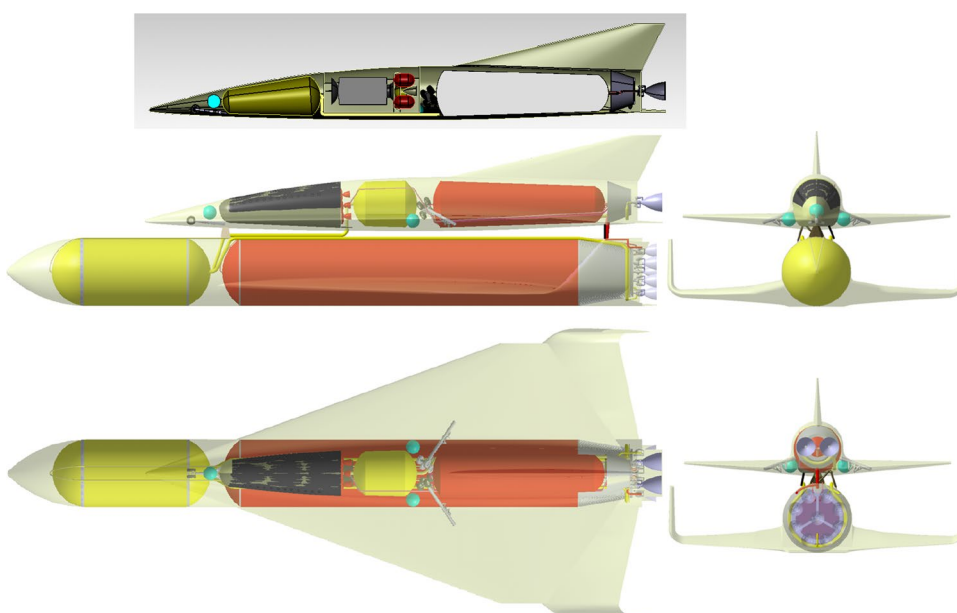
SpaceLiner 7-3 passenger or orbiter stage are summarized in Table 2.

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 & Super-Heavy with the Raptor engine [15]. This concept is in some aspects a similar multiple-mission reusable launch vehicle as SpaceLiner intends to become [7]. 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, turbomachinery, and combustion chamber are assumed to remain identical in the baseline configuration [16].

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 and 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 [17] 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 [17]. 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 [6, 16]. 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%.

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 layout. 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 layout [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

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

Table 3 SpaceLiner (SLME) technical data from numerical cycle analysis [17]

Operation point	O1	O1	O2	O2	O3	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

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 [17]. 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 predesigned: 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 [16]. 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 [9, 16] is maintained but in this consolidated design also considering the preliminary

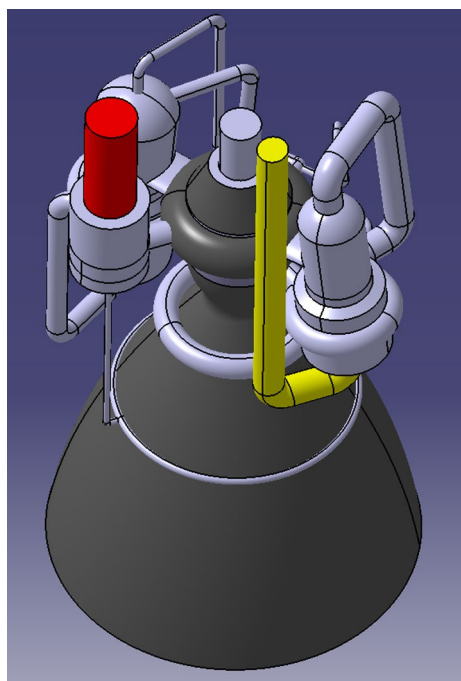**Fig. 3** SLME simplified CAD geometry showing arrangement of turbomachinery

sizing of the regenerative cooling and of the turbopumps. The view of the SLME-33 from above in Fig. 3 shows on the left the hydrogen fuel supply and on the right the oxygen flow side.

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 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 [17].

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].

2.2 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) layout [6]. 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 [10]. 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 [16, 17].

The booster wing (and winglet) airfoils have been selected as modified NPL-EC/ECH cut at trailing edge thickness of 75 mm [18]. 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 [18, 19]. 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 Fig. 4.

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 [18].

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 [5, 9]. Already early in the project, transpiration cooling using liquid water has been foreseen as a potential option for solving the problem [4, 20]. 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 [21]. Test results have been scaled to full-size by heat transfer correlations and numerical assessment of the complete SpaceLiner trajectory [20]. 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 [22].

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 [22].

The passenger stage's internal design has been adapted for its secondary role as an unmanned satellite launcher. The passenger cabin (see separate Sect. 3) is not needed for this variant and is instead replaced by a large internal payload bay [9]. 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 [6]. 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 [9]. These dimensions are close to the Space Shuttle (18.3 m × 5.18 m × 3.96 m) and should

Fig. 4 SpaceLiner 7-3 passenger stage
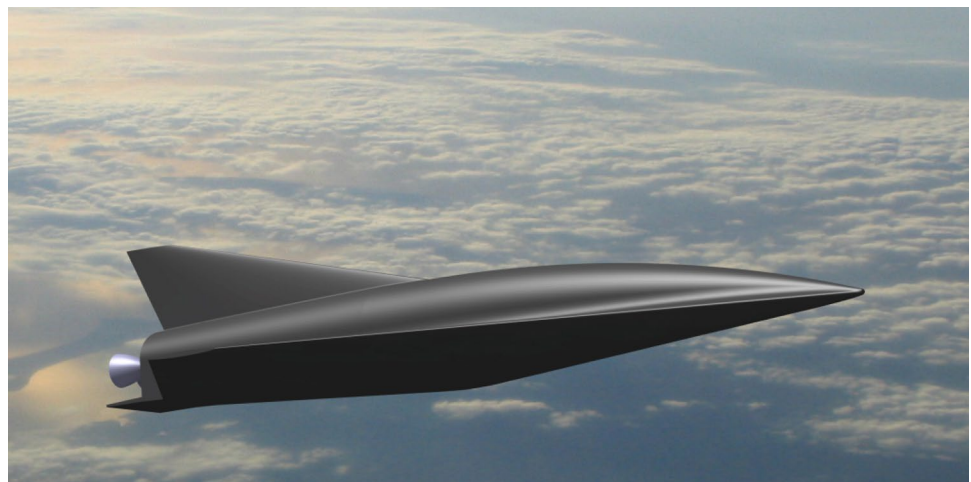
Table 4 Mass data of SpaceLiner 7-3 booster stage

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 and propellant loading [Mg]	GLOW incl. passengers and 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 and propellant loading [Mg]	GLOW incl. kick-stage and payload [Mg]
60.1	9.9	9.8	22.3	102	207	309.1

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 (Table 4).

The orbiter stage mass has been estimated based on the SpaceLiner 7-3 passenger stage budget (Table 5). 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 body flap has been preliminarily checked in numerical simulation under hypersonic flow conditions of atmospheric re-entry and is found feasible within the constraints of the 7-3 layout [9]. 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 re-entry trajectory simulations [9].

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

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

| Total empty [Mg]	Total propellant loading [Mg]	GLOW incl. passengers and 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 and payload [Mg]
300.6	1467	1807

water needed for the active leading edge cooling [4, 5, 9, 22]. 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.

3 Reference point-to-point trajectory

Possible SpaceLiner trajectories have been calculated since the early investigations started. The current configuration 7-3's flight path options are presented in references 2, 8, 9, 23. A systematic optimization of new point-to-point missions has been published in [13]. Figure 5 shows some key-characteristics of the reference mission Australia to Europe. After its vertical take-off the 7-3 configuration is initially following a typical ascent profile of a rocket launcher. Succeeding the booster stage separation, the passenger stage
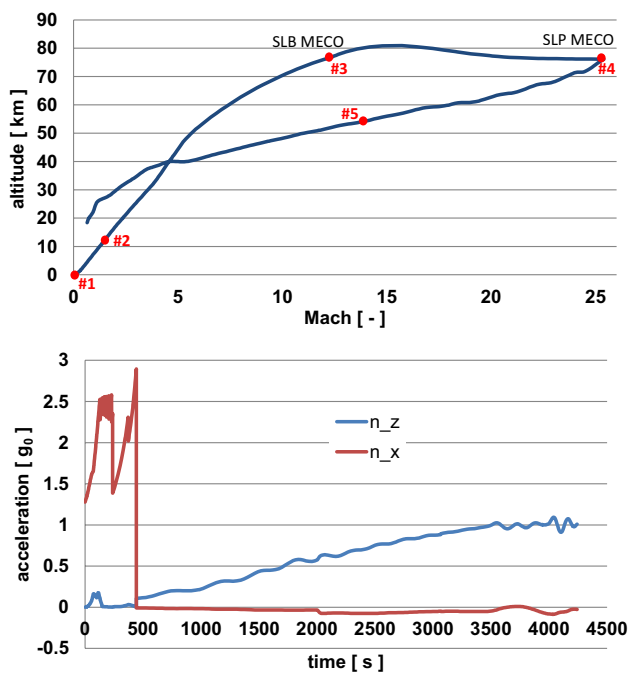
Fig. 5 Calculated trajectory characteristics of SpaceLiner 7-3 reference mission Australia to Europe

is accelerated almost horizontally being the most energy-efficient way for a stage with good hypersonic L/D-ratio and intentionally long unpropelled gliding phase. Thus, second stage MECO is at slightly lower altitude than booster MECO. The indicated flight points #1–#5 have been selected for the emergency capsule separation investigations described in Sect. 3. Axial acceleration is limited to 2.5 g which is achieved by engine throttling and subsequent engine shutdowns on the booster stage. The short acceleration-peak at SLP MECO exceeding this limitation is an artifact of the simplified simulation and disappears when assuming a realistic engine shutdown sequence. Normal acceleration n_z is smoothly approaching 1 g during the gliding phase while axial deceleration is then around -0.1 g.

3.1 Future development outlook

The biplane architecture of the mated launch configuration (Fig. 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 [8, 10, 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 re-entry [6, 10] 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 Sect. 3 which supports a future redesign of the passenger stage.

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 [6]. Alternative designs have been explored [6, 8]. 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 [6, 8]. 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 trimmable in hypersonic flight at high angles of attack.

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 [24] because the estimated nominal peak temperatures are excessively pessimistic.

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.

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 [25, 26]. 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 [12] and its architecture is similar to potential future SpaceLiner 8 booster, however, with significantly reduced propellant loading (380 Mg) and only four SLME [26].

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 MRD [9, 14] defines passenger safety requirements well beyond today's reliability of launch vehicles which are nevertheless indispensable to create a viable commercial product. A safety philosophy following a multiple step approach is chosen to address the MRD-requirement:

- built-in safety and redundancy with continuous monitoring of flight critical functions and if necessary early shutdown of systems to avoid catastrophic events,
- engine-out capability during the full mission including vehicle controllability in adverse conditions [23],
- capability of the passenger stage SLP to perform abort flight maneuvers in case an early separation from the booster stage would be required during ascent,
- in case of extreme emergencies in which the previously listed safety measures are not sufficient to save life on board or can't be used anymore, the SLC will be separated and rapidly distance itself from a launch vehicle no longer controllable. Only this special case of SLC separation and its subsequent free flight conditions are described in this part of the paper.

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 [9, 14], 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 [10].

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 [5, 9, 27]. 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., [10]) 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 (Fig. 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 [28]. 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,
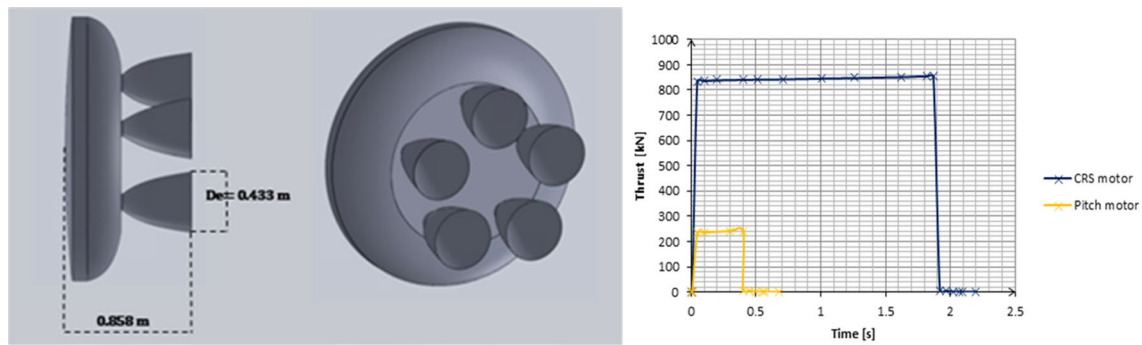
Fig. 6 SLC separation motor in multiple nozzle baseline [28] (left), sea-level thrust profiles of SLC motors [29] (right)

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 [29].

A preliminary design for the capsules main subsystems has been elaborated [10, 30]. 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 body flap and two deployable control fins on the upper surface support flight controllability and stability. The actual effectiveness of the devices is investigated in dynamic simulations (Sect. 3.5) and critically evaluated (Sect. 3.6). The 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 [10, 30].

The principal feasibility and flyability of an innovative morphing structure concept on the capsule has been demonstrated by numerical simulations within the HYPMOCES project [6, 10, 30]. 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 [10].

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 [9, 14]. 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 cannot 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 [27]. 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 Fig. 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.
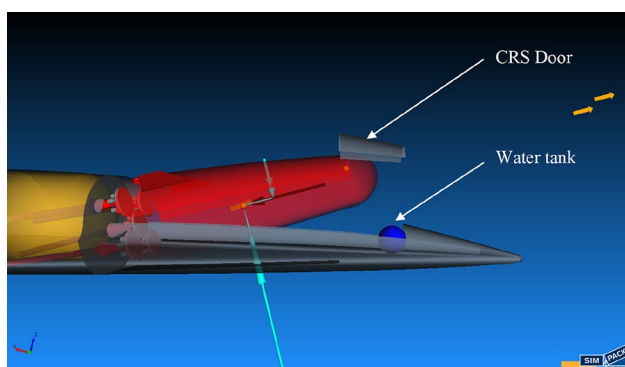
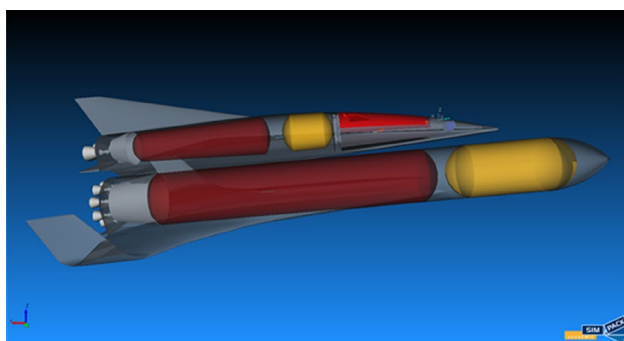**Fig. 7** SLC early in separation phase (Concept A) [29]

Fig. 8 Three-dimensional visualization of the primary and secondary bodies of the multi-body simulation

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.

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 Fig. 7 for which a consolidated pre-design with extensive data sets is available [7, 8]. The geometrical model was taken from the respective SpaceLiner CATIA model and is shown in its Simpack simplification in Fig. 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 [29]. 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 and stabilizers serve for visualization purposes but also to detect structural collisions [29]. 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.

4.4 Modeling 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. Any sloshing of residual propellants in the tanks is not considered.

External forces from rocket engines like the pitch-up and separation motors (Fig. 6) or the RCS thrusters including their actuation times are fully modeled including the thrust vector. However, exhaust plume interactions with another body would require sophisticated CFD-analyses and have been neglected in the simulations of the separation process. The main propulsion system with SLME has been assumed in this first systematic assessment being completely shutdown. This simplification makes sense for this study in order to decouple from the effects of abnormal engine behavior.

The aerodynamic data sets are complete for all three vehicles SLC, SLP, and 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 [29]. 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

Five abort cases with SLC ejection along the nominal operational flight (see positions in Fig. 5) have been analyzed with multi-body simulations:

- #1: Launch pad abort prior to lift-off with zero altitude and zero velocity
- #2: Maximum dynamic pressure in transonic flow conditions (29.8 kPa at Mach 1.37 in 10,995 m)
- #3: SLB separation (Mach 12.33 in 76,774 m)
- #4: MECO of SLP (Mach 25.39 in 76,087 m)
- #5: Maximum heat flux re-entry (Mach 13.95 in 54,218 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 Fig. 9 shows SLC ejection at the launch pad with zero altitude and zero velocity of the
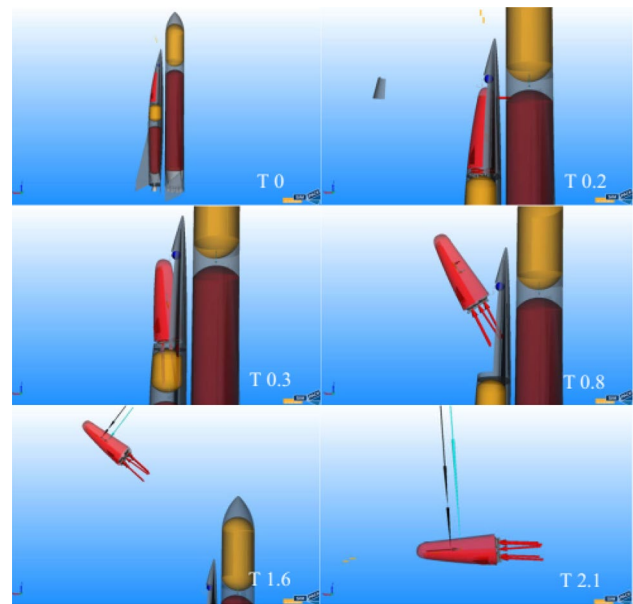
Fig. 9 Multi-body simulation of SLC separation at launch pad (case #1) with time in s after initiation [29]
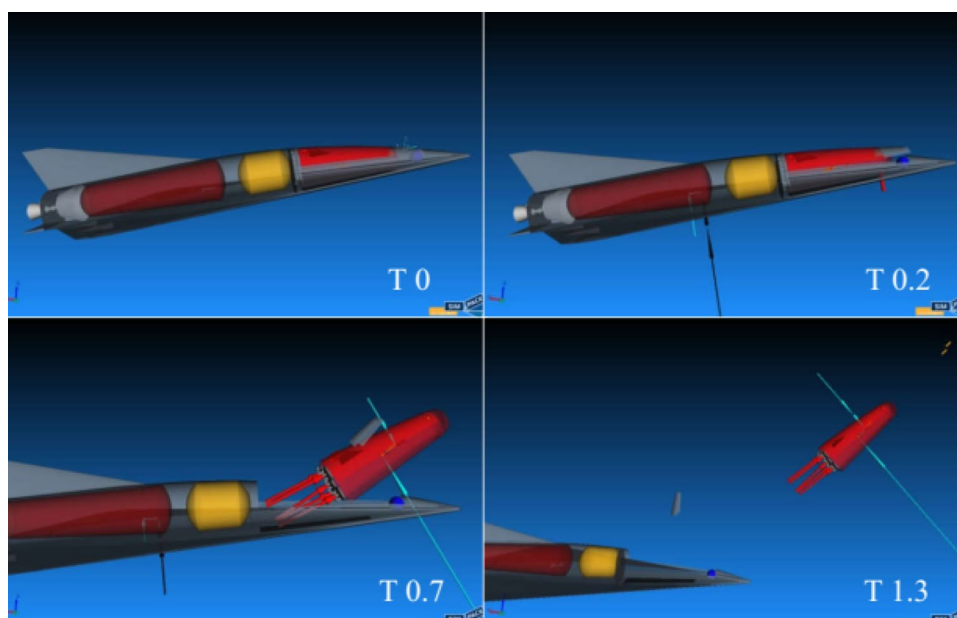
SpaceLiner. After the nose tilt-up, the outboard separation motors are ignited within 0.1 s after ignition of the center motor. The solid rockets burn until approximately 2.1 s at a distance to the launcher of 170 m. After burn-out, the capsule follows a ballistic trajectory stabilized and oriented by RCS.

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 and downward-oriented lift force is to be avoided. These are some 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 Fig. 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.

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

Fig. 10 Multi-body simulation of SLC separation at max. Heat flux during re-entry (case #5) with time in s after initiation [29]


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 s after ignition of the center motor and burn for about 2 s. 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 ± 2 g due to SLC rotation and the effect of aerodynamic forces. Attitude changes are already damped in the simulations shown in Fig. 11 by controlled firing of RCS. Minimization of resulting loads, however, has not been pursued.

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 or lifted upward out of the seats, the latter corresponding to negative n_z. While the extreme medical limits were not visible in the axial-direction plots, these limits are included in the normal acceleration plots (Fig. 12) as horizontal lines for load durations of 1 or 2 s.

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
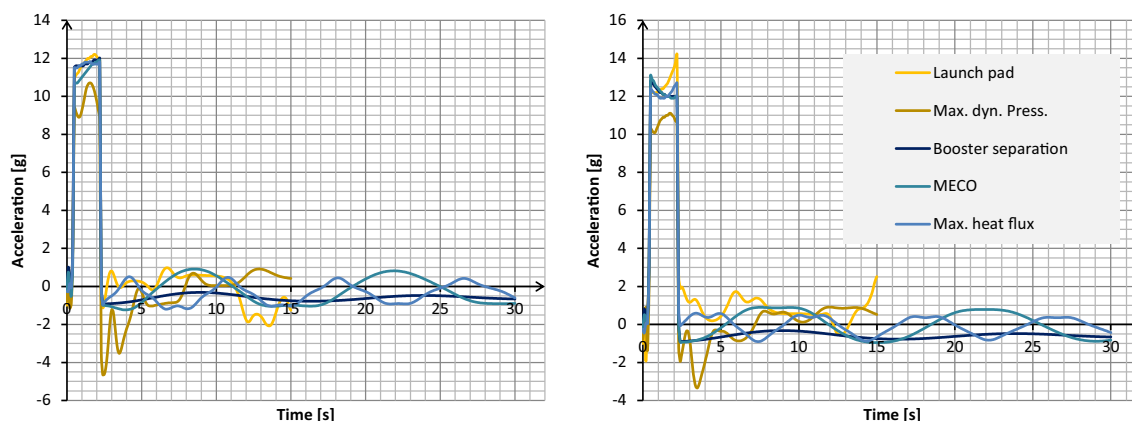
Fig. 11 Axial acceleration (n_x) acting on fwd. seat (left) and aft seat (right) obtained by Simpack simulations for different SLC separation cases [29]
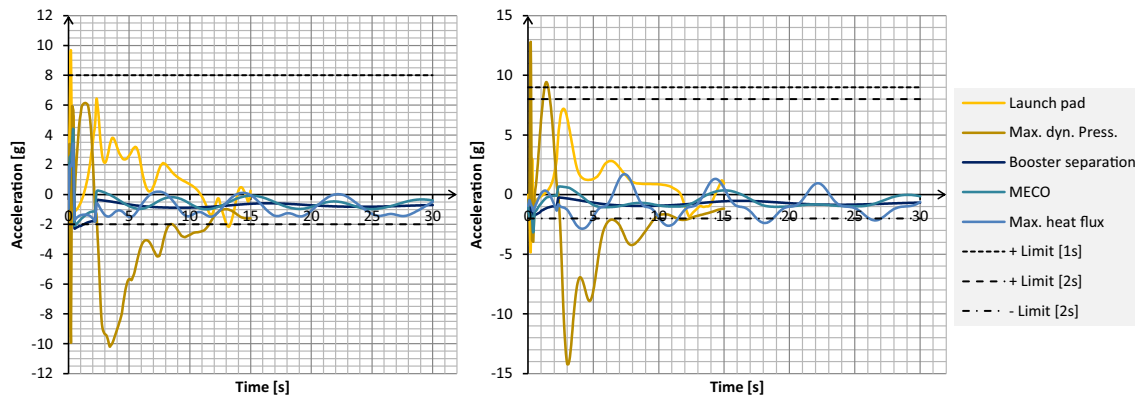
Fig. 12 Normal acceleration (n_z) acting on fwd. seat (left) and aft seat (right) obtained by Simpack simulations for different SLC separation cases [29]

aerodynamic forces are influencing the acceleration profile and severe oscillations with high angular accelerations [29] 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 [8]. 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 Fig. 7 (named Concept A) is complemented by two alternative concepts (Concept B and Concept C) which are presented in Fig. 13. The separation sequence of Concept A has been studied in simplified 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 Fig. 13). This approach resembles the capsule conception studied for a 2nd generation Space Shuttle (see e.g., [28]) 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 Space-Liner 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.

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 only 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. Inflatable devices might be attractive options to be assessed based on previous analyses for the SLC [10, 30] and the recent successful flight demonstration of LOFTID by NASA [31]. Further, the nose section of a future SLC derived of Concept C should

Fig. 13 Alternative SLC integration Concepts B and C [28]

Concept B   **Concept C**
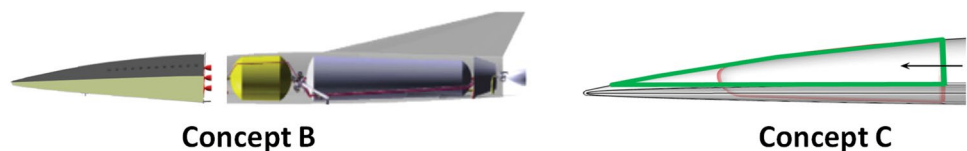
include part of the separation motors and thus help improving stability of the separation maneuver.

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 17,000 km in about 1.5 h.

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.

Data availability The empirical data referred to in this paper are available on request from the corresponding author, but are not public due to privacy restrictions.

Declarations

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this paper.

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