SpaceLiner Concept as Catalyst for Advanced Hypersonic Vehicles Research

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Since a couple of years the DLR launcher systems analysis division is investigating a visionary and extremely fast passenger transportation concept based on rocket propulsion. The fully reusable concept consists of two vertically launched winged stages in parallel arrangement. In a second role the SpaceLiner concept serves as a reusable TSTO space transportation launcher for which technical details are now available.

The SpaceLiner configuration serves as a catalyst for applied research on advanced hypersonic systems and reusable launchers. The paper presents the latest status of the SpaceLiner concept and its key mission and system requirements. At the same time the paper functions as the introduction to other papers addressing more detailed SpaceLiner design and research questions.

Abbreviations

CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CMC	Ceramic Matrix Composites
GLOW	Gross Lift-Off Mass
IXV	Intermediate eXperimental Vehicle (of ESA)
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MRR	Mission Requirements Review
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
SLME	SpaceLiner Main Engine
TAEM	Terminal Area Energy Management
TPS	Thermal Protection System
TSTO	Two-Stage-To-Orbit
TVC	Thrust Vector Control

1 Introduction

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

Ultra-long distance travel from one major business center of the world to another major agglomeration on earth is a huge and mature market. Since the termination of Concorde operation, intercontinental travel is restricted to low-speed, subsonic, elongated multi-hour flight. An interesting alternative to air-breathing hypersonic passenger airliners in the field of future high-speed intercontinental passenger transport vehicles is a rocket-propelled, suborbital craft. Such a new kind of 'space tourism' based on a two stage RLV has been proposed by DLR under the name **SpaceLiner** [1]. Ultra-long-haul distances like Europe – Australia could be flown in 90 minutes. Other interesting intercontinental destinations between e.g. East-Asia and Europe or the Trans-Pacific-route to North-West America could be reduced to flight times of slightly more than one hour [18].

First proposed in 2005 [1], the SpaceLiner is under constant development and descriptions of some major updates have been published since then [2, 19, 21, 22]. The European Union's 7th Research Framework Programme has supported several important aspects of multidisciplinary and multinational cooperation in the projects FAST20XX, CHATT [9], HIKARI, and HYPMOCES [22, 23, 24, 30].

Different configurations in terms of propellant combinations, staging, aerodynamic shapes, and structural architectures have been analyzed. A subsequent configuration numbering has been established for all those types investigated in sufficient level of detail. The genealogy of the different SpaceLiner versions is shown in reference 19. These configuration studies supported the definition of the current reference configuration SpaceLiner 7.

2 SpaceLiner 7 Mission Requirements

Another important milestone has been reached in 2016 with the successful completion of the Mission Requirements Review (MRR) which allows the concept to mature from research to structured development [21]. Intentionally, external reviewers with long-term experience in large-scale space projects had been invited for an independent assessment of all necessary requirements and soundly structured development logic.

The Mission Requirements Document (MRD) [4] constitutes the top-level mission requirements of the SpaceLiner System. The MRD is the baseline and starting point for all technical and programmatic follow-on activities of the SpaceLiner Program. The MRD takes already into account the two variants for passenger transport and for payload transport to orbit. The objective of the passenger version is to provide a safe, reusable, hypersonic, intercontinental, point-to-point, passenger transportation system [4].

The SpaceLiner has developed into a relatively complex System (referred to as SLS) which includes the SpaceLiner Vehicle (SLV) as well as the SpaceLiner Ground Segment (SLGS). Two different SpaceLiner versions exist as presented in Figure 1. The "PAX"-version is the point-to-point ultra-fast passenger transport vehicle - consisting of the Booster (SLB) and Passenger stage (SLP) including the cabin (SLC) powered by the main engine (SLME). The orbital version represents the SLB and the Orbiter (SLO) designed to operate as a space transportation system used for payloads delivery to and from orbit with maximum technical similarities to the passenger version.

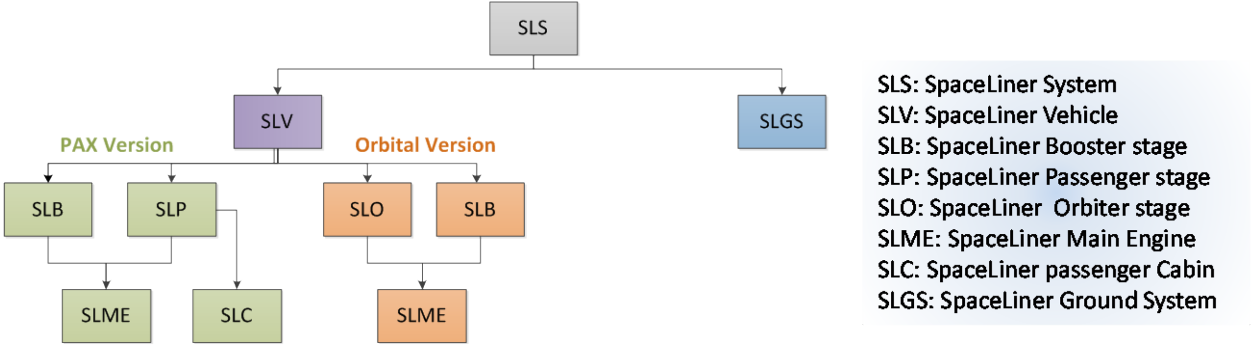

Figure 1: A visual representation of the association and relation between the various SpaceLiner System elements [4]

The ambitious west-bound Australia – Europe mission has been used as the reference case since the beginning of the SpaceLiner investigations. This flight distance should be served for 50 passengers on a daily basis in each direction. Several other, shorter intercontinental missions exist, which potentially generate a larger market demand. For this reason a SpaceLiner configuration derivative has been studied, which could transport up to 100 passengers [18]. In order to keep the number of different stage configurations at the lowest possible level, the potentially interesting flight destinations have been divided into three classes [19]. These three mission classes could be flexibly served by a suitable combination of four different vehicles (however with a lot of commonality in subcomponents like engines): 50 and 100 Passenger orbiter stage and large and shortened booster.

The SpaceLiner program must be in full agreement with international regulations and national laws of all participating nations. However, specific binding regulations for the operation of high-speed passenger transport vehicles operating at the edge of space do not yet exist in a similar way as for all kinds of manned and unmanned aviation. Nevertheless, a safety standard is in the preparation process which might become applicable to the SpaceLiner Program. The SpaceLiner Project structure shall also be oriented on the European ECSS standards and the Metric System (SI) shall be used.

The MRD lists 11 Technical Requirements, 30 Operational, Environmental, Exploitational Requirements, and 9 Programmatic and Cost Requirements [4]. Several of the specifications included here are to be verified in Phase A which is to be addressed by extensive trade-off studies. The current issue 1 of the MRD will be updated in future project phases based on the results of these studies or commercial and economical needs.

The MRD is available to all SpaceLiner project partners.

3 Interdisciplinary Design Process of RLV SpaceLiner

3.1 Design Process of RLV

The key disciplines of (any) launcher design are:

- Propulsion
- Mass estimation
- Aerodynamics
- Ascent Trajectory & Performance

An RLV-design poses even greater challenges due to enhanced complexity. A functional RLV design requires at least the return to Earth (or to the launch site) of the RLV-stage for all nominal missions. The functions of ascent and return are directly coupled. The inter-dependencies are highly non-linear, therefore an iterative process is the most promising approach.
The design process of a reusable launch system is inherently more complex than the design of an expendable system. The key disciplines of Reusable Launcher Design are:

- Propulsion
    - Rocket
    - (Fly-back (A/B))
- Mass Estimation
- Aerodynamics
- Aerothermodynamics
- Trajectory & Performance
    - Ascent Trajectory & Performance
    - Reentry & Return Trajectory

The key-challenge is the safe return of the reusable stages in a cost efficient way, taking into account system performance and (potentially) the stage and engine refurbishment after flight. The complex interactions of the different disciplines do not allow directly finding the best design solution. Therefore, an iterative design process is usually followed and several trade-studies help in identifying the optimum compromise.

3.2 Technical system studies performed for SpaceLiner preliminary sizing

Even more challenging then the RLV-design process is the design and commercial service of manned passenger operation. The top priority is passenger safety while a viable business case also requires highly cost efficient operations.

An RLV-based hypersonic passenger transport is THE perfect configuration for technical system studies on advanced reusable launchers. A concept like the SpaceLiner can serve as a catalyst for technology research on advanced reusable launchers.

3.2.1 Propulsion

Staged combustion cycle rocket engines with a moderate 16 MPa chamber pressure have been selected as the baseline main propulsion system right at the beginning of the project [1]. 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 [14]. The SLME nozzle expansion ratios of the booster and passenger stage are adapted to their respective optimums; while the mass flow, turbomachinery, and combustion chamber are assumed to remain identical in the baseline configuration. The average engine life-time should be 25 missions which is one of the key-challenges of an economic SpaceLiner operation and this requirement serves as a catalyst of advanced research.

Reference 14 gives an overview about major SLME engine operation data for the nominal MR-range as obtained by cycle analyses.

All main engines of the configuration should work from lift-off until MECO. A propellant crossfeed from the booster to the passenger stage is foreseen up to separation. No similar crossfeed system for a configuration like the SpaceLiner has ever been built and therefore numerical investigations have been performed in the FP7-project CHATT with steady-state flow-simulation along the full powered trajectory and transient simulation of critical phases like engine cut-off or valve closing. In particular, the process of booster separation is a dimensioning factor for the design of the crossfeed system due to the switch of the propellant supply from the booster to the orbiter tanks. Different design solutions of “tank-to-tank” or “line-to-line” propellant crossfeed have been traded. [14, 15]

A preliminary design for the RCS has been performed and three maneuvers are identified as cases of interest: compensation of potential thrust imbalance caused by the separation rocket motors, roll maneuver of cabin, stabilization of flight in nominal, almost exo-atmospheric conditions when the capsule is integrated within the passenger stage. 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. 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 [22].

Solid Separation Motors are foreseen for rapid and safe distancing of the passenger cabin in case of extreme emergencies [28].

3.2.2 SpaceLiner 7 Architecture and Geometry

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

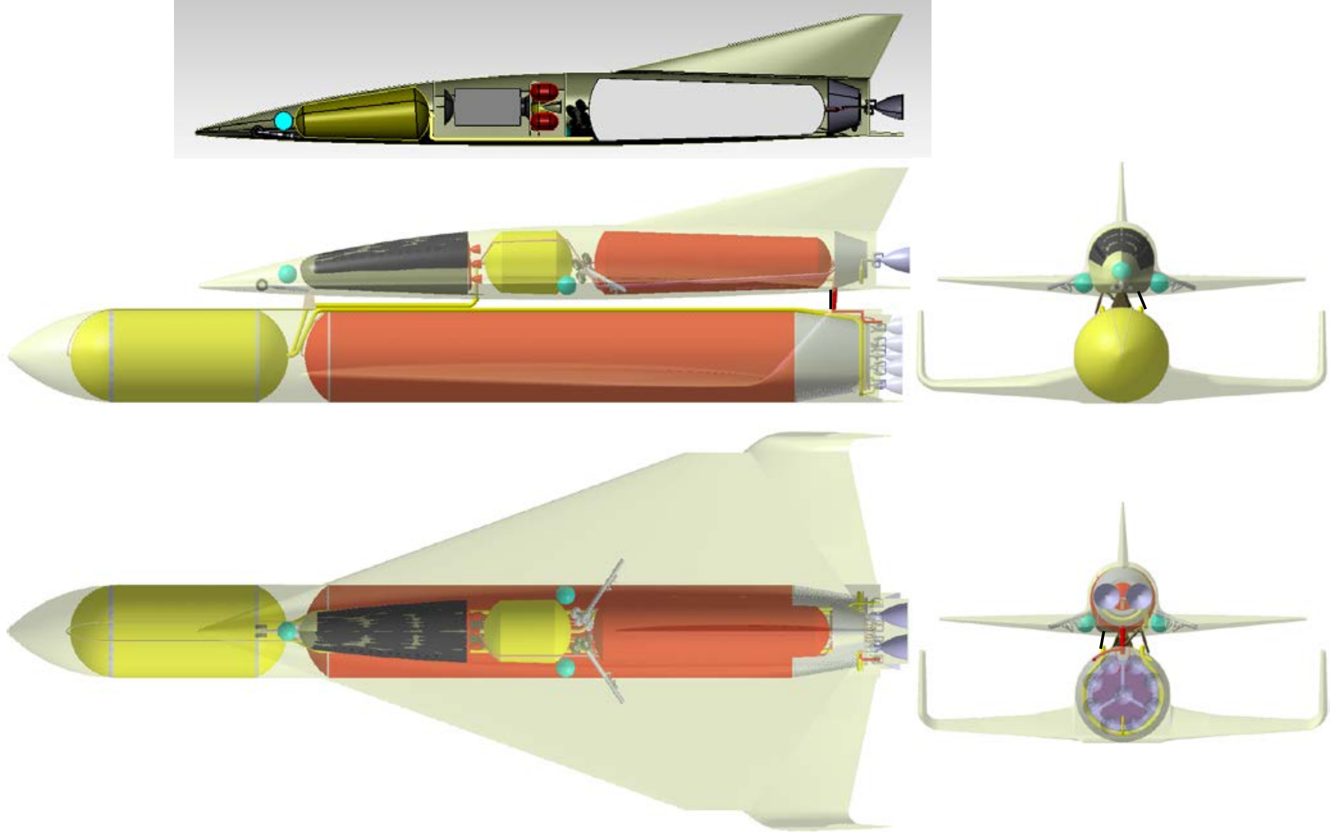

Figure 2: Sketch of SpaceLiner 7-3 launch configuration with passenger version (SLP) with its booster stage at bottom position and orbital stage of SLO in insert at top

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

Careful vehicle mass management is essential for any successful RLV design. An iterative approach might be appropriate:

- 1st step: mass estimation of major components based on empirical data
- 2nd step: collection of mass data from preliminary sizing of major components (e.g. mechanical architecture and structural sizing)

The SpaceLiner 7 Structural Design and Analyses has been performed for major elements of both reusable stages: the booster and the passenger stage/orbiter. Structural sizing trade-off studies are currently performed, where the focus is on the identification of optimum structural design solutions rather than on precise mass predictions. The finite element (FE) based parametric structural analysis and optimization tool HySAP (Hypersonic vehicle Structural Analysis Program) [17] is used for this task.

The current 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 lay-out. 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. For the structural architecture of the passenger stage, always non-integral tank integration has been assumed in expectation of the severe thermal loads in atmospheric flight beyond Mach 20. The vehicle structure is an all honeycomb-sandwich design. Stringer stiffening of the fuselage has been investigated as well, but was found to be not competitive in terms of structural mass [22]. The cut-out in the fuselage necessary for passenger cabin integration (see section 3.2.5 below!) are included in the vehicle's FE-model.

3.2.3 SpaceLiner 7 mass model

The SpaceLiner mass budget is constantly tracked; however, the mature status of the configuration 7 usually shows only minor changes. System margins of 14% (12 % for propulsion) are continuously added to all estimated mass data despite more and more detailed vehicle and subsystem design. This relatively conservative approach is chosen in order to ensure a robust development phase of this advanced vehicle with ambitious safety and reusability requirements.

The SpaceLiner 7-3's GLOW reaches about 1832 Mg (Table 3) for the reference mission Australia – Europe while the TSTO is at 1820 Mg (Table 4); still considerably below that of the Space Shuttle STS of more than 2000 Mg and therefore technically within reach.

Table 3: 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 4: Mass data of SpaceLiner 7-3 TSTO launch configuration

Total dry [Mg]	Total propellant loading [Mg]	GLOW incl. kick-stage & payload [Mg]
300.6	1480	1820

Part of the mass management is the vehicle's CoG- and Inertia calculation in all mission phases to support the flight dynamic assessment and definition of its trimming requirements. For winged vehicles, usually, an iterative approach including mass management, aerodynamics, and flight dynamics is required.

As typical for every rocket launch system and even intensified by the propellant crossfeed from the booster to the passenger/orbiter stage (see references 15, 19!), the SpaceLiner's CoG is subject to a major movement during mated ascent flight. Right before stage separation when the booster propellant tanks are almost drained, the CoG had moved 21.7 m backward and 3.4 m towards the attached upper stage (Figure 3). The current model describes the SpaceLiner as a rigid body. The effects of fuel sloshing and dynamic structural deformations or aeroelastics, while still neglected here, are to be included in future research.

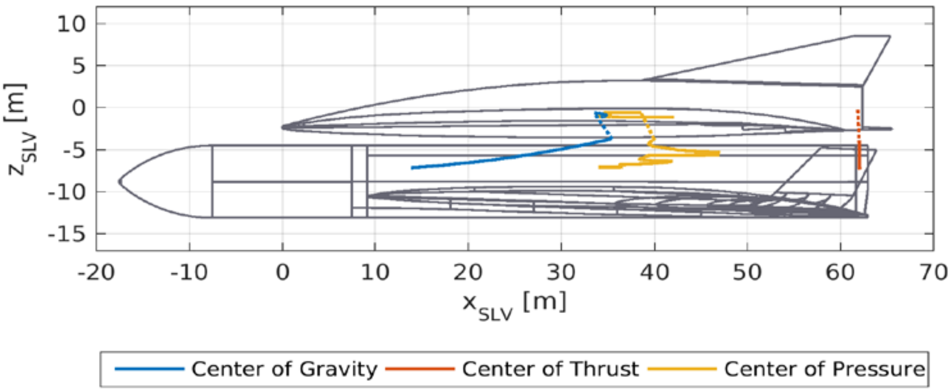

Figure 3: Transient movement of center of gravity, approximate center of pressure and center of thrust during ascent flight; instantaneous jump at stage separation indicated by dashed lines

3.2.4 Aerodynamics

The vehicle aerodynamics has a much stronger influence on winged RLV and their overall performance than on expendable launchers.

The Mach number range of the SpaceLiner's booster and passenger stage both stretches from the hypersonics through the transonic regime to the low speed subsonic landing approach. Aerodynamic data sets have been generated with different numerical tools and an aerodynamic database for preliminary engineering design work has been established [20] for all four SpaceLiner flight configurations: The mated launch vehicle, the booster stage, the passenger stage, and the rescue capsule.

Several technical papers describe the SpaceLiner's aerodynamic shape definition and important research results [6, 7, 16, 20, 33].

The SpaceLiner7 aerodynamic shape of the passenger stage results from a fully automated optimization process. In order to consider a wide range of the hypersonic trajectory, three points with different flight Mach numbers (20.1, 13.6, 6.0) and corresponding altitudes were chosen for the optimization [16]. The SpaceLiner 7-3 configuration passenger stage wing airfoils keep a finite minimum thickness at the trailing edges. At the wing's root a modified NACA 66-003.5 is implemented which is cut when the trailing edge thickness reaches 50 mm.

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 [20].

Experiments of the 7-3-configuration are planned in the windtunnels TMK and H2K at DLR-Cologne. A model in scale 1:158 with different wingflap (+/- 20°) and bodyflap (10°) deflections has been manufactured. The model is shown in Figure 4 in an early run in hypersonic flow condition.

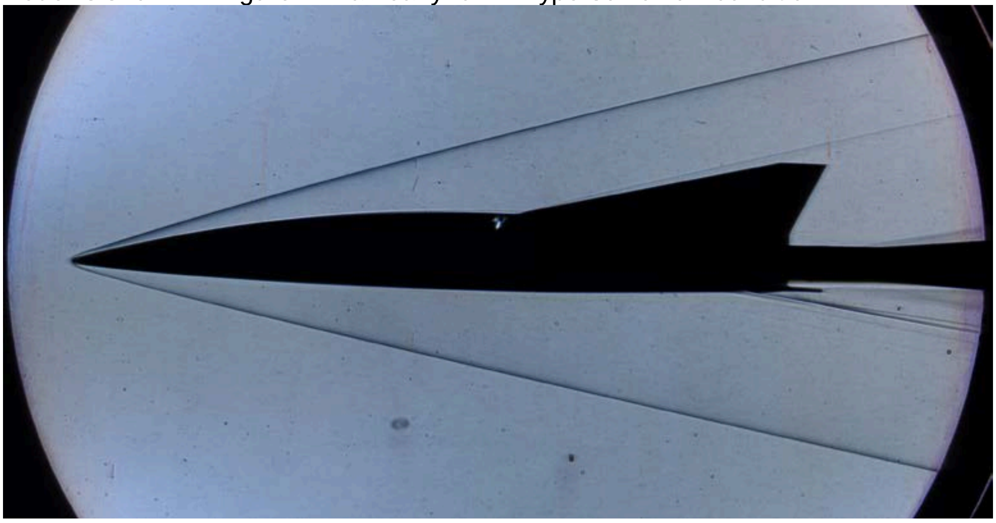

Figure 4: Schlieren image of the SpaceLiner 7-3 passenger stage model in DLR hypersonic windtunnel H2K (M= 5.3, α= 2°, Re= $16 \cdot 10^{6}$ m^{-1})

The range of SpaceLiner altitudes in which early rarefactions effects are expected is 75÷85 km. The inviscid conditions are based on the continuum aerodatabase, while the free molecular flow data have been computed by means of Direct Simulation Monte Carlo (DSMC). In between bridging functions are applied which deliver the altitude dependence of longitudinal aerodynamic coefficients for the SpaceLiner configuration [33].

3.2.4.1 Aerothermodynamics

Atmospheric reentry of RLV at high speed is a major challenge to reusability due to severe thermal loads. Usually a Thermal Protection System (TPS) is needed. The preliminary sizing of the SpaceLiner7's TPS has been carried out for several different heat loads according to nominal flight and also for different abort cases [10]. A metallic skin on the vehicle's surface is the preferred option for the TPS. Despite an additional mass it should be operationally more robust which is highly important for a commercial product as the SpaceLiner should eventually become. A suitable integration of the external TPS with a reusable cryogenic insulation on the tanks is an important area of current RLV-technology research in DLR.

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 [10, 19, 21]. Already early in the project, transpiration cooling using liquid water has been foreseen as a potential option for solving the problem [2, 5, 7]. In FAST20XX this innovative method has been experimentally tested in DLR's arc heated facility in Cologne using subscale probes of different porous ceramic materials [8]. A similar advanced cooling technique research project has afterwards been inspired in China [13]. The water storage tank system, a feed-line manifold including control and check-valves and some bypass and redundancy lines were sized for accommodation inside the SpaceLiner volume [32].

Despite the overall promising results, 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 [32]. 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 like water sprayed for vaporization on the internal surface of the leading edge [32]. The SpaceLiner requirements of safe transport in a high L/D-hypersonic airplane open another field of challenging research.

3.2.5 SpaceLiner 7 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 current requirement of capsule separation being feasible at any flight condition and attitude is highly challenging from a technical point of view. Analyses revealed some critical issues to be addressed in order to improve the safe functionality of the cabin rescue system. Further investigations have been initiated to find a promising and reliable separation concept and system. 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 of separation motor, retro-rockets and RCS [22].

A highly innovative investigation on design options to improve the capsules' flight performance after separation has been performed in the European Commission funded FP7-project HYPMOCES (HYPersonic MOrphing system for a Cabin Escape System) aiming to investigate and develop the technologies in the area of control, structures, aerothermodynamics, mission and system aspects required to enable the use of morphing structures [22, 23, 24, 26]. The project was led by DEIMOS Space S.L.U. with participation of Aviospace, ONERA, and DLR-SART.

A multidisciplinary design approach has been successfully introduced since the beginning of the project to achieve a satisfactory design. From an initial trade-off of conceptual designs in a Concurrent Engineering Session in the very early phase of the project where all the partners contributed actively in the project objectives [24, 29] two preliminary design solutions (one “baseline” and one “backup” CES morphing system) were designed as an optimum equilibrium of conflicting objectives among the different disciplines involved, namely: mission analysis, flying qualities, GNC, aerodynamics, aerothermodynamics, structure, mechanisms, and system.

Inflatable as well as rigid deployable wing options have been studied [25]. The baseline design is inflating its lower section after safe separation in order to increase the flat lower surface for increased lift in hypersonic flight enabling better gliding range. The shape of the capsule's lower side before its inflation is compact for storage inside the passenger. The fully inflated lower section and capsule with deployed rudders and deflected bodyflaps are visible in Figure 5.

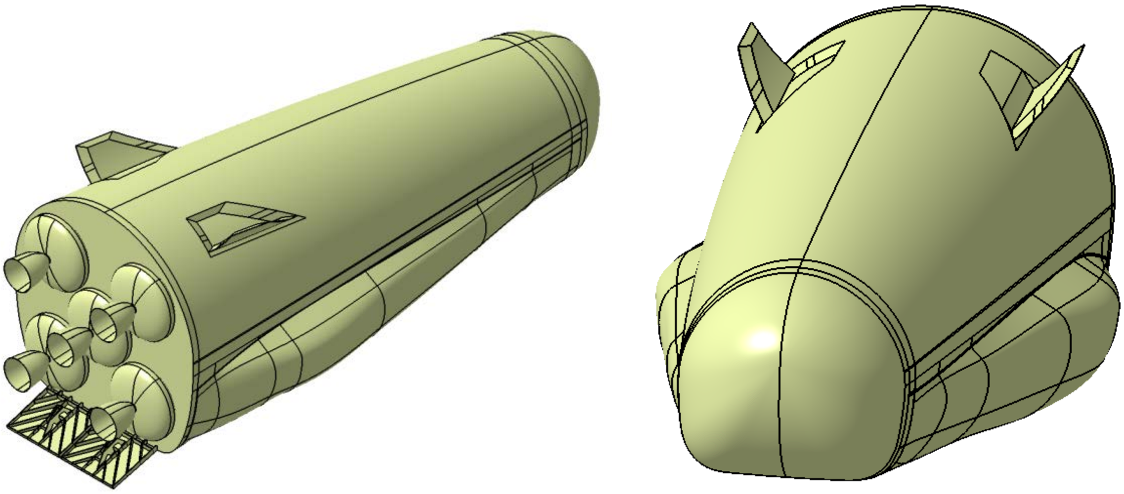

Figure 5: SpaceLiner capsule option with inflatable morphing lower section and deployable fins

Within the HYPMOCES project also micro-aerothermodynamic phenomena have been investigated by ONERA for the capsule including protuberances like steps and gaps, cavities or stiffeners for flaps [27]. Cutting edge research has been accomplished in the fields of aerothermodynamics in these CFD computations of the complete capsule geometry based on an ONERA unstructured 3D Navier-Stokes solver [27]. Wall catalycity has a well-known strong effect on heat transfer and hence surface temperatures. A configuration where the nose and the inflatable membrane are assumed with fully non-catalytic wall and the rest of the vehicle surface considered as fully catalytic has been simulated. The heat flux on the morphing membrane is dramatically reduced in case of non-catalytic behavior, supporting the feasibility of the concept [22, 27].

The detailed CFD results produced by ONERA have been used by DEIMOS Space as anchor points for the fitting of a full aerothermodynamic database, covering the extensive range of flight conditions (Mach, angle of attack, angle of sideslip, flaps deflections) where the vehicle is expected to fly. Based on this input, advanced multidisciplinary optimization tools [24] focused on the tightly coupled areas of mission analysis, Flying Qualities and GNC have been applied by DEIMOS Space.

3.2.6 Trajectory & Performance

Ascent trajectory and payload performance is key element of any launcher design. In case of the SpaceLiner passenger version, as no payload is delivered to orbit, the range performance is optimized for a minimum vehicle size.

3.2.6.1 Intercontinental passenger flight mission

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

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

The covered range Australia to Europe is approximately 16000 km and the simulated flight time no more than 71 minutes to TAEM cylinder before final landing approach. The MECO conditions reached at the end of the ascent flight is approximately 7.2 km/s in an altitude of 73.1 km and the flight path angle γ is close to 0°. The corresponding maximum Mach number is slightly beyond 25 and approximately 9000 km (more than 50 % of the overall distance) are flown at Mach numbers larger than 20 [22].

3.2.6.2 TSTO satellite launcher

The baseline design of the orbital launcher remains unchanged to the passenger version (Figure 2) with a fully reusable booster and passenger stage arranged in parallel and the external shapes will be very similar. This approach intends enabling dramatic savings on development cost and moreover by manufacturing the vehicles on the same production line, also significantly lower hardware cost than would result for a dedicated new lay-out. The satellite launch configuration as shown in Figure 6 is described in more detail in [21].

Figure 6: Artists impression of satellite payload release from SpaceLiner 7 Orbiter's open payload bay in LEO

Launch of the SpaceLiner 7 TSTO has been simulated from the Kourou space center into a low 30 km × 250 km transfer orbit. This trajectory allows for the GTO mission that the orbiter stage becomes a once-around-Earth-vehicle capable of reaching its own launch site after a single circle around the planet. Trajectory optimizations show that the orbiter is able to deliver internally more than 26900 kg of separable payload to the very low and unstable orbit. Subsequently, an orbital transfer is necessary from LEO to GTO. A generic storable propellant upper stage has been selected for payload transfer to the 250 km × 35786 km GTO. A separated satellite mass in GTO of more than 8000 kg is achievable, ready for super-heavy communication platforms of the future.

3.2.6.3 RLV-stage re-entry and return flight

A major challenge of all RLV is the approach to the landing or return to the launch site of all reusable stages. The SpaceLiner Orbiter reentry has been simulated with an entry interface speed of approximately 7.37 km/s. Reaching its once-around destination is without problem for the orbiter due to its very good hypersonic L/D well above 2. The vehicle crosses Central America at high altitude and turns to the South over the Caribbean Sea with almost no sonic boom audible on ground [21].

The maximum heatloads remain slightly lower than for the reference passenger concept because of a different AoA-profile and lower vehicle mass. [21] For the reusable booster the innovative 'in-air-capturing' [34] should be employed which is currently in lab-scale-testing at DLR.

3.2.6.4 Ascent flight Control

In order to investigate the attitude dynamics of the asymmetric launcher configuration (Figure 2), a 6 DOF trajectory simulation has been established. The main objective of this model is to evaluate the controllability of the vehicle in all nominal and off-nominal flight conditions.

During ascent flight the SpaceLiner trajectory is primarily controlled by the thrust vector control system (TVC). Its main task is to trim the variable position of the CoG as well as the aerodynamic moments by means of gimballing the SpaceLiner Main Engines. Based on the developed SpaceLiner model a simulation study has been concluded investigating the flight dynamics of the SpaceLiner on the reference mission from Australia to Europe. Besides the determination of the undisturbed ascent trajectory, this study considers also simulation cases with atmospheric disturbances. As shown in [22], the maximum vertical deflections are limited to ±2.5° while the lateral deflection angles remain below ±0.6°. Crosswinds are significantly increasing the necessary deflections for roll control, raising the lateral deflection range up to ±1.4° in the disturbed simulation cases. However, these deflection angles are far below the gimbal limit of ±8.5° of typical rocket engines providing good control margins. Off-nominal flight conditions including engine-out situations are currently under investigation.

3.2.7 Operational aspects

3.2.7.1 Environmental constraints

The launch and ascent noise as well as the sonic boom reaching ground are most critical for a viable SpaceLiner operation in the future. The selection of potential SpaceLiner launch and landing sites will likely be influenced by constraints due to generated noise. Most of SpaceLiner trajectory at high altitudes, thus sonic boom noise is much less than for Concorde. Therefore, operational scenarios of the SpaceLiner are established taking into account realistic launch- and landing sites as well as groundtracks which are acceptable with respect to sonic boom constraints overflying populated areas and fast accessibility to major business centers [22]. Final approach requires routes considering noise and ATM-integration.

The rocket engine exhaust is water steam; thus completely CO2-free if LH2 and LOX are produced via environmentally friendly means. No NOx is generated as no air is burned in the propulsion system. The climatic impact of water in the stratosphere, distributed locally during early ascent, needs to be carefully studied. In the mesosphere the impact on climate is probably low due to photochemical processes removing the water.

3.2.7.2 Cost Assessment

The SpaceLiner development and operations should be funded mostly by private investment. Forms of private public partnerships are potential options to limit the investment risks in this revolutionary concept. In any case a reliable estimation of to-be-expected costs during development, production, and operations is already required early in the technical design process. Using this approach, a market oriented development can be performed.

Sophisticated analyses of the expected SpaceLiner development and production costs have been parametrically assessed [35]. Based on different cost estimation approaches the development and production costs are estimated and sensitivity of data is obtained. The SpaceLiner aims at securing a small portion of the 350+ million PAX/a on intercontinental routes. Results of a business case assessment indicate that the SpaceLiner is not only a technically feasible concept but also one for which a viable business case might exist [11]. A simplified operational scenario has been established and key elements of the SpaceLiner ground infrastructure are identified and compared [36]. Further elaboration of this concept is a crucial part of the Phase A activities.

4 Conclusion

The DLR proposed reusable winged rocket SpaceLiner for very high-speed intercontinental passenger transport has successfully completed its Mission Requirements Review (MRR) in summer 2016 and is progressing in its conceptual design phase. Research on the vehicle has been performed with support from the EU projects FAST20XX, CHATT, HIKARI and HYPMOCES with several 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 fully reusable 2-stage concept is a perfect example to demonstrate the complexities of the interdisciplinary RLV design process and technical systems analysis. Several challenging research areas are identified in the fields of propulsion, structural design, aerothermodynamics, environmental & medical issues, as well as operations and economics.

Beyond its visionary potential of new ultrafast passenger transportation and low-cost cargo delivery to orbit, the SpaceLiner configuration serves as a catalyst for applied research on advanced reusable launchers.

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