The SpaceLiner 7 – Vehicle and Rescue Capsule

By Carola BAUER, Nicole GARBERS and Martin SIPPEL

German Aerospace Centre (DLR), Space Launcher System Analysis (SART)
Institute of Space Systems, Bremen, Germany

The SpaceLiner high speed passenger transport concept has been under investigation since 2005, and during this time the geometry has changed due to the application of progressively more detailed analyses. However, from the beginning safety was seen as an important issue and as such, the idea of having a passenger capsule within the orbiter was born. In addition to the capsule, other subsystems, the thermal protection system (TPS) in particular, increase the safety of the passengers. In the case of nominal missions, the capsule is used to increase the comfort of the passengers, whilst the reusable TPS of the orbiter protects against the heat loads. However, during the unlikely event of an emergency, the capsule separates from the orbiter and flies autonomously back to the Earth without harming the people inside. In this case, the TPS of the capsule will protect against the heat loads occurring during this emergency re-entry flight. This paper's focuses are the latest geometry of the SpaceLiner 7 (orbiter, booster, capsule), and the different thermal protection system for the orbiter and the capsule.

Key Words: SpaceLiner 7, Orbiter, Capsule, Geometry, Thermal protection system

Nomenclature

SART	Space Launcher System Analysis
TOP 2	Thermal protection system Optimization Program
TPS	Thermal protection system
LH2	Liquid hydrogen
LOX	Liquid oxygen
SSME	Space Shuttle Main Engine

1. Introduction

The reusable SpaceLiner concept has been under investigation at DLR since 2005 [1]. The idea is to design a passenger transport vehicle which is able to fly 50 untrained passengers within 90 minutes from Australia to Western Europe. To achieve these requirements, the vehicle must fly with hypersonic speed and rocket engines will be used to achieve high acceleration with minimal development risk. In order to obtain this high speed, the SpaceLiner has been designed as a two-stage rocket (booster and orbiter) and will launch vertically. Figure 1 shows the SpaceLiner 7 launch configuration during the ascent before booster separation. This picture shows the booster and the orbiter shortly after lift-off. The SpaceLiner concept is now in phase A study, funded by DLR and EU FP 7 research projects.

Due to the fact that untrained people will fly with the SpaceLiner, the concept includes a capsule which sits within the orbiter. The capsule has two tasks: first, to provide a level of comfort to the passengers, and second, to increase the safety of the passengers. For the first task, this capsule will contain the same facilities as in today's airplanes. Additionally, the passengers will enter when the cabin is in the horizontal position. For the second task, the capsule needs to be able to protect the passengers.

In previous papers of the SpaceLiner, the vision [2],[3], the roadmap and its development [4],[5],[6], structure [7],[8] and other subsystems [9], and scientific challenges [10],[11],[12] have been presented.

The objectives to be discussed in this paper are the geometries of the orbiter and the capsule, the thermal protection systems of the orbiter and the capsule, and the geometry of the booster.

Figure 1: Launch configuration of the SpaceLiner 7 (booster & orbiter) during ascent

2. Launch Configuration

In Figure 2, the booster is the lower part of the assembly and the upper part shows the orbiter. Figure 3 shows the launch configuration from another view point. For launch the entire vehicle is rotated to the vertical and has a mass of approximately 1 838.7 Mg including fuel.

In the pictures below (Figure 2 and Figure 3), several remarkable concepts can be seen. The booster, as well as the orbiter, has engines. The booster is equipped with nine engines and the orbiter with two. As chosen baseline propulsion system, staged combustion cycle rocket engines with a moderate 16 MPa chamber have been selected. 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 [13].

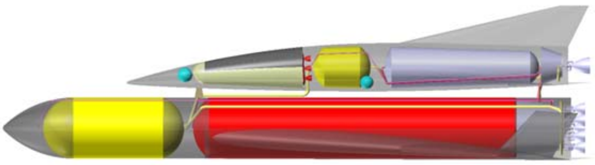

Figure 2: SpaceLiner 7: booster and orbiter (side view)

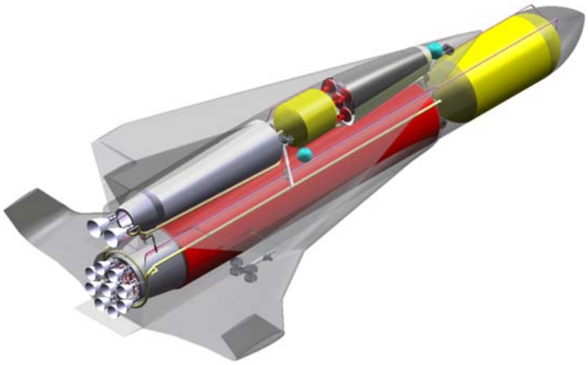

Figure 3: SpaceLiner 7: booster and orbiter (isometric view)

In the pictures above (Figure 2 and Figure 3), several remarkable concepts can be seen. The orbiter, as well as the booster, has engines. The booster is equipped with nine engines and the orbiter with two. As the chosen baseline propulsion system, staged combustion cycle rocket engines with a moderate 16 MPa chamber have been selected. The engine performance data is not overly ambitious and has already been exceeded by existing engines (e.g. SSME, RD-0120). However, the requirement of a passenger carrying 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 [13].

Both the booster and the orbiter have their own tanks. The booster, as well as the orbiter, contains one LH2 tank and one LOX tank. In the figures above, the LOX tanks have yellow coloring and the LH2 tanks are red on the booster side and grey on the orbiter side.

To provide the fuel to all of the engines during the booster phase (approx. the first 200 s after lift-off), the concept of crossfeeding will be applied. This means that all engines provide the thrust and all engines are fed by the booster during mate ascent. Two concepts can be applied: first, tank to tank, and second, tank to engines. Both concepts have advantages and disadvantages, and highly depend on the system to which they shall be applied.

For the SpaceLiner 7, both concepts will be used. For the LOX, the tank to tank solution has been chosen and for the LH2, the tank to engine solution has been chosen [14].

3. Orbiter

The orbiter is the vehicle which flies the passengers from the launch pad to the destination. However, during this flight the orbiter needs to withstand different loads and thus, all subsystems are designed to withstand these. Furthermore, the orbiter is a reusable vehicle and hence, all subsystems are designed to be used multiple times.

The mass of the orbiter is estimated empty 145.4 Mg including its TPS, the capsule and all subsystem. The fuel inside the orbiter has a mass of 215 Mg.

In the following sections, the geometry of the SpaceLiner 7 orbiter is presented, as well as the active and the passive thermal protection system.

3.1 Geometry

The latest geometry of the SpaceLiner 7 orbiter is presented in Figure 4. This figure shows (from left) the capsule including the separation motors, the LOX tank (yellow) and the LH2 tank (grey). Furthermore, the landing gears are displayed, as well as the thrust frame and the engines. From the outer shell, the fin can be seen.

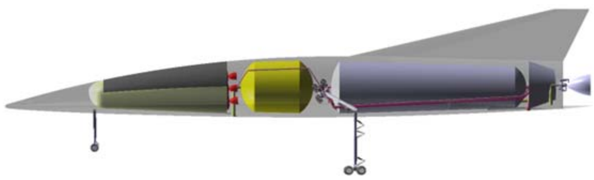

Figure 4: SpaceLiner 7 orbiter (side view)

In Figure 5, the outer shape of the SpaceLiner 7 orbiter is shown. It can be seen that there are two flaps on each side of the wing for trimming and control purposes. The black color of the wing leading edge symbolizes the area of the active cooling system (see below).

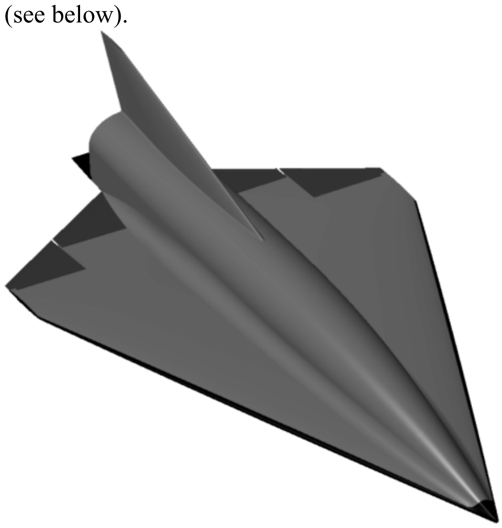

Figure 5: SpaceLiner 7 orbiter (isometric view)

3.2 The reusable thermal protection system (TPS)

Due to the requirement of reusability, the thermal protection system (TPS) as well as all other subsystems is designed for multiple flights.

However, the temperatures at the wing's leading edge of the orbiter exceed at very high speed flight (22 > M > 11), the maximum allowable temperature of 1800 K. Therefore, the concept of the TPS is to have two systems: one passive and one active thermal protection system. This makes a mass of 31047 kg for the entire TPS for the orbiter.

Passive thermal protection

The passenger stage's TPS is required to be dimensioned for the heat loads of the nominal trajectory, as well as for potential abort cases without emergency separation of the rescue capsule. Two abort cases were considered: abort after booster separation and abort at highest altitude [15].

The capsule's upper half is part of the orbiter's outer shell. Hence, this area is considered in the calculation of passenger cabin temperature where there exists a requirement for a maximum inner temperature of less than 303 K in order to always ensure the passenger's comfort. In contrast, for the rest of the orbiter, the permitted maximum structure temperature is to rise up to 530 K. To investigate the impact of different maximum structure temperatures, the cases of 400 K and 480 K were also considered.

In Table 1 it can be seen that in the case of simulation until landing, the total mass of 34.25 t (400 K) is reduced by 16.2 % to 28.7 t for an allowed structure temperature of 480 K and by 25.2 % to 25.6 t for an allowed structure temperature of 530 K.

Table 1: TPS Mass (Passenger stage without fin & without passenger cabin)

Temperature [K]	Mass [kg]		
	Until landing	Until landing + 300 s	Until landing + 600 s
400	34249	34624	35032
480	28700	29243	29255
530	25605	25969	26181

To see the impact of the amount of flight time inclusive a certain amount of time after landing, different durations were simulated. In this case, flight time also includes the time of deboarding and additional buffer times, and gives the period in which the maximum structure temperature should not be exceeded. Three different scenarios were considered: flight time until landing, until landing plus 300 s and until landing plus 600 s.

In the case of a structure temperature of 400 K, the total mass of 34.25 t (simulation until landing) increases by 1.09 % to 34.6 t for simulation until landing plus 300 s and by 2.28 % to 35.0 t for simulation until landing plus 600 s.

In Figure 6, the maximum surface temperatures of the upper part of the orbiter are displayed. It can be seen that very high temperatures occur at the wing leading edge (T < 1850 K) and therefore, the active cooling will be applied at these areas.

The surface temperature distribution of lower part of the orbiter is shown in Figure 7. In comparison with the upper part it can be seen that the lower part has higher surface temperatures. However, in both figures (Figure 6 and Figure 7), the surface temperature is colder the further away from the nose of the orbiter. The reason of this distribution is the flight alteration of the orbiter during the descent.

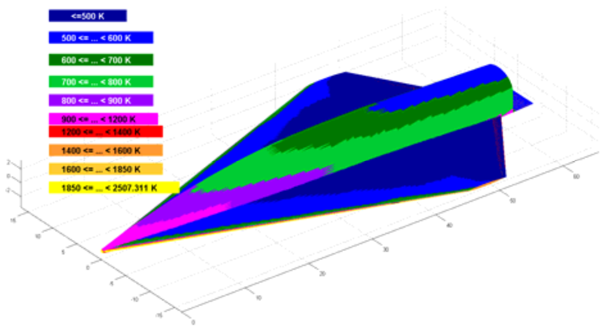

Figure 6: Temperature areas (Passenger stage, upper half)

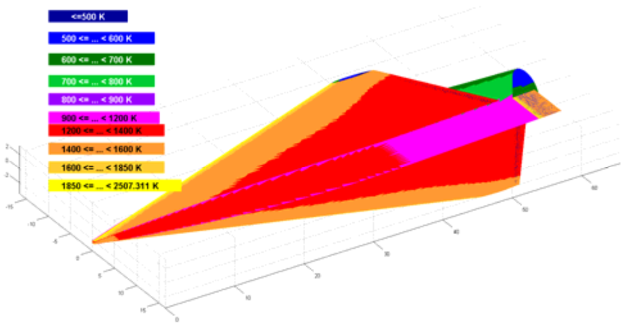

Figure 7: Temperature areas (Passenger stage, lower half)

Figure 8 shows the TPS depending on maximum allowed surface temperatures of the fin occurring during the flight of the SpaceLiner 7. The highest temperature is lower than 1200 K.

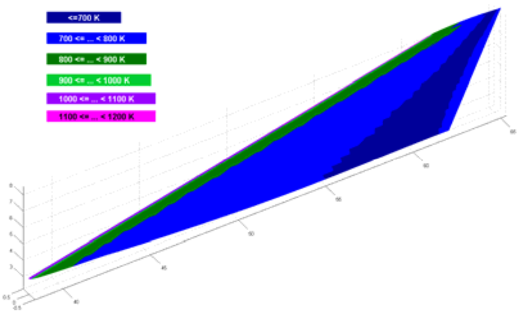

Figure 8: Temperature areas (Fin)

Active thermal protection

The active TPS will be applied where the surface temperatures exceed 1800 K. This maximum temperature occurs at the wing leading edges of the orbiter (see figures above). To cool these areas, an active cooling system with transpiration of water will be applied. The principle of transpiration cooling is based on two phenomena: first, by evaporation of the coolant through the porous structure and second, by "blocking" due to the coolant flow. For evaporation of liquid water, certain energy is needed. This energy comes from the external heat flow and thus, heating of the surface is significantly reduced. A blocking layer develops on the outer surface of the porous structure because of the coolant flow passing through the porous structure into the ambient environment. Due to this blocking layer, the heat transfer to the surface of the orbiter is reduced [10], [11]. For the SpaceLiner concept, liquid water is chosen as coolant.

To cool the areas exceeding 1800 K (wing leading edge), approx. 10 t of liquid water is needed [16]. Within [16], several flight trajectories were investigated and the result was that the nominal mission from Australia to Western Europe required the most water for cooling the wing leading edges.

The biggest challenge however was to fit the corresponding water tanks within the orbiter. To accommodate a water mass of approx. 10 t, the decision was taken to divide the mass in three tanks. One tank sits in the nose section of the orbiter whilst the other two sit near the LOX tank. In Figure 9 and Figure 10, the chosen locations for the tanks are displayed.

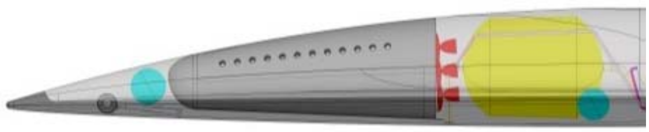

Figure 9: Potential location of the water tanks for the active cooling (side view)

The tank in the nose section is responsible for feeding the nose and surrounding areas with water. The other two tanks are responsible for feeding the remaining areas of the wing leading edges.

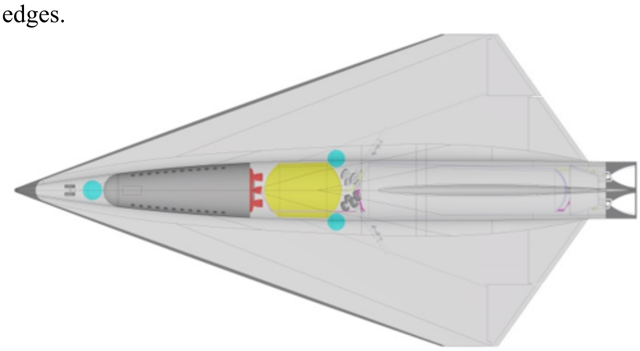

Figure 10: Potential location of the water tanks (top view)

4. Booster

The booster of the SpaceLiner 7 is also required to be reusable. This means that the subsystems for the booster must be designed for reusability.

An additional requirement for the booster is that the booster can fly back to the launch site either by itself or by in-air capturing. Due to this reason, the booster has wings as well as landing gears. These items can be seen in Figure 11. Furthermore, the lines for the crossfeeding can be seen.

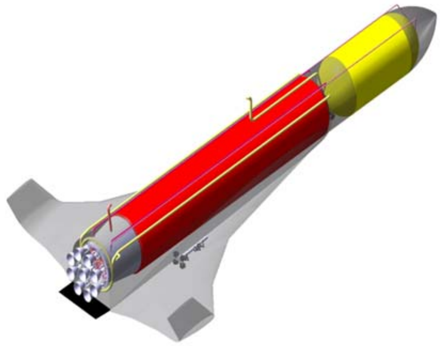

Figure 11: Booster (isometric view)

In Figure 12, the landing gears of the booster can be seen. The booster will be equipped with a nose landing gear with two tires and two main landing gears with four tires each. The location of the gears was defined in order to calculate the available space inside the booster. From this definition, the length and the number of the tires were calculated.

Figure 12: Booster upon landing approach

5. Capsule

The purpose of having a capsule is firstly to provide a certain level of comfort for the passengers, and secondly to have an opportunity to increase safety during an emergency. For providing a certain comfort level, the capsule must look like and provide the same standard of comfort compared to a modern airplane cabin.

The challenge of designing the capsule is to fit all of the necessary and important subsystems within such a limited space.

The capsule's mass inclusive all required subsystems is below 37 Mg. This mass contains a TPS mass for the capsule of 3070 kg and the passengers with approximately 5000 kg.

5.1 Geometry

The capsule is integrated in the orbiter (see Figure 13) and sits in front of the LOX tank. Furthermore, the capsule has two shells: one is the outer shell with TPS, and the second is the inner shell. The inner shell is a pressurized cabin for the passengers comfort and survival.

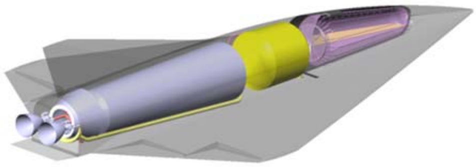

Figure 13: SpaceLiner 7 orbiter including the capsule

In Figure 14, the capsule is presented in the side view. In this figure, the seats are roughly indicated. Additionally, a stair case can be seen. This 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 the boarding is completed, the stair case will be folded and the capsule will be integrated vertically into the orbiter on the launch pad.

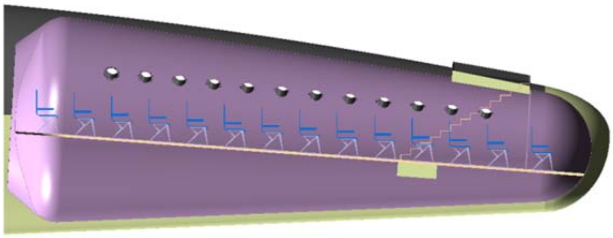

Figure 14: Capsule (side view)

5.2 Thermal protection system

The thermal protection system (TPS) of the capsule is designed with two different TPS types: ablative and reusable. The ablative TPS must be used due to the very high heat loads during an emergency re-entry. However, this TPS is only needed in the nose section.

In Figure 15, the area of the nose requiring an ablative TPS is displayed in grey. The material of the ablative TPS is assumed as AVCOAT. This ablative TPS has the mass of 1347 kg with a thickness of 133 mm.

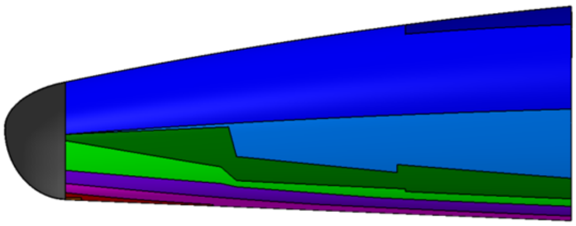

Figure 15: Capsule TPS (side view)

As mentioned earlier, the upper side of the capsule is also the outer shell of the orbiter. In Figure 16, the dark blue colored area indicated the upper half of the capsule. The temperature range of this dark blue area is 900 – 1200 K. Furthermore, it can be seen that the thickness of this dark blue area is larger than the other areas, even though, the other areas experience higher temperature ranges. The reason for this is that this area has been dimensioned to withstand the heat loads which occur not only during an emergency re-entry flight but also during the nominal flight.

Figure 16: Capsule TPS: several thicknesses of the different layers

In Figure 17, the TPS of the capsule from behind is shown. Note that the nose and thus the ablative TPS is not shown in this picture. Figure 18 displays the view of the capsule's TPS from the side. The colors indicate the different temperature ranges: The darker the color, the lower the temperature. The lowest temperature range (< 900 K) is on the back on the upper surface of the capsule.

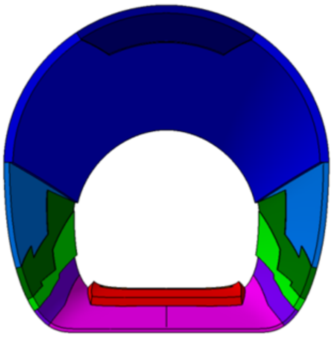

Figure 17: TPS of the capsule (back view)

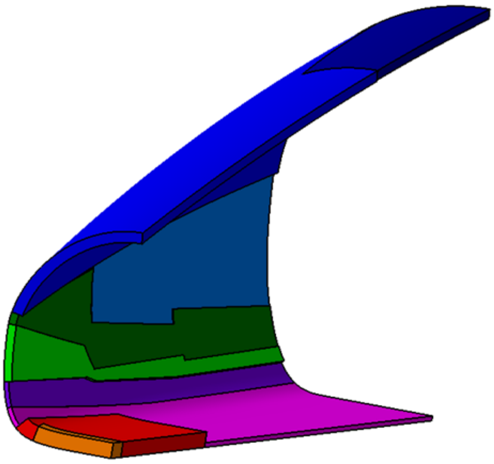

Figure 18: TPS of the capsule (side vies)

In Table 2 the temperature ranges and the corresponding thicknesses, masses, materials and colors are listed. This table gives the thicknesses of the different TPS layers, where it can be seen that the very low temperature ranges are quite thick compared to the other layers. Only the very high temperature range layer (orange in the figures) is thicker.

As mentioned previously, the reason why the lower temperature layers are thicker is due to the common outer shell of the capsule and orbiter. Therefore, the upper side of the capsule's TPS needs to resist the longer load impact during the nominal mission [15].

Table 2: TPS of the capsule

Temperature range	Thickness [mm]	Mass [kg]	Material	Color in Figure 15, Figure 16, Figure 17, Figure 18
< 900 K	141	211	AFRSI	very dark blue
900 – 1200 K	160	1611	TABI	dark blue
<1200 K	98	151	TABI	light blue
1200 – 1300 K	108	177	TABI	dark green
1300 – 1400 K	116	145	TABI	light green
1400 – 1500 K	66	113	AETB-12	purple
1500 – 1600 K	67	568	AETB-12	red
1600 – 1850 K	220	208	CMC	orange

6. Discussion and Conclusion

The SpaceLiner 7 configuration and the passenger capsule have been analyzed with respect to nominal and emergency trajectories as well as subsystems. These investigations give a first realistic guess of values for the masses of the capsule and the center of gravity.

The mass of the TPS strongly depends on the reentry trajectory, and significant analysis has been undertaken to reduce this mass. However, due to the limited space in the orbiter or the capsule, the lightest TPS may not fit within the available space of the orbiter or the capsule. The optimum TPS combines the lightest possible TPS that will fit within the available space in the orbiter or the capsule.

Analyses show that the primary requirements to carry 50 passengers in 90 minutes from Australia to Western Europe are fulfilled by the SpaceLiner 7. The presented data reflect a growing maturity in the SpaceLiner 7 concept and provide a basis for continued investigations.

Acknowledgement

Part of this work was performed within the 'Future High-Altitude High-Speed Transport 20XX' project investigating high-speed transport. FAST20XX, coordinated by ESA-ESTEC, is supported by the EU within the 7th Framework Programme Theme7 Transport, Contract no.: ACP8-GA-2009-233816. Further information on FAST20XX can be found on http://www.esa.int/fast20xx.

Part of this work was performed within the 'Cryogenic Hypersonic Advanced Tank Technologies' project investigating tank technologies for high-speed transport. CHATT, coordinated by DLR-SART, is supported by the EU within the 7th Framework Programme Theme 7 Transport, Contract no.: ACP1-GA-2011-285117. Further information on CHATT can be found on http://www.chatt.aero

The authors gratefully acknowledge the contributions of Ms. Mona Carlsen.

References

[1] Sippel, M., Klevanski, J., Steelant, J., *Comparative Study on Options for High-Speed Intercontinental Passenger Transports: Air-Breathing- vs. Rocket-Propelled*, 56th IAC, Fukuoka, Japan, October 16-21, 2005

[2] Sippel, M., *Introducing the SpaceLiner Vision*, 7th International Symposium on Launcher Technologies, Barcelona, Spain, April 2-5, 2007

[3] Sippel, M., *SpaceLiner – a Visionary Concept of an Ultra Fast Passenger Transport under Investigation in FAST20XX*, 16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference, Bremen, Germany, October 19-22, 2009

[4] Sippel, M., *Promising Roadmap Alternatives for the SpaceLiner*, Acta Astronautica, Vol. 66, No. 11-12, pp. 1652-1658, 2010

[5] Schwanekamp, T., Bauer, C., Kopp, A., *The Development of the SpaceLiner Concept and its Latest Progress*, 4th CSA-IAA Conference on Advanced Space Technology, Shanghai, China, September 5-8, 2011

[6] Sippel, M., Schwanekamp, T., Bauer, C., Garbers, N., van Foreest, A., Tengzelius, U., Lentsch, A., *Technical Maturation of the SpaceLiner Concept*, 18th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Tours, France, September 24-28, 2012

[7] Kopp, A., van Foreest, A., Sippel. M., Dalenbring, M., Jarlas, R., *Investigation of Structure for the Hypersonic Transport System SpaceLiner*, 17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, San Francisco, USA, April 11-14, 2011

[8] Kopp, A., Garbers, N., *Parametric Structural Analysis for the SpaceLiner*, 18th AIAA/3AF International Space Planes and Hypersonic Systems and Technologies Conference, Tours, France, September 24-28, 2012

[9] Bauer, C., Garbers, N., Lentsch, A., *Investigations of the SpaceLiner Passenger Capsule and Various Abort Scenarios*, 61. Deutscher Luft- und Raumfahrtkongress, Berlin, Germany, September 10-12, 2012

[10] Sippel M., Klevanski J., van Foreest A., Gülhan A., Esser B., Kuhn M., *The SpaceLiner Concept and its Aerothermodynamic Challenges*, 1st ARA-Days, Arcachon, July 3-5, 2006

[11] van Foreest, A. , Sippel, M.; Gülhan, A.; Esser, B.; Ambrosius, B.A.C.; Sudmeijer, K., *Transpiration Cooling Using Liquid Water*, Journal of Thermophysics and Heat Transfer, Vol. 23, No. 4, October–December 2009

[12] van Foreest, A., Sippel, M., *The Logistical Challenges of the SpaceLiner Concept*, 1st Symposium on Private Human Access to Space, Arcachon, France, May 28-30, 2008

[13] Yamashiro, R., Sippel, M., *Preliminary Design Study of Staged Combustion Cycle Rocket Engine for SpaceLiner High-Speed Passenger Transportation Concept,* 63rd IAC, Naples, Italy, October 1-5, 2012

[14] Sippel, M., Kopp, A., Sinkó, K., Mattsson, D.; *Advanced Hypersonic Cryo-Tanks Research in CHATT*, 18th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Tour, France, September 24-28, 2012

[15] Garbers, N., *Overall Preliminary Design of the Thermal Protection System for a Long Range Hypersonic Rocket-Powered Passenger Vehicle (SpaceLiner)*, 7th European Workshop on Thermal Protection Systems and Hot Structures, ESA/ESTEC, Noordwijk, The Netherlands, April 8-10, 2013

[16] Bauer, C., Özerson, N.; *System Design for the Active Water Cooling System for the SpaceLiner 7*, SART-TN-020/2012