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Progress of SpaceLiner Rocket-Powered High-Speed Concept

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DLR's launcher systems analysis division is investigating since a couple of years a visionary, extremely fast passenger transportation concept based on rocket propulsion. Thanks to the multi-national collaboration, the technical lay-out of the SpaceLiner has now matured to Phase A conceptual design level. Iterative sizing of all major subcomponents in nominal and off-nominal flight conditions has been performed.

The paper describes the technical progress achieved for the most recent SpaceLiner 7 configuration:
- **system aspects of the reference vehicle's preliminary design including its nominal trajectory,**
- **main propulsion system definition,**
- **pre-development of a passenger cabin and rescue capsule,**
- **establishment of a preliminary structural concept,**
- **preliminary sizing of the thermal protection and active cooling systems,**
- **evolution of the passenger stage for different missions allowing for increased passenger numbers on shorter flight distances**
- **cost estimation and preliminary business case analyses**

Nomenclature

D	Drag	N
I_{sp}	(mass) specific Impulse	s (N s / kg)
L	Lift	N
M	Mach-number	-
T	Thrust	N
W	weight	N
g	gravity acceleration	m/s^2
m	mass	kg
q	dynamic pressure	Pa
v	velocity	m/s
α	angle of attack	-
γ	flight path angle	-

Subscripts, Abbreviations

AOA	Angle of Attack
CAD	computer aided design
CMC	Ceramic Matrix Composites
DSMC	Direct Simulation Monte Carlo
GLOW	Gross Lift-Off Mass
LFBB	Liquid Fly-Back Booster
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MECO	Main Engine Cut Off
MR	mixture ratio
NPSP	Net Positive Suction Pressure
PEEK	Poly-ether-ether ketone
RLV	Reusable Launch Vehicle
SSME	Space Shuttle Main Engine
TPS	Thermal Protection System
TRL	Technology Readiness Level
cog	center of gravity
cop	center of pressure

1 INTRODUCTION

A strategic vision of DLR which ultimately has the potential to enable sustainable low-cost space transportation to orbit is under technical evaluation since a couple of years. The number of launches per year should be strongly raised and hence manufacturing and operating cost of launcher hardware should dramatically shrink. The obvious challenge of the vision is to identify the very application creating this new, large-size market.

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 might be 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. Another interesting intercontinental destination between Europe and North-West America could be reduced to flight times of slightly more than one hour.

Ultra-fast transportation far in excess of supersonic and even potential hypersonic airplanes is definitely a fundamental new application for launch vehicles. By no more than partially tapping the huge intercontinental travel and tourism market, production rates of RLVs and their rocket engines could increase hundredfold which is out of reach for all other known earth-orbit space transportation. The fast intercontinental travel space tourism, not only attracting the leisure market, would, as a byproduct, also enable to considerably reduce the cost of space transportation to orbit.

Figure 1: The SpaceLiner vision of a rocket-propelled intercontinental passenger transport could push spaceflight further than any other credible scenario

2 GENERAL DESCRIPTION OF SPACELINER CONCEPT

2.1 Status of Previous Technical Development

First proposed in 2005 [1], the SpaceLiner is under constant development and descriptions of some major updates have been published since then [2, 5, 7, 11, 19, 22]. The European Union's 7th Research Framework Programme has supported several important aspects of multidisciplinary and multinational cooperation in the projects FAST20XX [6, 15], CHATT [15], and HIKARI.

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 Figure 2. The box is marking the configuration trade-offs performed in FAST20XX in 2009/10.

These configuration studies supported the definition of the next reference configuration SpaceLiner7. The level of engineering detail of the traded configurations was not exactly the same as for the previous reference SpaceLiner2 type. E.g. full CAD models have not always been generated. However, obtained data of the interim research configurations 3, 4, 5, and 6 are at sufficiently high quality because they have been iteratively sized with careful scaling of the reference mass break-down, preliminary aerodynamic sizing and always trajectory optimization. An overview on these configurations can be found in [7].

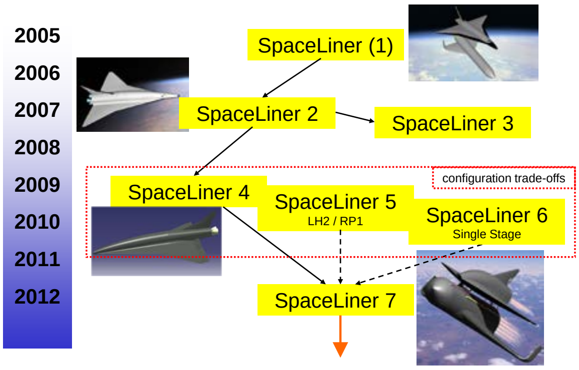

Figure 2: Evolution of the SpaceLiner concept

At the end of 2012 with conclusion of FAST20XX the SpaceLiner 7 reached a consolidated technical status which is described in the following section 3.

The general baseline design concept consists of a fully reusable booster and passenger stage arranged in parallel. All rocket engines should work from lift-off until MECO. A propellant crossfeed from the booster to the passenger stage (also called orbiter) is foreseen up to separation to reduce the overall size of the configuration. After fast acceleration to its maximum speed the hypersonic transport is gliding for the remaining more than one hour flight to its destination.

2.2 Mission Definition

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 [24]. In order to keep the number of different stage configurations at the lowest possible level, the potentially interesting flight destinations have been divided into three classes:

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

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

3 LATEST SPACELINER 7 CONFIGURATION

Since the last IAC2010-overview paper on the Space-Liner [7] significant technical progress related to the overall launch configuration as well as to both stages, the reusable booster and the orbiter or passenger stage, has been achieved. The current arrangement of the two vehicles at lift-off is presented in Figure 3. Stage attachments are following a classical tripod design. The axial thrust of the booster is introduced through the forward attachment from booster intertank into the nose gear connection structure of the orbiter. The aft attachment takes all side and maneuvering loads. The option of a belly to belly connection is not preferred for two reasons: A strong unintended aerodynamic interaction of the two wings and propellant crossfeed lines on the booster which would be directly affected by hypersonic flow during reentry of this stage. Thus, the arrangement in Figure 3 is the current baseline, however, it is still subject to trade-offs and optimization and hence might be changed in the future.

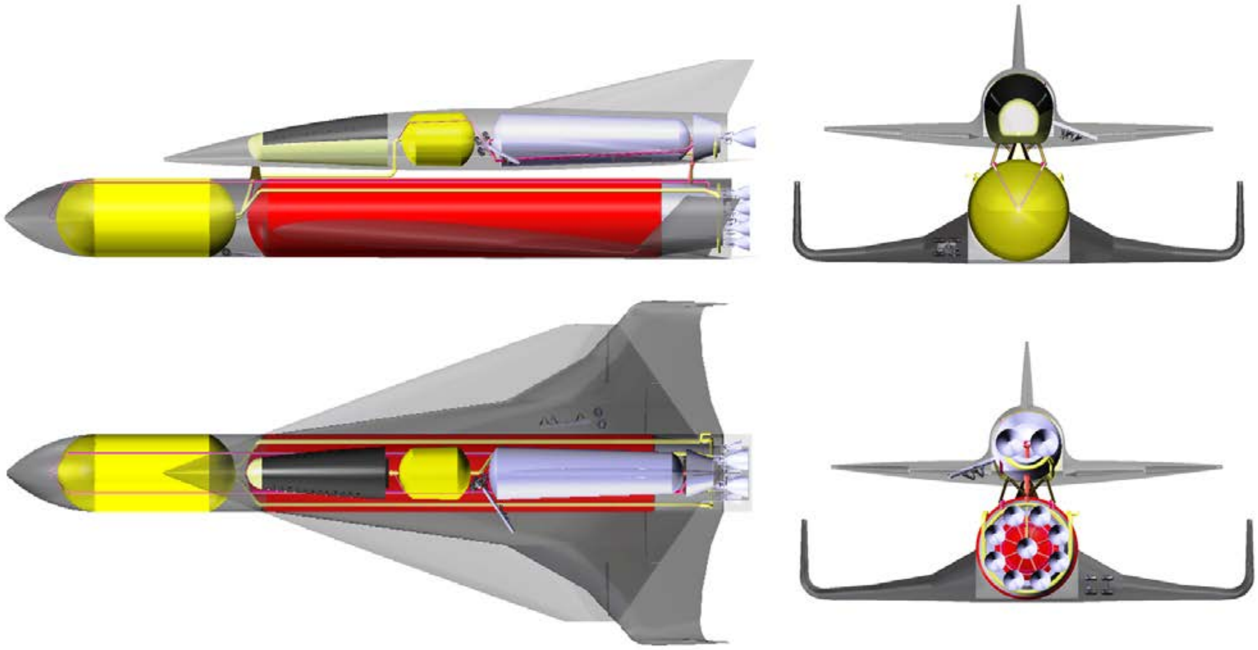

Figure 3: Sketch of latest SpaceLiner 7-2 launch configuration with passenger stage on top and booster stage at bottom position with approximate location of stage attachment

Table 1: Geometrical data of SpaceLiner 7-2 booster stage

length [m]	span [m]	height [m]	fuselage diameter [m]	wing leading edge angles [deg]	wing pitch angle [deg]	wing dihedral angle [deg]
83.5	36.0	8.7	8.6	82/61/43	3.5	0

Table 2: Geometrical data of SpaceLiner 7-1 passenger 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

3.1 Definition of reusable booster stage

Since the beginning of the SpaceLiner investigations the reusable booster stage has always been somewhat in the shadow of the orbiter which is carrying the passengers and is experiencing the highest thermal loads and reaching maximum velocity and altitude. However, the booster is a also very high performance launch vehicle stage and critical to the overall success of the SpaceLiner configuration.

The separation Mach number of the reference mission is approximately 12.5 which is already too high for any powered fly-back with acceptable amount of on-board fuel. A down-range landing site, if available at all, is not attractive for logistical reasons. Therefore, the patented in-air-capturing method [**16**, **17**] should be used. The empty stage is to be captured during subsonic descent and subsequently towed back by an airplane and finally released for an autonomous gliding landing on a runway. In simulations of the SpaceLiner booster's reentry it is always assured that sufficient time for the in-air-capturing maneuver is available.

Several booster design trade-offs have been performed always carefully considering the trimmability and flyability of the aerodynamic configuration. Also flexible wings (e.g. foldable or rotatable) could be interesting because the aerodynamic interference of both stages in mated ascent would become significantly lower. Such a design has been systematically investigated by DLR for another booster configuration [**18**] and was assessed as feasible. However, a flexible wing design is always related to additional structural and mechanical system mass.

The current SpaceLiner 7-2 booster geometry is more conventional with two large tanks with separate bulkheads for LOX and LH2 which resembles the Space Shuttle External tank lay-out. The only 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 latest shape update to configuration 7-2 included a larger and more complicated wing with long strakes which became necessary for aerodynamic reasons in low speed landing approach. The overall size of the booster is reaching significant dimensions of more than 80 m in length, if the ambitious reference mission is to be served. Major data are listed in Table 1.

A structural pre-dimensioning of the previous SpaceLiner 7-1 booster with similar fuselage but different wing has been performed at FOI in Sweden. For the design of these structural members inspiration was taken from the current conventional way of construction aircraft fuselages called semi-monocoque. The semi-monocoque utilizes a substructure of formers and stringers that help prevent local bending of the stressed skin and relieves it of some of the global bending stresses. The two tanks are part of the load carrying structure and therefore the structural members are placed internally. The well-proven aluminum alloy 2024 is chosen as material for the booster's primary structure. The structure of the wing also follows aircraft convention with ribs to make up the shape of the wing profile and spars to carry the main bending load (Figure 4).

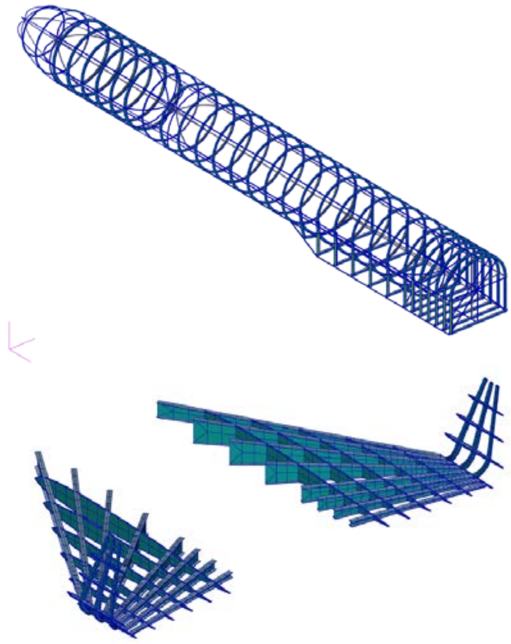

Figure 4: Finite elements of SpaceLiner 7-1 booster substructure from FEM analysis at FOI [26]

The FOI structural design has not only been looking into static load analyses but was also addressing structural dynamic issues which are potentially critical for the feasibility of the design. During the Eigenfrequency analysis it became necessary to increase the stiffness of the structure. Therefore the skin is now a sandwich made up of CFRP face sheets and polymer foam in-between.

The results from the static aeroelastic analysis show that the winglets need reconsideration because stress and strain peaks in the wing-winglet connections close to and above the limits of the materials were found. [26] Another critical point has been detected by Eigenmode analysis: The huge winglets are keeping the first few Eigenmodes of the smaller version7-1-wings as low as around 4 Hz and below the global bending mode of the fuselage. If this unfortunate situation would remain for the new larger and stiffer wing of version 7-2, it might become necessary to reposition the lateral stability surfaces to another vehicle station, preferably the fuselage. However, then an integration challenge will arise for the launch configuration which could require the attachment of foldable or movable fins.

FOI's booster lay-out is not meant to be a final model of the structure, but should serve as an initial conceptual model for future work when the next iteration of the SpaceLiner is undertaken [26].

A preliminary definition of the landing gear has been performed assuming a landing speed of 100 m/s. A margin of 2.5° has been added to the computed AoA required by simplified aerodynamics not considering ground effect and vortex generation. Two wheels have been selected for the nose gear and the main gear utilizes 4 wheels per strut. The nose and the main gear are integrated in intertank structure and in the wing root region respectively. The struts' lengths might be reduced somehow when more detailed low-speed aerodynamic data are available.

As the structural pre-design is not yet finished, all dry mass data are still based on empirical estimation relations derived of launch vehicles or hypersonic transport studies (see Table 3). System margins of 14% (12 % for propulsion) are added to the estimated mass data.

3.2 Definition of reusable passenger stage

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

The SpaceLiner7 is the first SpaceLiner configuration characterized by an aerodynamic shape arisen 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. The final result of the optimizations, a trade-off between the optima of the three trajectory points, showed considerable improvements in glide ratio and heat loads and pointed out the clear advantages of a single delta wing [10, 19].

Further design refinement of components and subsystems added some mass to the configuration and resulted in a shift in center of gravity. The latest shape optimization in 2012 resulted in a different trailing edge angle which affects the center of pressure position in a way that the pitching moment at maximum L/D hypersonic flight is very close to its trimmed state without any significant control surface deflection. Thus, the optimum gliding efficiency and hence range is achieved. The aft fuselage height has been increased allowing additional fuel to be accommodated without almost any impact on drag and a vertical stabilizer with very large leading edge inclination has been chosen [22]. The resulting shape of the latest SpaceLiner7 passenger stage is shown in Figure 5. The SpaceLiner's wing flaps' definition is based on the most extreme flight maneuvers to be expected: an abort scenario starting at the time of booster separation with the passenger stage's propulsion system inoperative. A re-entry trajectory for this case is simulated with the constraint of maximal allowed loads [12]. The wing flaps shown in blue in Figure 5 are following this sizing approach. The flap's hinge line attachment is influenced by the Space Shuttle example. The overall design will still require a more detailed assessment of efficiency and aerothermodynamic issues in the future.

Major geometry data of the SpaceLiner 7-1 orbiter stage are summarized in Table 2.

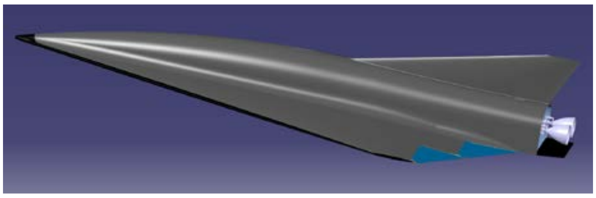

Figure 5: SpaceLiner 7-1 orbiter shape

3.3 Preliminary aerodynamic database

Aerodynamic data sets have been generated with different numerical tools and an aerodynamic database for preliminary engineering design work has been established [27] for all four SpaceLiner flight configurations: The mated launch vehicle, the booster stage, the passenger stage, and the rescue capsule.

The SpaceLiner 7-1 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. Figure 6 demonstrates the strong effect of boundary layer transition and by different trailing edge flap deflections on L/D. Therefore, any significant flap deflection is to be avoided in hypersonic gliding flight in order to achieve good range efficiency.

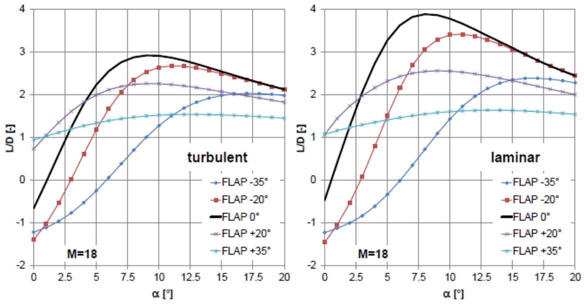

Figure 6: Lift-Drag-ratio of SpaceLiner 7-1 passenger stage at M= 18 in 58 km (fully turbulent boundary layer at left, laminar at right), example from aerodynamic data base [27]

ESA has been calculating the shape of the SpaceLiner 7-1 passenger stage with Euler CFD (Figure 7). An unstructured grid with several million elements has been generated. Obtained coefficients have been used for establishing the aerodynamic data base. In the hypersonic flight regime these CFD lift and drag data are in very good agreement with those of engineering methods previously generated by DLR which justifies the programs used in the aerodynamic optimization process mentioned in section 3.2.

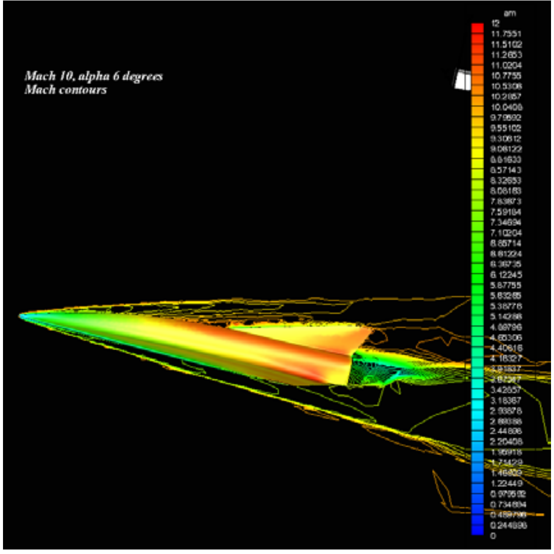

Figure 7: Mach contours of SpaceLiner 7-1 passenger stage at M= 10, α= 6° from ESA-ESTEC Euler CFD-calculation

The range of SpaceLiner altitudes in which rarefactions effects are expected is 75÷85 km. The inviscid conditions are based on the continuum aerodatabase [27], while the free molecular flow data have been computed by means of DSMC. In between bridging functions are applied which deliver the altitude dependence of longitudinal aerodynamic coefficients for the 7-1 configuration [33].

3.4 Subsystem definitions

3.4.1 Main propulsion system

Staged combustion cycle rocket engines with a moderate 16 MPa chamber pressure have been selected as the baseline propulsion system. The engine performance data are not overly ambitious and have already been exceeded by existing engines like SSME or RD-0120. However, the ambitious goal of a passenger rocket is to considerably enhance reliability and reusability of the engines beyond the current state of the art. The expansion ratios of the booster and orbiter engines are adapted to their respective optimums; while the mass flow, turbo-machinery, and combustion chamber are assumed to remain identical in the baseline configuration.

Two types of staged combustion cycles (one full-flow and the other fuel-rich) have been considered for the SLME and traded by numerical cycle analyses [13, 20]. 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 a preferred design solution for the SpaceLiner. This approach should allow avoiding the complexity and cost of additional inert gases like Helium for sealing.

In a Full-Flow Staged Combustion Cycle (FFSC), two preburners whose mixture ratios are strongly different from each other generate turbine gas for the two turbo pumps. All of the fuel and oxidizer, except for the flow rates of the tank pressurisation, is fed to the fuel-rich preburner (FPB) and the oxidizer-rich preburner (OPB) after being pressurised by each turbo pump. After the turbine gas created in each preburner work on each turbine they are all injected in hot gaseous condition into the main combustion chamber (MCC). The regenerative cooling of the chamber and the nozzle is made with hydrogen fuel after being discharged by the FTP. The fuel tank pressurization gas is supplied from the fuel line after leaving the regenerative circuit while the oxidizer tank pressurization gas is bled from the oxidizer line behind the OTP discharge and then heated-up in a heat exchanger [13, 20].

The mixture ratios of FPB and OPB are controlled to be 0.7 and 130 so that TET is restricted to around 770 K. at each turbine a bypass line is foreseen for which the flow should be controlled by a hot gas valve in order to allow engine operation in the mixture ratio range from 5.5 to 6.5 without changing TET or excessively raising pre-burner pressures. The limitation of the nominal characteristic conditions should enable an engine lifetime of up to 25 flights. Further, this approach gives some margin to significantly raise engine power in case of emergency by increasing TET beyond the limitation [13].

Table 4 gives an overview about major SLME engine operation data for the nominal MR-range as obtained by cycle analyses. Note that the thrust level has been increased compared to previous engine configurations described in [7, 12, 13] to take into account the SpaceLiner 7-1 lift-off weight increase.

Cycle analyses results for the full-flow has been used for preliminary turbo-machinery sizing. An Integrated Power Head (Pre-burner + Turbine + Impeller pump) as used on the SSME is 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. Figure 8 shows the integration of all major components in the upper section of the engine and their integration with the combustion chamber injector head.

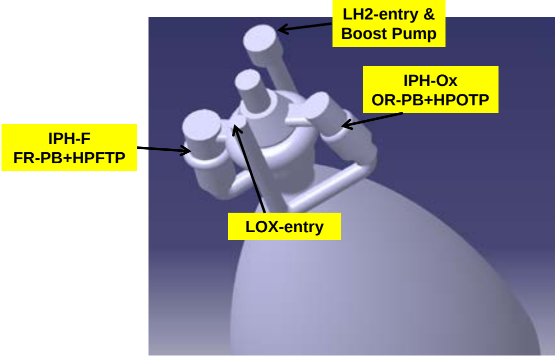

Figure 8: SLME simplified CAD geometry showing arrangement of turbomachinery

Table 3: Mass data of SpaceLiner 7-2 booster stage

Structure [Mg]	Propulsion [Mg]	Subsystem [Mg]	TPS [Mg]	Total dry [Mg]	Total propellant loading [Mg]	GLOW [Mg]
91.7	36	21.6	22.8	172.2	1290	1462

Table 4: SpaceLiner Main Engine (SLME) technical data

	Booster			Passenger Stage		
Mixture ratio [-]	5.5	6.0	6.5	5.5	6.0	6.5
Chamber pressure [MPa]	15.1	16.0	16.9	15.1	16.0	16.9
Fuel-rich Preburner pressure [MPa]	29.4	30.0	30.8	29.5	30.2	31.0
Oxidizer-rich Preburner pressure [MPa]	29.1	29.7	30.5	29.2	29.9	30.7
Fuel-rich Preburner TET [K]	732	735	738	720	722	724
Oxidizer-rich Preburner TET [K]	773	775	778	772	774	777
Mass flow per engine [kg/s]	481	517	555	481	518	555
Expansion ratio [-]	33	33	33	59	59	59
Specific impulse in vacuum [s]	439	437	435	451	449	448
Specific impulse at sea level [s]	387	389	390	357	363	367
Thrust in vacuum per engine [kN]	2061	2206	2356	2116	2268	2425
Thrust at sea level per engine [kN]	1817	1961	2111	1678	1830	1986

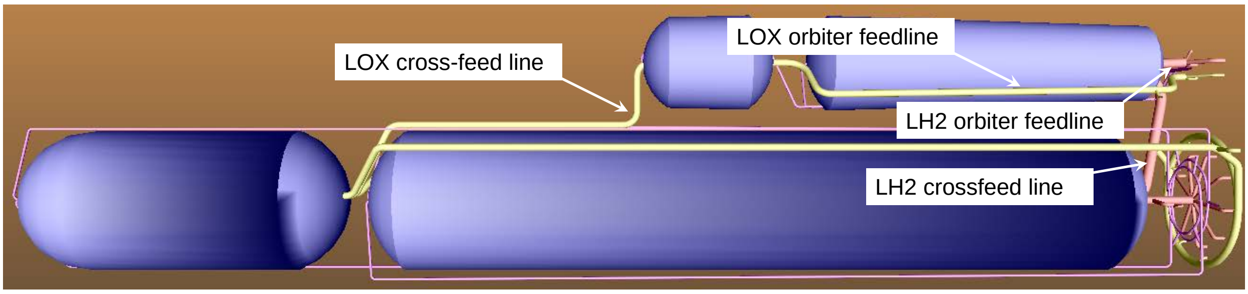

Figure 9: Arrangement of propellant tanks, feed- and pressurization system of SpaceLiner 7

On the fuel side a boost pump driven by an expander turbine fed from the regenerative circuit is feeding the HPFTP. HPFTP is a 2-stage Impeller pump powered by a 2-stage reaction turbine. On the LOX-side a conventional HPOTP with inducer and single stage impeller on the same shaft is proposed. A single stage turbine is probably sufficient to power the HPOTP. In case of the full-flow staged combustion cycle no LOX-split pump is necessary for raising discharge pressure to the fuel-rich preburner level.

3.4.2 Propellant feed and tank pressurization system

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 to reduce the latter's overall size. No crossfeed system for a configuration like the SpaceLiner has ever been built and therefore some investigation is required to determine how such a system could be implemented and how complexity issues can be addressed. Three main options of crossfeed exist:

- Line-to-line
- Tank-to-tank
- Tank-to-buffer-tank

All these are investigated 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.

The propellant feed- and pressurization system is preliminarily designed using the DLR-tool pmp. A preliminary arrangement of feed- and pressurization lines with the tanks of both stages in the mated configuration is shown in Figure 9.

Figure 10 shows the interesting pressure history inside the passenger stage's LOX-feed system obtained by steady simulation. A tank to tank crossfeed from the booster LOX-tank, positioned more than 25 m forward, generates significant hydrostatic pressure, indirectly forcing ullage pressure in the upper stage tank up to more than 8 bar. Further downstream in the feedline pressure values can exceed 16 bar. The effects of throttling and staging are clearly visible in Figure 10. Engine NPSP is generous and might allow for reducing the ullage pressure after staging.

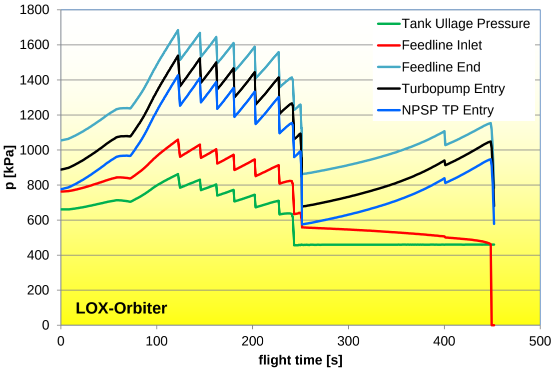

Figure 10: Pressure history at certain stations inside the orbiter LOX-tank feed system

The LOX-tanks are pressurized by gaseous oxygen and the hydrogen tanks with gaseous hydrogen. This approach is selected in order to avoid any excessive use of expensive and rare helium.

Tank pressures are selected that the minimum NPSP requirements in all feedline segments are respected along the full mission; especially those at the engine entry. A variation of pressurization gas temperatures has been performed. The booster LOX tank pressure can be limited to 2.1 bar because of its forward position always generating a lot of hydrostatic pressure down the line which is beneficial for good NPSP. Due to this fortunate situation, the required oxygen gas at stage booster MECO is below 3000 kg. The hydrogen gas mass inside the very large 2632 m^3 LH2-tank is no more than 1400 kg because of hydrogen's low molecular mass.

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

Four critical flight points are chosen to simulate the abort trajectory to demonstrate the SpaceLiner7 capsule is able to fly safely back to Earth during any perceived abort scenario:

- Launch pad
- Booster separation
- Highest altitude of the SpaceLiner7 orbiter
- Main engine cut-off (MECO)

Results of the trajectory simulations are presented in [21].

The separation motors are designed to separate the capsule from the orbiter, without exceeding recommended maximum acceleration limits. The following requirements are considered:

- reliability in performance
- ability to reach a safe distance in a short period of time
- ability to reach a certain altitude
- requirement to fit within the SpaceLiner7 orbiter

In order to fulfill these requirements, the SRM must provide a high acceleration in a very short period of time. Due to severe geometry constraints, it has been decided to utilize a five motor configuration. With a chamber pressure of 150 bar, an expansion ratio of 25 and a half angle of 15°, the length of the nozzle is slightly under 1 m and the entire length of one motor is approximately 1.4 m. The motor has an approximate thrust of 800 kN and a burn time of almost 2 s while the total mass of the propellant for all five motors adds up to 2.6 t [21].

The capsule can be subdivided in a pressurized cabin of conical shape and an outer aerodynamic shell formed by the Thermal Protection System (TPS) and which provides space for housing several non-pressurized subsystems as shown in Figure 11.

The TPS of the SpaceLiner7 capsule is required to withstand several different heat load conditions driven by the different nominal and abort cases it encounters. In the course of this investigation, it has to be distinguished which areas of the capsule (i.e. the nose area, upper half or lower half) are considered. During nominal flight, the capsule is considered part of the orbiter. This means that the lower half and nose are protected by the orbiter structure and its TPS. They are therefore, not subjected to the external heat load until the capsule is separated in an abort case. In contrast, the capsule's upper half is part of the orbiter's outer shell and so is heated up during nominal flight.

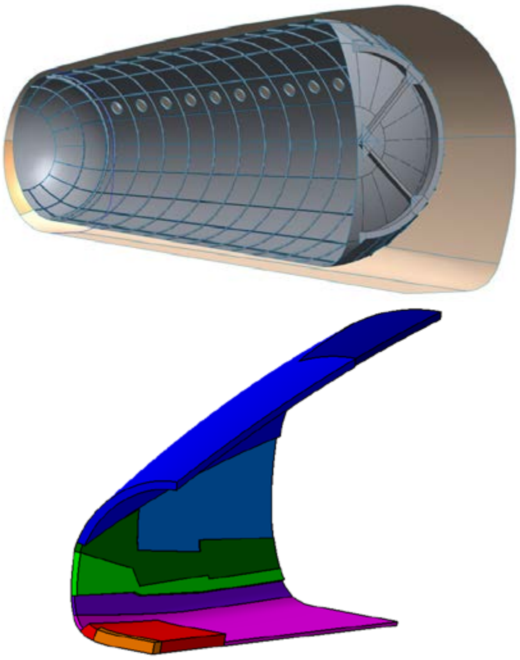

Figure 11: Integration of pressurized passenger cabin inside aerodynamic capsule shell (top) and TPS thickness distribution (bottom)

A potential internal cabin pre-design and the necessary life-support system mostly driven by medical requirements have been studied. Absolutely essential is a small shell-like protection around each seat which would automatically close in case of sudden cabin pressure drop. Light-weight inflatable solutions are most attractive.

In Figure 12, the capsule is presented in the side view. In this figure, the cabin floor and seats are roughly indicated. The nominal entry door will be in the forward upper section of the capsule where experiencing relatively small heat loads. The stair case will be used during boarding with the plan being for people to walk on board and take their seats while the capsule is still in a horizontal position. After passenger boarding is completed, the capsule will be lifted and subsequently be integrated into the orbiter on the launch pad.

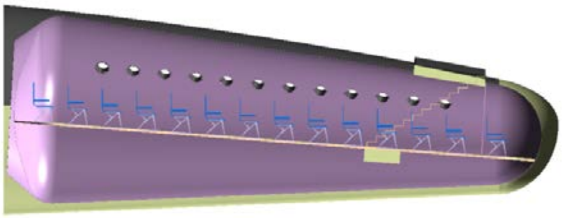

Figure 12: Capsule (side view) with cabin floor and access door

Overall length of the capsule without separation motors is 15.6 m and its maximum external height is 5.6 m. The estimated masses are slightly less than 30 tons for the dry capsule, about 7600 kg for the passengers, crew and luggage, and 3400 kg for all propellants of separation motor and RCS. The RCS propellants could also partly be used in the nominal mission of the SpaceLiner.

3.4.4 Structural pre-sizing

A structural analysis of the SpaceLiner7 is progressing in DLR and with the FAST20XX support of FOI from Sweden and Orbspace from Austria. Preliminary sizing of the passenger stage's tanks as CFRP structure will be performed within the CHATT research program.

An aeroshell-like structure for the passenger stage is most promising because of decoupling the maximum thermal gradients between cryogenic tanks and the outside surface. The internal protected structure could be metallic or CFRP. The Hypersonic vehicle Structural Analysis Program (HySAP) has been developed at DLR-SART which allows for fast and accurate structural pre-sizing of complicated integrated structures of hypersonic vehicles.

The main aim of the analyses for the SpaceLiner up to now has been the identification of tendencies, rather than generation of exact component mass values which will follow at a later stage. Main subjects of these investigations are [23]:

1) Variation of stiffening concepts
2) Variation of stiffener layer thickness
3) Variation of materials and impact on TPS mass
4) Variation of minimum gauge thickness
5) Impact of considering TPS thickness on structural mass
6) Impact of different load cases

In the first steps, strength and stability analyses of major components, like the fuselage with its frame and bulkheads and the wing with its spars, are addressed. A large number of load cases for the SpaceLiner have been defined. These will subsequently be analyzed for different material options and the necessary wall thickness will be determined.

Already early in the SpaceLiner structural design process, FOI started in FAST20XX investigations on the structural dynamic behavior of the passenger stage [9, 23]. Recently, DLR performed an Eigenmode analysis of the latest SpaceLiner 7-1 shape. Figure 13 shows the 3rd Eigenforms for two different potential structural solutions. In the top figure the nose fuselage frames are assumed to be closed as in typical aircraft design. The lower figure is representing the current SpaceLiner reference design with its large opening for integrating the passenger capsule. Without surprise, the reduced stiffness of the latter has significantly lower Eigen-frequencies which might become a critical issue, especially in case of torsion.

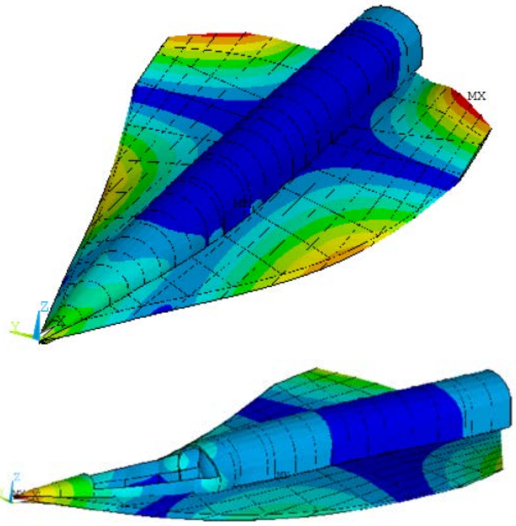

Figure 13: SpaceLiner 7-1 orbiter 3rd Eigenforms with different fuselage modeling

Alternative capsule integration options have already been discussed which could allow for more conventional fuselage lay-outs. However, the actual mass impact on the overall system is not easily assessed by a few structural design calculations. A much broader system impact is to be considered which includes aspects like the late on-launch-site-integration capability of the capsule, nominal and off-nominal flight conditions, and the emergency case separation of the capsule. The resulting mass distribution changes will influence the cog-position and hence trim-requirements which might even force an adaptation of the aerodynamic shape. Such an investigation which will assess the capsule integration design options under the same set of system requirements has just started at DLR.

Orbspace has been in charge of the structural assessment of the passenger capsule to obtain its conceptual structural design, in particular with respect to the window design, which is considered a critical vehicle subsystem. The main structure consists of a conical pressure vessel with a cone angle of about 12°. The nose is closed with a spherical bulkhead of 3100 mm diameter, and the rear with a convex tori-spherical bulkhead. The pressurized cabin is made of Al2219 T87.

The three dominant load cases of the capsule are the cabin pressure and the loads from the thrust of the separation rocket motors in axial and normal direction. The latter are generating axial and bending loads. The FE analysis has been carried out with shell elements only. An automatic unstructured mesh is generated for a half-symmetry of the cabin with about 8000 elements and 16000 nodes [28].

Based on the results of the analyses presented in [21], an axi-symmetric (conic) structural concept has been chosen for the pressurized cabin. In the following step of structural assessments, the structural response to the loads during the firing of the escape ejection motor has been addressed. The combined thrust of all escape ejection motors is in the order of 4000 kN. This subjects the passenger capsule to an acceleration of about 10 g. A thrust frame consisting of a cone, a ring frame and a cross-beam has been chosen to distribute these high thrust loads uniformly into the main vehicle structure. The structure itself has also been stiffened by a number of stringers and frames. The load case for the launch site abort has been chosen, because there is no differential pressure across the cabin wall which would provide a positive stiffening effect.

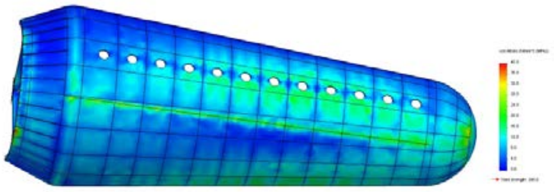

Figure 14: Von Mises stress distribution in passenger capsule under bending loads [28]

3.4.5 Thermal protection and active cooling subsystem

The preliminary sizing of the SpaceLiner7's Thermal Protection System (TPS) has been carried out for several different heat loads according to nominal flight and also for different abort cases. To be able to determine the heat loads for a full vehicle surface along different trajectories, fast engineering methods have to be used. HOTSOSE is a fast code for preliminary flow analyses in hypersonics based on modified Newtonian surface inclination techniques. Friction drag is estimated for each panel with the classical analytical methods for compressible laminar or turbulent flow of van Driest and White-Christoph. The surface temperatures are calculated under assumption of an adiabatic wall in radiation equilibrium. Heat fluxes are determined by using the Fay-Ridell equation close to the stagnation point and the Zoby-Moss-Sutton approach further downstream. The real gas effects on gasdynamic and transport properties can be considered in the calculation for chemically reacting air in equilibrium [2]. A fully turbulent flow along the flight path has been assumed for the TPS dimensioning as a conservative assumption. HOTSOSE calculates the heat fluxes at each mesh point at selected flight conditions with Mach number, altitude, and angle of attack known from trajectory simulations. By this approach a heat flux profile over time is obtained for the complete vehicle surface.

Due to the requirement of reusability, only non-ablative materials are suitable on the SpaceLiner's surface. According to the different maximum temperatures occurring at the different surface areas, different materials are chosen. Most important are [29]:

- **AFRSI** (Advanced Flexible Reusable Surface Insulation) was developed as a partial replacement for FRSI and LRSI on the Space Shuttle orbiter. It should be easier to maintain and withstands temperatures of up to 922 K. AFRSI, as currently selected for the SpaceLiner, is composed of an outer fabric with C-9 coating, a Q-fiber felt insulation and

an inner fabric layer and is attached to the structure with RTV adhesive.
- The multi-layer **CMC**-Alumina insulation is a composite of a ceramic matrix composite and fibres. Typically the fibres are carbon and the matrix is siliciumcarbide. The insulation material is ZIRCAR Alumina Mat, because it has a low density and a low conductivity. The thickness of the CMC cover is kept at 6 mm with the potential option of reducing the thickness. The maximum temperature for CMC is 2000 K and for the alumina insulation 1923 K.

The maximum acceptable temperature of any passive TPS on the SpaceLiner is 1850 K. The leading edge and nose areas exceed this limit and need an advanced active cooling (see below). Optimizing the material thickness for each of the thousands of mesh points on the vehicle would be excessively computational intensive. Additionally, this would yield a design without sufficient margin on the TPS thickness and which would be unpractical for manufacturing. Therefore, the vehicle surface is divided into a number of different regions, depending on the overall maximum temperature for all nominal and abort trajectories. To determine the optimum thickness of every area, TOP2, another in-house tool is used. It provides additionally the masses and corresponding CoGs of the different TPS areas (see Figure 15).

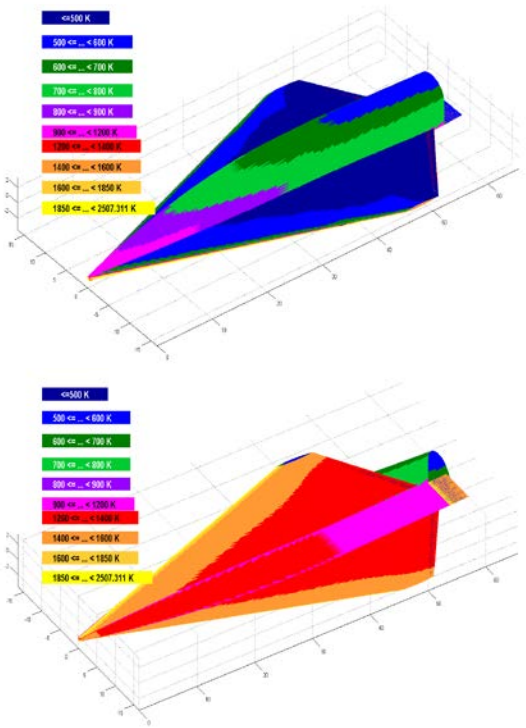

Figure 15: Overall maximum surface temperature areas (considering nominal and abort trajectories) on upper and lower side of passenger stage [29]

The maximum acceptable temperatures for the passive TPS is limited to approximately 1850 K to be compliant with the reusability requirement. The structure is set to be allowed to heat up to 530 K. This leads to a total TPS mass on the passenger stage (without capsule and tank insulation) of approximately 26.2 tons [29] (29.8 tons including system mass margin).

In a similar design procedure the TPS of the reusable booster stage has been defined, however, only for the nominal trajectory because no flight abort maneuvers were considered necessary. Large upper surface areas are to be covered by thermal blankets. The booster's TPS mass reaches approximately 17.2 tons (without cryogenic tank insulation) [29] (19.6 tons including system mass margin).

In those areas where the heatflux and temperatures exceed those values acceptable by CMC, transpiration cooling using liquid water is foreseen [2, 8, 12]. This relatively small area is highlighted in Figure 16 in violet color. 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 [31]. Tests have now been concluded and results of cooling efficiency are in good agreement with earlier research [2, 8] using a different material. The pressure drop of the cooling flow going through the leading edge or nose wall material is no more than 200 or 300 kPa. A simplified numerical simulation of the transpiration cooling has also been performed.

Although this advanced cooling process is still at a TRL of 3, a first preliminary active cooling pre-design has been executed at DLR-SART for the SpaceLiner geometry. Approximately 10000 kg of water are needed for cooling during a nominal mission. The transpiration of H_2O is already starting during the final phase of the powered orbiter flight when leading edge temperatures are already becoming excessively high. Flight abort missions have also been assessed and the water coolant mass is found to be much lower than for the nominal case despite some more severe heat flux peaks. However, the overall energy of the off-nominal cases is lower, resulting in reduced coolant demand.

A water storage tank system, a feedline manifold including control and check-valves and some bypass and redundancy lines are sized for accommodation inside the SpaceLiner volume. It is interesting to note that already in 1970 TRW studied and pre-dimensioned a somewhat similar system under NASA contract [25].

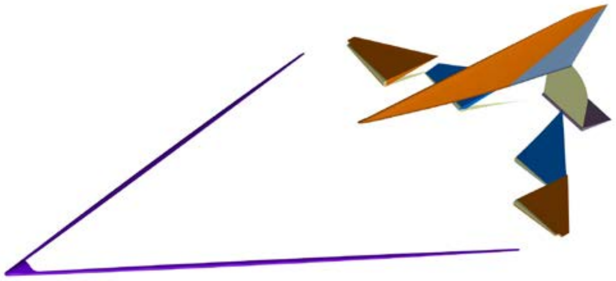

Figure 16: Actively cooled regions on SpaceLiner 7 relative to aerodynamic control surfaces

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. However, real flight conditions usually are more complex and demanding than those in a laboratory. 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. A more detailed system assessment of the different design options based on reliable mass estimations should be performed in the next iteration steps.

3.5 System masses

Based on available subsystem sizing and empirical mass estimation relationships, the orbiter mass is derived as listed in 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. The stages' MECO mass is approximately 162.6 Mg. The SpaceLiner 7-1's GLOW reaches now almost 1840 Mg (Table 6) for the reference mission Australia – Europe. This relatively large value is still below that of the Space Shuttle STS of more than 2000 Mg and therefore technically within reach.

Table 5: Mass data of SpaceLiner 7-1 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]
56.2	10.1	43.5	30.8	140.6	229.6	376.8

Table 6: Mass data of SpaceLiner 7-1 launch configuration

Total dry [Mg]	Total propellant loading [Mg]	GLOW incl. passengers & payload [Mg]
310.9	1520	1838.7

3.6 Nominal trajectory

Several trajectory options have been traded for the Australia – Europe reference mission. These are all 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. This is the same baseline trajectory which has been established for the SpaceLiner 4 using ASTOS optimizations [11]. Maximum speed of the vehicle is around 7.1 km/s at 69 km and the flight path angle γ at MECO is close to 0° (Figure 17). Then the propulsive phase is directly followed by hypersonic gliding.

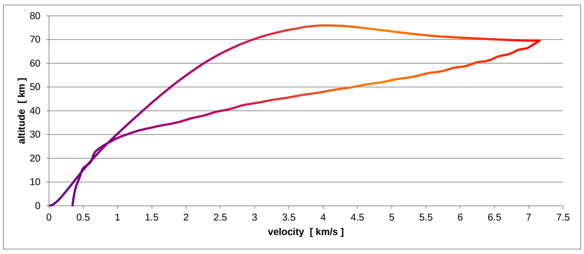

Figure 17: Nominal reference trajectory of SpaceLiner 7-1

An alternative option is a trajectory with a few degrees of γ in this point which would result in a ballistic arc duration of a couple of minutes for the SpaceLiner. The vehicle would travel during this phase more than 1000 km almost outside of the atmosphere at very low drag. However, in order to avoid excessive heatrates, an increased angle-of-attack is subsequently needed at lower altitude which has a strongly decelerating effect. A definitive answer on the best trajectory requires detailed system studies taking into account flight path optimization, adapted TPS-sizing, and reliable data on the friction drag in low atmospheric density. The Italian aeronautical research establishment CIRA's DSMC calculations of the SpaceLiner at high altitudes [15, 33] are providing realistic drag coefficients under these conditions (see also section 3.3 above).

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 [22]. New trajectory optimizations should take into account such constraints of a realistic operational scenario which are restrictions in acceptable flight corridors and relative proximity to potential customers.

4 COST ESTIMATION AND BUSINESS CASE ANALYSES

The SpaceLiner development and operations should one day be funded mostly by private investment. Forms of private public partnerships are other potential options. 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. Recently a paper has been published [32] giving a detailed description from which the most important results are summarized here.

4.1 Cost estimation

In the early phase of development, a parametric cost estimation approach is most promising. The TransCost model of cost engineering for space transportation systems has been used as the baseline tool. However, some adaptations or modifications are included if found appropriate. [32] At least concerning the development cost fraction, the TransCost model seems to be well suited as it includes a lot of reference data also on different RLV-projects of the past. All cost estimation is done for major components, e.g. stages or main propulsion systems.

The SpaceLiner is a two stage vehicle system comprising of the reusable booster stage (SLB) and the passenger stage (SLO). Furthermore, the SLO features an integrated passenger segment (SPC) which has a hybrid function of serving as a passenger cabin, and as a rescue capsule in case of a catastrophic emergency. Its prime goal is to eject from the SLO body, and autonomously and safely return the passengers back to the ground. In this regard, the SPC features its own solid propulsion system and is a potentially flying vehicle. As such, within the scope of the calculations and also in line with the TransCost definition, the SPC is taken to be a separate stage in its own right. Ramifications of this assumption are quite large, since development costs, if calculated for a separate stage, would be significantly higher than if this stage was considered as an integrated component within another already existing stage. [32]

In terms of propulsion, the SpaceLiner main engine needs to be newly developed, with the key challenge being the required reusability of at least 25 missions. The booster uses engines very similar to those of the passenger stage (see section 3.4.1), and thus only one common engine development cost is incurred. [32]

So, in summary, there are four SpaceLiner components which are foreseen to encounter both non-recurring development costs, as well as consequent production costs. These are:

- SpaceLiner fly-back Booster (SLB or SLFBB)
- SpaceLiner Orbiter (SLO)
- SpaceLiner main engine (SLME)
- Passenger cabin and passenger rescue capsule (SPC or PC-PRC)

The TransCost 8.1 calculated results of the SpaceLiner development costs are presented with a certain range of uncertainty in [32]. Actual cost for development, ground testing, and prototype flying is in the range 25 to 32 B€. Figure 18 shows the relative shares of the major components.

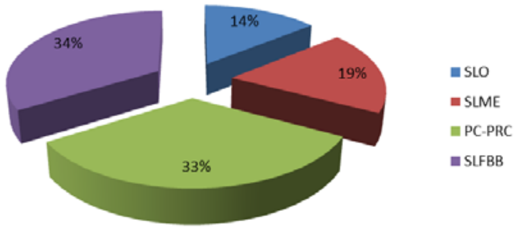

Figure 18: Relative distribution of SpaceLiner development costs according to major components

A similar calculation for the production cost based on TransCost estimation of the Theoretical First Unit (TFU) cost and a learning curve assumption has been performed [32]. However, the SpaceLiner production should be much more organized like in civil aviation than in launcher hardware production. Therefore, the TransCost estimation is less suitable and other relationships should be introduced in the future.

4.2 Business case

The preliminary cost inputs derived from the TransCost calculations were fed into an Orbspace developed Business Case Simulator (BCS) software tool, for the preliminary establishment and analysis of a business case. The combination of the process to establish initial and justifiable development and production cost estimates to use as input for a tool business case simulation tool is considered a solid foundation and methodology for future development of the SpaceLiner LCC assessment.

The simulator has been written in Octave57. A number of simplifications have been introduced in the process to build a fair and representative model of the economic reality. These are listed below:

- Primary costs expressed in effort (WYr): The costs in high-technology undertakings are primarily defined by the effort. The primary cost unit in the simulator is therefore in effort, or the work-year (WYr). After estimating the required work force, the costs are then derived based on basic WYr cost assumptions. Only in cost modules, where this approach is not meaningful, direct cost estimation has been implemented.
- “All-in-one company” approach: To avoid the complexity of estimating the cost of outsourcing or subcontracting it has been assumed that the entire business, from vehicle development, production to flight operations is conducted by one single company.
- Maintaining technical competences has been given particular attention in the modeling. Monthly hiring limitations have been applied to account for the limited availability of competences as well as the additional penalty costs when laying off personnel (if so required by a reduction in demand). Moreover, a parameter has been introduced defining a minimum level of development staff required to keep the business operational and functioning (i.e. in order to be able to properly conduct accident investigations and to resolve any underlying technical issues to maintain or regain the safety of the vehicle). [32]

The overall model is still much simplified, only based on the reference configuration for the Australia – Europe mission which is the technically best matured design. Potential derivatives of the SpaceLiner for shorter missions and higher passenger demand (see section 2.2 and [24]) are not yet included in the BCS simulation. The total number of flights is already assuming world-wide operations. A significant profit could be generated as is shown in Figure 19.

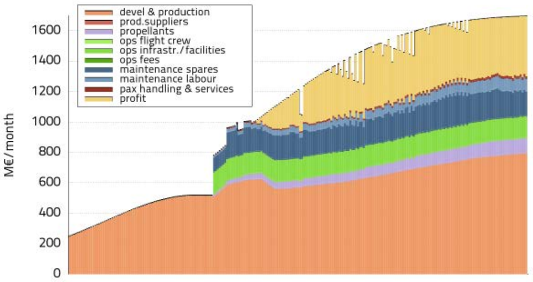

Figure 19: Typical plot of Orbspace Business Case Simulator (BCS) for SpaceLiner operations

All assumptions made for the early business case simulation of the SpaceLiner are described in [32]. A more sophisticated model will be established and improvements on the cost estimation will be implemented in the future.

5 CONCLUSION

The DLR proposed reusable winged rocket SpaceLiner for very high-speed intercontinental passenger transport is constantly maturing in its conceptual design. Research on the vehicle has been performed with support from the EU projects FAST20XX and CHATT 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 potential intercontinental SpaceLiner missions have been subdivided into three classes of which class 1 is the ambitious Australia – Europe reference flight presented in this paper. A variable engine mixture ratio along the ascent is able to boost average Isp-performance and in combination with interstage propellant crossfeed allows for significantly reducing the overall size of the vehicle.

The latest iteration step of the SpaceLiner concept is the version 7 which is based more and more on preliminary design of different subsystems and vehicle structures. An integrated interdisciplinary design process of the passenger stage is ongoing and has delivered a convergent configuration. The paper presents the latest investigation status on major subsystems like the full-flow staged combustion main engine, the tank-, feed-, crossfeed- and pressurization system, the integrated passenger cabin and rescue capsule, the structural design, and the thermal protection- and active cooling subsystem.

Furthermore, early cost estimations have been concluded and a first business case simulation has been performed. Early results indicate that the SpaceLiner is not only a technically feasible concept but also one for which a viable business case might exist.

Work on the visionary SpaceLiner concept is gaining momentum in the European aerospace community.

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Further information on FAST20XX can be found on http://www.esa.int/fast20xx.

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Further updated information concerning the SART space transportation concepts is available at:
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