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Latest Progress in Research on the SpaceLiner High-Speed Passenger Transportation Concept

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A vision aimed at revolutionizing ultra-long distance travel between different points on earth could be realized by a high-speed intercontinental passenger transport using rocket based, suborbital launchers.

The paper gives an overview on the latest progress in conceptual design of the DLR SpaceLiner presenting geometrical size and mass data and describing results of trajectory simulations. The rockets are based on an advanced but technically conservative approach not relying on exotic technologies. The two-stage, fully reusable vehicle is designed as an "exceedingly reliable" system to overcome the safety deficits of current state-of-the-art launchers.

The paper further outlines the latest technical lay-out and flight performance. The question on how to flexibly adjust diverse passenger volume and range distances for different interesting destinations is discussed. The paper also briefly describes innovative active cooling technologies investigated in DLR's arc-heated facility including most recent efficiency data and presents first assessments on system performance.

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
CMC	Ceramic Matrix Composites
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
GLOW	Gross Lift-Off Mass
HSCT	High Speed Civil Transport
LBK	Lichtbogen Beheizter Kanal Köln (arc heated experimental facility) of DLR
LEO	Low Earth Orbit
LFBB	Liquid Fly-Back Booster
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MECO	Main Engine Cut Off
RLV	Reusable Launch Vehicle
SSME	Space Shuttle Main Engine
SSTO	Single Stage to Orbit
TSTO	Two Stage to Orbit
cog	center of gravity
cop	center of pressure

1 INTRODUCTION

A strategic vision has been recently proposed by DLR which ultimately has the potential to enable sustainable low-cost space transportation to orbit (references 1, 3, 4). The baseline idea is simple and quite conventional: Strongly surging the number of launches per year and hence dramatically shrinking manufacturing and operating cost of launcher hardware.

The obvious challenge of the vision is to identify the very application creating this new, large-size market. All recent assessments of the launch business are sobering. The required new market must be significantly different from today's orbiting of communication or earth observation satellites because almost no growth is to be expected in these conventional application areas.

Nevertheless, a market, well beyond the recent assessment, could be created if the conventional thinking of what rocket propelled vehicles are to be used for is exceeded.

Ultra fast transportation, much faster than supersonic and even potential hypersonic airplanes, is definitely a fundamental new application for launch vehicles. Even in the case that only a very small portion of the upper business travel segment could be tapped by a rocket-propelled intercontinental passenger transport, the resulting launch rates per year would be far in excess of any other credible scenario. By no more than partially tapping the huge intercontinental travel and tourist 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 applications. The fast intercontinental travel form of space tourism, not only attracting the leisure market, would, as a byproduct, enable to also considerably reduce the cost of space transportation to orbit.

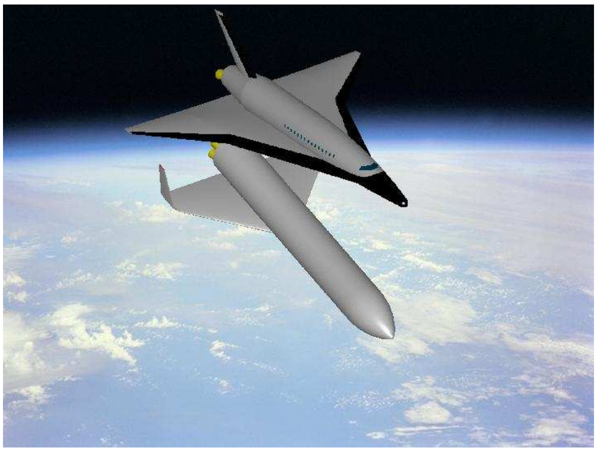

Figure 1: The SpaceLiner vision of a rocket-propelled intercontinental passenger transport, shown here in an artist's impression, could push spaceflight further than any other credible scenario

The current paper briefly presents the recent status of the worldwide launcher business and derives the motivation for developing a new application, the ultra fast passenger transport. Afterwards the technical evolution of the SpaceLiner up to its latest configuration is described. Options for adapting the mass and size of the cabin to diverse passenger market volume on different routes are investigated on their technical feasibility. Experimental results of a high enthalpy windtunnel campaign which proofed the attractiveness of advanced transpiration cooling including a first system assessment are described.

2 BACKGROUND AND ANALYSIS OF CURRENT SITUATION

Currently, the worldwide launcher sector including research and industry is running into a deep crisis.

A recent assessment of the launch business already including some kind of optimism is sobering. The Futron *Analysis of Space Concepts Enabled by New Transportation* (ASCENT) Study [6] was carried out by NASA Marshall Space Flight Center (MSFC) and Futron Corporation to 'provide the best possible estimates of global launch vehicle demand for the next twenty years'. The ASCENT study prognosis of an almost flat launch demand in the next 15 to 20 years (Figure 2) contains already new emerging applications. Without the launch demand generated by these new businesses, (notably public space travel), there would be a rather rapid decline of the launch industry during the forecast period.

Figure 2 shows that even the most optimistic "Robust" scenario would only see a slight increase in the number of launches until 2021. The recent history of the past few years sadly demonstrated that the "Constrained" lower end of the prognosis was still too optimistic. The actual number of launch attempts to orbit in *every year* up to 2006 remained *beneath* even the most pessimistic prognosis as shown in Figure 2.

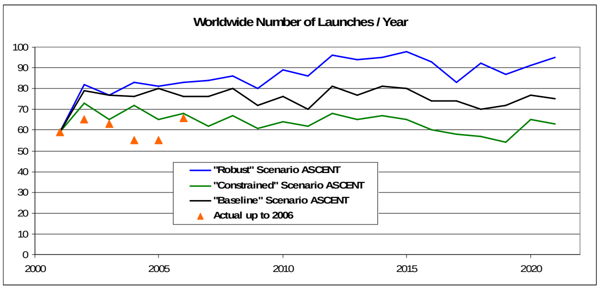

Figure 2: Baseline, Robust and Constrained forecasts of worldwide number of launches per year for different ASCENT study [6] scenarios compared with actual number of launches

The consequences for the development and operation for all kinds of launchers are catastrophic. The ruinous competition on the shrinking commercial telecommunication market requires heavy subsidies only for continuing the operation of existing launchers. On the launcher development side the situation is even worse: The very small market volume and the underutilization of existing infrastructure do not require any new large development project. Everything needed could be served by the available, sometimes 50 years old rocket designs. Technological progress is slowing or stopping because of the decline in development budgets. Without fascinating and challenging tasks a 'brain-drain' of the best and brightest engineers and scientists seems to be inevitable in the near future.

If one postulates that a surge in launches requires a dramatic reduction in launch prices and vice versa, the perspective is quite desperate. The required new market must be significantly different from today's orbiting of communication or earth observation satellites because almost no growth is to be expected in these areas. As has been demonstrated by the ASCENT study, "most of today's markets, both commercial and governmental, are virtually unaffected by even massive reductions in launch prices." [6]

Fortunately, the idea for a new application of spaceflight is gaining momentum: **The space tourism market.**

A number of initiatives on commercial space flight have been recently started with companies developing privately-funded crew vehicles and launchers. For human space flight, this phenomenon was initially triggered by the Ansari X Prize, a contest focused on sub-orbital crew vehicles for space tourism. The Ansari X Prize was won in October 2004 when a privately funded crew vehicle, SpaceShipOne developed by Scaled Composites, reached an altitude of 111 km. Presently, a number of privately-funded companies are completing the development of suborbital vehicles, claiming to begin commercial operations as early as 2008. Check for a brief overview on these activities in reference 4.

Although, what is called "suborbital space travel" is assessed as an additional promising market, Futron's forecast for suborbital space travel outside of the ASCENT analysis is relatively limited (annual revenues in excess of US$ 700 million [7]). However, despite all achievements and promising developments, one has to realize that the overall impact of all recent developments in space travel on the launch industry and its technology is limited at best. The 'low-tech'-approach seems to be the only affordable one for small and medium private companies in the near-term. As a result, it is unlikely that the necessary advancement in launch vehicle technology is notably assisted. Further, the overall emerging market volume is insufficient to significantly support the classical rocket launch business. The question comes up if a business could be conceived which significantly raises the number of launches exceeding all current prognoses and hence reduces costs.

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. Travel times between other interesting intercontinental destinations are even shorter.

Ultra fast transportation far in excess of supersonic and even potential hypersonic airplanes is definitely a fundamental new application for launch vehicles. Even in the case that only a very small portion of the upper business travel segment could be tapped by a rocket-propelled intercontinental passenger transport, the resulting launch rates per year would be far in excess of any other credible scenario. By no more than partially tapping the huge intercontinental travel and tourist 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.

A first assessment of the SpaceLiner’s potential business case is described in the references 1, 3, and 4.

3 TECHNICAL DESCRIPTION OF THE SPACELINER CONCEPT

3.1 Basic Requirements for a Rocket-Propelled Intercontinental Passenger Stage

One of the most demanding missions in terms of Δv is the west-bound flight from south-east Australia to a central European destination which is selected as the reference design case.

The rocket engine powered ‘SpaceLiner’ is based on an advanced but technically conservative approach which does not rely on any exotic technologies. From an operational point of view, a single stage configuration would have been preferable. However, the minimum Δv-requirement of more than 6500 m/s without losses would have required SSTO technology and would have nevertheless resulted in a very large and outsize stage [2]. Thus, a two stage, fully reusable vehicle is designed as an “exceedingly reliable” system to overcome the safety deficits of current state-of-the-art launchers. The cryogenic propellant combination LOX-LH2 is selected for its superior performance characteristics.

Although the reusable upper stage with the passenger payload does not reach stable orbital velocity during nominal missions of the reference design, its conditions are so similar to those of an orbiter that the vehicle is also dubbed as 'orbiter' in the following paragraphs.

Different configurations and take-off modes have been analyzed [2]. Horizontal take-off options, which are far more conventional for passenger flight, have been dismissed because of unsolved problems related to cryogenic propellant sloshing and rocket engine feed. Moreover, in this case an unproven sled launch would be required because no take-off gear is imaginable for the high mass and velocity required. A parallel stage arrangement is preferred over a tandem configuration mostly due to the latter’s expected outsize length of more than 100 m. The large wings of the two reusable stages in tandem arrangement would generate high bending loads on the structure.

The technical lay-out is new and rocket propelled vehicles of historical studies have not been used as a design reference. However, reusable TSTO concepts like the LFBB derived configuration of DLR [8] or the French EVEREST launcher [9] which have been designed for payload delivery to orbit come quite close with their overall architecture.

The most important requirement for the overall design of the 'SpaceLiner' concept is an acceptable safety record. The specific number of fatalities in its operation should not exceed those of early jet-airliner travel. It has to be realized that such a requirement is a notable technical challenge in itself, far beyond the capability of today's manned spaceflight. In a first approach, the rocket engines are intentionally not designed to their technical limits to improve their reliability. Intensive testing and qualification of the propulsion system is further essential. Nevertheless, an engine-out capability during all acceleration flight phases is to be integrated. Despite all effort, tight margins are intrinsic of all launch systems and significantly reduce the achievable safety and reliability. Thus, a passenger rescue system will be indispensable. This could be envisioned as the cabin in form of a large capsule to be separated from the orbiter in case of an emergency and then safely returning to Earth.

3.2 Evolution of the SpaceLiner vehicles and latest reference design

The relatively new SpaceLiner concept has already undergone some technical evolution in the last two years based on the results of experimental tests of an innovative cooling system (see section 4.3) and subsequent systems analyses.

The booster and orbiter engines were preliminarily assumed to be identical in the first generation configuration. Fuel rich staged combustion cycle engines with a moderate chamber pressure, approximately 1700 kN thrust and 448 s I_{sp} in vacuum were selected for the propulsion system of the two stages [1, 2]. These 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 size of the vehicle has been iteratively found in combination of mass estimation and trajectory simulation. The overall length of this early SpaceLiner lay-out reached 63 m. Its total take-off mass has been estimated at 905 Mg [1, 2].

This "first generation" design has subsequently been used for more detailed studies [15], especially in the fields of trajectory simulations, aerothermodynamics, and for defining the requirements for the active cooling system. One of the most important results is a first engineering estimation on the amount of cooling fluid required during skip and glide reentry after the orbiter's MECO (see section 4.3).

All engines should work from lift-off until MECO. A propellant crossfeed from the booster to the orbiter is foreseen up to separation to reduce the overall size of the orbiter stage. During the SpaceLiner's design evolution the expansion ratios of the booster and orbiter engines are adapted to their respective optimums, while mass flow, turbo-machinery, and combustion chamber remain identical. Recent engine characteristics are listed in Table 1.

Table 1: Engine data of SpaceLiner2

	Booster	Orbiter
Number of engines	8	2
Mixture ratio	6:1	6:1
Chamber pressure [MPa]	16	16
Mass flow per engine [kg/s]	384.5	384.5
Expansion ratio [-]	33	59
Specific impulse in vacuum [s]	437.6	448
Specific impulse at sea level [s]	388.4	360.4
Thrust in vacuum per engine [kN]	1650.6	1689.8
Thrust at sea level per engine[kN]	1465.0	1359.4

An optimum configuration of minimum total size and mass has been iterated based on preliminary subsystem sizing and trajectory analyses of the ambitious Australia – Europe reference design mission. See Figure 3 for the resulting launch configuration including booster.

The booster is a large unmanned tank structure providing thrust and propellant crossfeed to the orbiter up to staging. Its total propellant loading including residuals reaches 760 Mg, 105 % of the Space Shuttle External Tank. Compare the latest characteristic SpaceLiner data in Table 2.

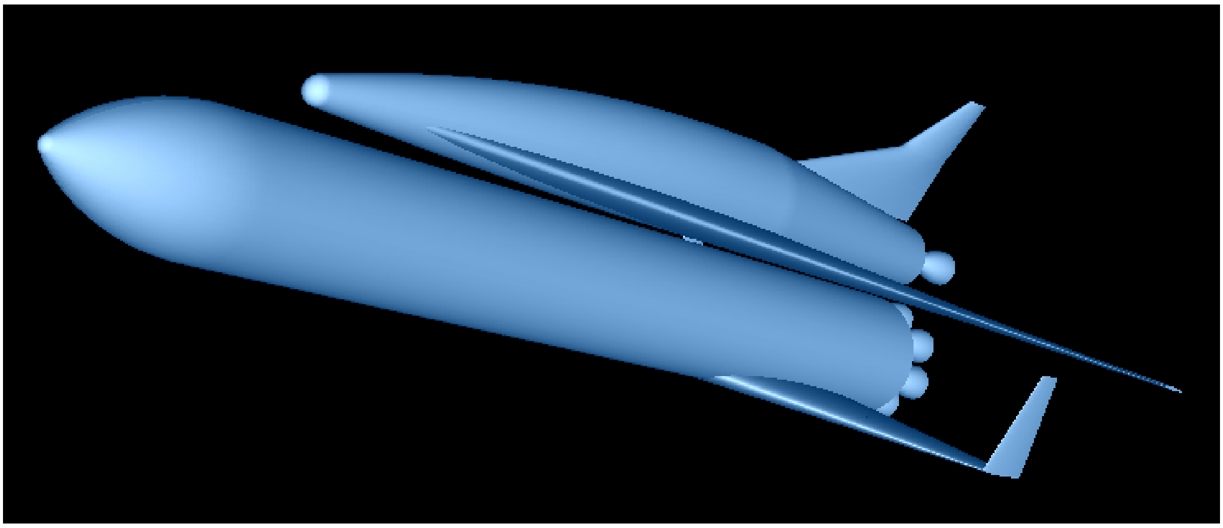

Figure 3: Generic rocket powered intercontinental passenger spaceplane SpaceLiner with booster

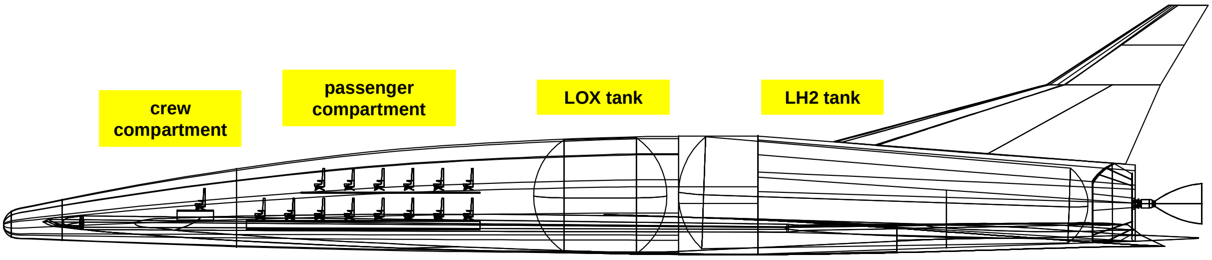

Figure 4: Conceptual internal lay-out of the SpaceLiner2 orbiter

Table 2: SpaceLiner2 characteristic vehicle data (reference mission)

	GLOW Mass [kg]	Mass at burnout [kg]	Nominal Ascent Propellant mass [kg]	Total length [m]	Max. fuselage diameter [m]	Wing span [m]	Projected wing surface area [m^2]
Orbiter	277900	122900	155000	60.4	6	40	955
Booster	870950	116950	754000	73.4	7	25.5	325

The orbiter, designed to transport 50 passengers with their luggage, accommodates no more than 155 Mg propellant in the aft section which is designed as an aeroshell-like concept. Aerodynamic considerations and severe thermal conditions in the atmospheric skipping phase (see section 4.1 below) exclude any integral tank structure. The orbiter's structural index is at 60 %, relatively conservative for a large cryogenic RLV. However, it has to be considered that the vehicle has to include a passenger cabin and safety features.

The combined dry mass of both SpaceLiner stages is estimated at 212 Mg. Total take-off mass of the latest SpaceLiner2 is about 1150 Mg. This value is slightly above other proposed reusable, but unmanned TSTO. The total lift-off mass of the Space Shuttle is much higher in contrast; but the Space Shuttle is designed for increased payload capability to higher circular orbits and has a lower average specific impulse due to its solid motors.

3.3 Simulation of the Reference Trajectory

Different SpaceLiner trajectories with intercontinental destinations have been analyzed. One of the most demanding practical missions is the west-bound flight from south-east Australia to a central European destination which has been selected early as the reference design case [1, 2].

After performing a vertical take-off, the combined launcher accelerates for 215 s up to 3.2 km/s (beyond Mach 11) when the booster separates. The booster main engines are throttled or are subsequently cut-off when the axial acceleration reaches 2.6 g. After its MECO the booster performs a ballistic reentry and should be transferred back to its launch site. A classical technical solution is the powered fly-back by turbojet engines because the distance is by far too large for a simple glide-back. An innovative alternative is the capturing of the reusable stage in the air by a large subsonic airplane and subsequent tow-back.

This patented method dubbed 'in-air-capturing' has been investigated by DLR in simulations and has proven its principle feasibility [10, 11]. Recently, a quite similar method has been proposed and studied in Russia [12]. The massive advantage of this approach is the fact that a booster stage caught in the air does not need any fly-back propellant and turbo-engine propulsion system. The mass savings on the RLV stage by in-air-capturing allow for a significantly smaller vehicle or a payload increase [10]. The innovative capturing has been selected as the baseline technology for the booster retrieval, enabling a total lift-off mass reduction of at least 150 Mg. Conventional turbojet fly-back or a downrange landing site, if available, are the backup options, if 'in-air-capturing' would be deemed as unfeasible or as too risky.

Following separation, the orbiter with the passengers inside accelerates for another 200 s to its MECO conditions close to 6.55 km/s at a relatively low apogee altitude of 85 km. Conditions are still clearly suborbital with a perigee of -3360 km.

Different flight options exist in principle after MECO. The atmospheric skipping looked most attractive considering achievable flight range, launch mass, and mechanical loads [2]. However, the stagnation point heat flux might exceed 4 MW/m^2 (2.1 MW/m^2 in nose region) for a short time [2] because the orbiter has to fly with a Mach number of almost 20 at altitudes below 50 km (see Figure 5). According to a preliminary estimation the adiabatic equilibrium temperature might exceed 3000 K in the nose and leading edge regions. First results of CFD analyses at these highly challenging orbiter conditions are described in section 4.1. New approaches for the structural materials and thermal protection including advanced active cooling have to be implemented. Some promising design options are outlined in chapter 4.2 below.

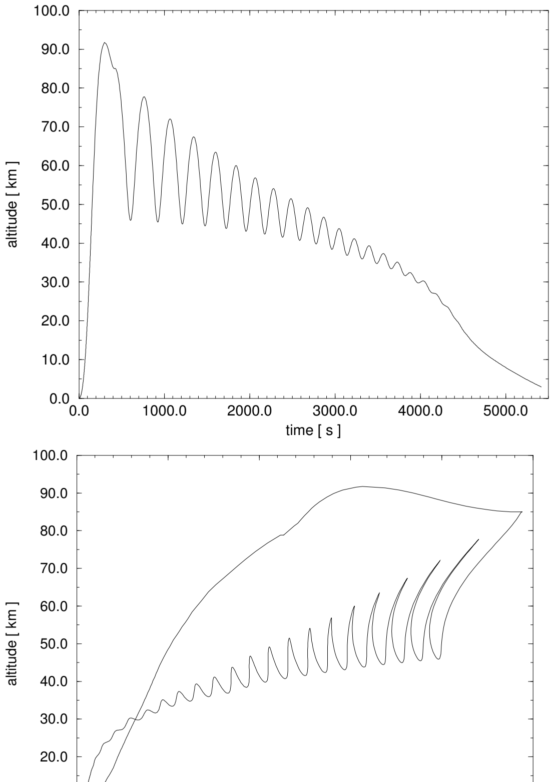

Figure 5: Altitude as function of time and of Mach number of SpaceLiner along reference trajectory

The highly challenging technical issue of the extremely high heat flux might be circumnavigated if the SpaceLiner would achieve a higher MECO velocity. This would effectively stretch the range of a single ballistic arc to a point where the following atmospheric entry could be kept within mechanical and thermal loads of existing orbiter vehicles like Space Shuttle or Buran. The SpaceLiner would thus not use a skipping trajectory anymore, but instead a single ballistic arc followed by conventional re-entry. On the downside this solution would require almost 1000 m/s additional Δ–v resulting in a much heavier launcher and heavier and larger orbital stage. Therefore, the low orbital option is only a backup in case the reference skipping variant should turn out to be technically unfeasible or too risky.

After approximately 5400 s (1.5 hours) flying along the orthodrome, the SpaceLiner should reach its final destination.

3.4 Load-Environment and other missions

The Australia – Europe mission is one of the technically most challenging distances with significant passenger volume. However, several northern hemisphere flights like trans-Pacific or trans-Atlantic are less challenging but offer a larger market potential. Thus, the flight from Europe to the west coast of North America, with a minimum orthodrome distance around 9000 km, is investigated for its suitability with the SpaceLiner2 configuration.

As the Δ-v requirement of the shorter distance is lower than for the reference mission, two options exist: The launch vehicle's size could be reduced or the number of passengers or payload could be increased. The latter option has been selected in this paper in order to investigate how far the SpaceLiner configuration can be flexibly adapted to different missions. The large booster stage (compare Table 2) is assumed unchanged and the modifications to the orbiter are tried to be kept at a minimum. The complete aft section including tanks, wing and propulsion is similar to that of the baseline vehicle. The fuselage's cylindrical part is lengthened by 13 m to accommodate additional passengers or cargo. The mass models as well as the aerodynamic models were adapted for this case. Aerodynamic properties of the orbiter show only little change. Mass estimation and trajectory analysis reveal that an increase of 50 passengers to a total of 100 passengers can be achieved. This still leaves room for a margin of almost 7.5 tons, potentially used for additional payload. The elongation of the orbiter, the extra passengers and the payload result in a MECO mass increase to 172.3 tons.

This higher mass reduces the need for throttling and therefore booster separation will occur a bit earlier. After 208 seconds, the booster separates at an altitude of 65 km and a velocity of 2.8 km/s (almost Mach 9). Another 202 seconds later the SpaceLiner has reached a velocity of 5.33 km/s, enough to reach northwest America using the powerless skipping motion. The difference in required Δ-v compared to the Australia – Europe flight is 1.2 km/s. In addition, the required apogee altitude has dropped from 85 km for the Australia – Europe case to 54 km for the Europe – Northwest America trajectory. After a flight time of 3600 s or 1 hour, the final destination is reached.

These strongly reduced energy requirements also result in a far less severe thermal environment. Analysis shows that the stagnation point heat flux in the nose region has dropped from 2.1 MW/m^2 to 1.27 MW/m^2. This less severe heat load combined with shorter flight time could result in a significant reduction of the cooling water needed. This could mean that the payload "margin" of 7.5 tons would further increase. The exact influence of this trajectory on coolant mass still has to be investigated.

It has been assessed if the elongation of the fuselage for the shorter flight has a potential negative influence on stability and trimmability of the orbiter. Stability of the orbiter has been investigated for both the reference and for the long orbiter version. In the hypersonic region both orbiters are stable. The orbiters are trimable in the complete speed regime. The elongation of the fuselage to accommodate the extra passengers does not seem to result in difficulties regarding stability and trim behavior. The change in moment accompanying the shift in Center of Pressure (COP) due to the longer nose of the vehicle is effectively counteracted by the forward shift of the COG.

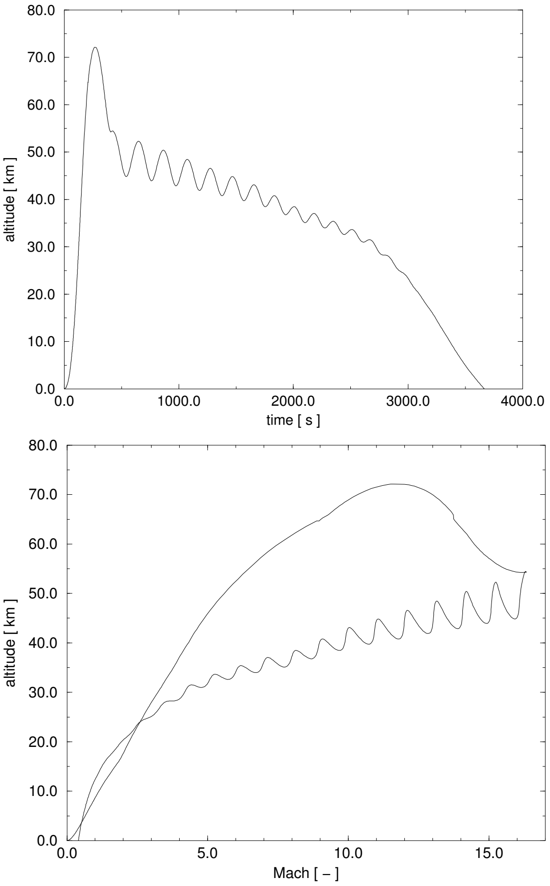

Figure 6: Altitude as function of time and of Mach number of SpaceLiner along Europe – Northwest America trajectory

The overall flight environment for SpaceLiner passengers inside the cabin with respect to acceleration loads is, as expected, very different to conventional subsonic airplanes. After a vertical take-off the axial load factor reaches a maximum of 2.6 g maintained by engine throttling. During that period the nominal normal load factor remains considerably below 1 g. After about 120 s of almost 0 g weightlessness following orbiter MECO, the skipping trajectory starts. The periodic drag deceleration n_x never exceeds -0.2 g. The normal load factor n_z is controlled at a nominal design maximum of +1.5 g and a minimum of +0.026 g in the ballistic arc succeeding the first skip. Afterwards both extremes are closing in on the normal flight condition of 1 g.

According to FAA/EASA standards the airframe and the passengers aboard all civil airliners are required to withstand maximum off-nominal n_z loads up to 2.5 g. The SpaceLiner comfortably stays within these limits. However, the load frequency (starting with a period of approximately 320 s for the reference mission and a period of 220 s for the shorter flight) is much different to that in conventional passenger aircraft which will have to be checked for acceptable passenger comfort. The environment could best be characterized by that experienced while sitting on a gently moving very long swing.

Table 3 shows a comparison of flight environment data for the reference mission and for the less demanding air travel to Northwest America. The maximum axial accelerations are identical due to engine throttling demand but the normal acceleration maximum is even more benign for the reduced skipping loads of the shorter flight.

		reference SE-Australia - Europe	Europe – North West America
Flight time	h	1.5	1.0
passengers	-	50	100
maximum n_x	-	2.6	2.6
minimum n_x	-	-0.2	-0.15
maximum n_z	-	1.5	1.12
minimum n_z	-	0	0

Table 3: Passenger flight environment of the SpaceLiner on Australia – Europe and Europe – Northwest America mission

4 SOLUTIONS TO THE AEROTHERMODYNAMIC CHALLENGES OF THE SPACELINER CONCEPT

4.1 Data of CFD Analyses

Analyses of the aerothermodynamic conditions at the SpaceLiner’s most critical skipping trajectory points have been carried out by using the DLR tool Hotsose. 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 the 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. Note that Hotsose is a tool with limited accuracy and obtained aerothermal surface data provide no more than a first quantified assessment.

The most severe aerothermal conditions are found at the SpaceLiner's first skip. Figure 7 shows the distribution of the wall temperature assuming adiabatic equilibrium and a fully turbulent boundary layer at this brutal flow condition of Mach 19 and below 50 km altitude. The leading edges are charged to the highest temperatures of 3000 K while the nose with 0.75 m radius still reaches 2600 K. Although the heat peaks are relatively short transient phenomena of about 100 s, a first estimation reveals that actual wall temperatures might come close the radiation adiabatic assumption. The maximum heat flux at the stagnation point is about 2 MW/m^2 but could reach 4 MW/m^2 on the leading edge. The outboard leading edge is found most critical and might be subject to additional shock-shock and shock-boundary layer interaction further raising the heat loads in this region.

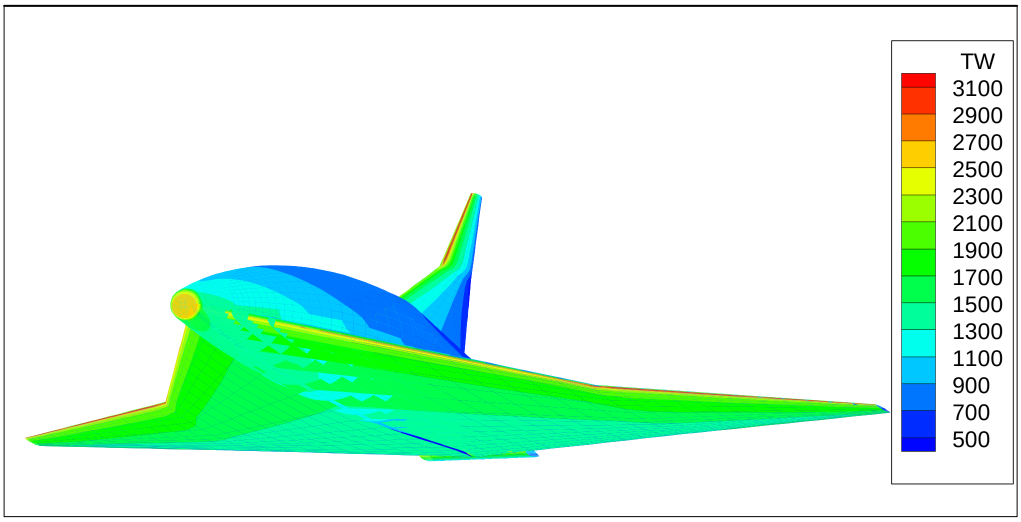

Figure 7: SpaceLiner 2 Equilibrium Temperatures at M= 19.9, 46.5 km, α= 6.5° fully turbulent obtained with an emissive coefficient of 0.83

In case of the latest SpaceLiner maximum heating is experienced at an altitude of 46.5 km and a Mach number of 19.9. A heating analysis using the equilibrium gas model results in the plot of Figure 7. The figure assumes a turbulent boundary layer, which can be considered a worst case scenario in terms of heating. Temperatures on the leading edges and nose are about equal in both cases and reach about 3000 K and 2600 K, respectively. Such temperatures exceed the limitations of all current thermal protection materials. Therefore, some way to reduce these temperatures has to be found.

A peak temperature of 3000 K is well beyond the capabilities of any available material. Thus, in a limited area of the vehicle advanced active cooling processes have definitely to be implemented should the SpaceLiner orbiter maintain its ambitious skipping flight.

4.2 Material Options and Advanced Cooling Concepts

Fortunately, some promising ceramic materials exist which sustain very high temperatures and which are also capable of transpiration cooling due to their porosity. Usually, the cooling of ceramic matrix composites (CMC's) thermal protection hot structures relies solely on radiation cooling. In the severe environment of the Spaceliner even the capabilities of these materials can be exceeded if conventionally implemented. The vehicle's reusability requires some kind of active cooling techniques but excludes ablative protection systems. The principle of transpiration is a promising cooling approach making use of two phenomena: Firstly, the porous structure will be cooled by convection of the coolant flow. Secondly, a thermal blocking coolant layer is built on the outer, hot surface of the porous structure, which reduces heat transfer to the surface.

Ceramic matrix composites are very suitable for this kind of cooling [14]. They further exhibit excellent mechanical, thermomechanical and thermal properties. In contrast to metal foams, they do not fail if local hot spots occur.

To make the cooling system as light as possible, a coolant with high cooling capacity per kg has to be used. For the SpaceLiner it is therefore proposed to use liquid water as a coolant, potentially much more effective than gas. Liquids will not become hotter than their boiling temperature. In case of water this boiling temperature is 100°C at 1 bar and increases proportional to the pressure. If water remains in its liquid state during the transportation through the porous material, the convective cooling will be very efficient due to the large temperature difference of liquid water and the uncooled material. When a material with a very high porosity is used, it will be cooled down to approximately the boiling temperature of the water. To prevent water from evaporating within the porous material, new water has to be supplied at a sufficiently high mass flow rate. The higher the heat of vaporization of a cooling fluid is the lower the coolant mass flow can be.

A liquid in a porous material will introduce a capillary pressure. This pressure will cause water to flow into regions where no water is present. This capillary action will therefore automatically distribute the liquid over the porous material. As soon as a capillary tube has completely filled itself with water, there will be no capillary action anymore. In case of the cooling method using liquid water, this means that when water evaporates at the surface of the material, the liquid water level in the material will drop. Capillary tubes are not completely filled with water anymore and this then causes capillary action. New water is automatically supplied to the surface at exactly the required mass flow rate.

4.3 Results of an Early Test Campaign and System Analysis

Today's knowledge on transpiration cooling efficiency (especially in case of water coolant) and its impact on the hypersonic boundary layer are still limited. Therefore, DLR initiated a fundamental research test campaign on active nose cone cooling in high enthalpy flow. The arc heated facilities LBK at the DLR Cologne site, consisting of two test legs dubbed L2K and L3K were used.

The cooling concept was tested in the L2K wind tunnel. The test facility L2K, with a maximum electrical power of 1.4 MW, is equipped with a Huels type arc heater and allows to achieve cold wall heat flux rates up to 2 MW/m^2 at stagnation pressures up to 150 hPa. The different combinations of conical nozzles' throat and exit diameters provide Mach numbers between 4 and 8 at Reynolds numbers up to 10000/m. Models with a size of 150 mm (W) x 250 mm (L) x 70 mm (H) can be tested in the homogeneous hypersonic flow field of this facility. A detailed description of both facilities can be found in several publications, e.g. [16, 17, 3].

Three different nose cone models were made out of a porous material called Procelit 170. This material consists of 91% Al_2O_3 and 9% SiO_2. Although the Procilit-170 material is not actually suited for an application in a real size vehicle it is nevertheless attractive to be used in the research of transpiration cooling. The main reasons for this material selection were its high porosity and its ability to withstand temperatures of up to 2000 K. The models have a varying nose radius, the smallest radius being 1 cm, the middle radius being 1.75 cm and the largest radius being 2.5 cm. The nose radius was varied to be able to investigate the influence of the model geometry on the cooling efficiency. Inside the models, a reservoir has been drilled out. A copper tube enters the reservoir for water supply. Water mass flow could be adjusted using a valve. The models and their connection to a stagnation probe holder are shown in references 5 and 15.

Test results of cooling using the model with nose radius of 2.5 cm are presented here. Figure 8 (top) shows an infrared image of the temperatures in the radiation adiabatic case. As can be seen temperatures in the stagnation point reach over 2040 K. The lower part of the image represents the behavior of the temperature on certain spots on the model with water cooling over time. The water mass flow rate was 0.2 g/s. Time is presented in minutes.

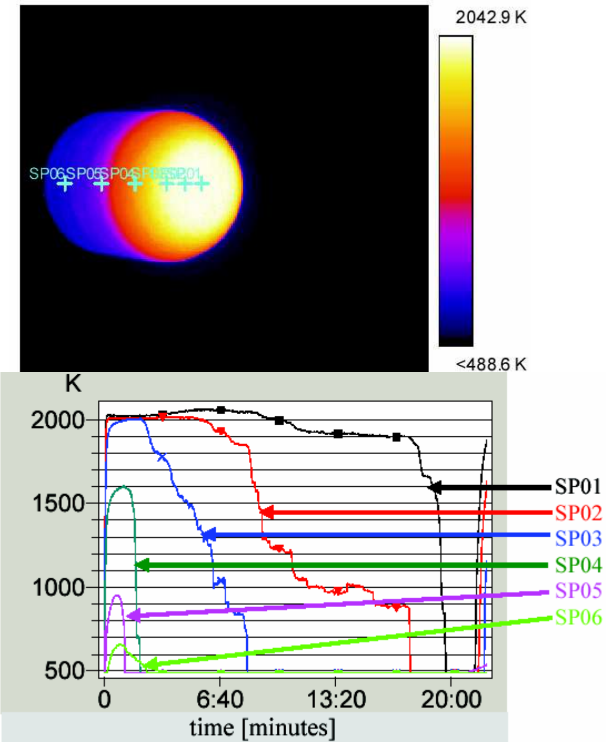

Figure 8: Test results with liquid water mass flow of 0.2 g/s for the probe

What can be seen is that the whole model is eventually cooled to temperatures below 500 K. The infrared camera is not able to measure temperatures lower than this value, but as explained before it is expected the temperature will be equal to the boiling temperature of the water (which is about 290 K at wind tunnel conditions).

Transpiration cooling using liquid water has been proven to be much more efficient compared to gas cooling [5, 15]. To be able to make predictions of the required water mass flow for cooling a vehicle like the SpaceLiner, the results have to be quantified. Because heat flux was not measured during the tests, it has to be determined numerically.

Such calculations for heat fluxes at wind tunnel conditions result in Figure 9. Here the x axis represents the distance along the centerline of the model and the vertical axis represents the heat flux in W/m^2 at the surface of the model. Note that in case of radiation adiabatic conditions (cooling switched off), heat flux is much smaller than in case of a cooled wall. As explained, during the tests the model is cooled down to about 300 K. So the red line is representative for the test conditions. By integrating the heat flux over the surface of the model, the total heat flow into the model can be obtained. In case of water cooling this results in 578 W. Dividing this value through the heat of vaporization of water (2460 kJ/kg at wind tunnel conditions), a required water mass flow of 0.235 g/s is calculated. This is close to the 0.2 g/s of water flow rate, which was measured during the test. The difference is due to not considering the blocking effect in calculations [15].

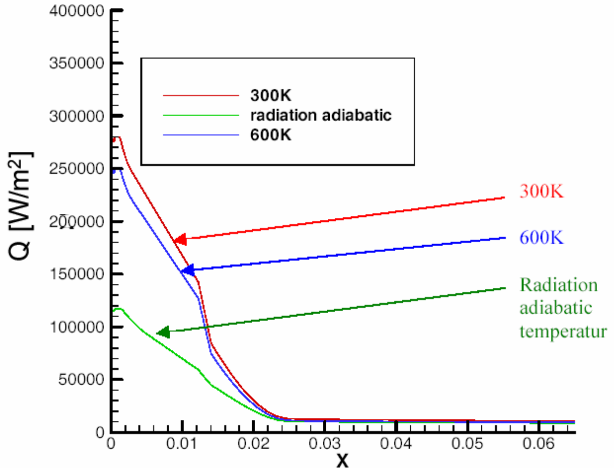

Figure 9: Numerical analyses of heat flux along the surface of the model [15]

The amount of water needed to cool down the nose and leading edges of the SpaceLiner vehicle during its mission is estimated based on the above described experimental and numerical analyses. To be on the safe side, the TPS is designed for the case of a turbulent boundary layer. Furthermore, it is assumed that a TPS material is used that can withstand temperatures of up to 1800 K. Assuming an emission coefficient of 0.8 this results in a heat flux of 0.48 MW/m^2. If the heat flux drops below this value no active cooling is needed. In this case, only the nose and the leading edge radii have to be cooled down actively during the low skipping paths of the very high speed flight. Integrating the water usage along the Australia – Europe trajectory a total required coolant mass of 9110 kg is estimated [15].

Note that this preliminary analysis is based only on the measured nose cooling efficiency, while the same might be different for leading edges. Additional heat flux due to shock-shock and shock-boundary layer interaction is not yet considered. On the other hand the cooling correlations are assuming wall temperatures of below 500 K as tested in the wind tunnel. Such relatively low temperatures are considerably below the material limits required by an actual TPS. By allowing the material temperature to be higher, water can be saved.

In conclusion, at this preliminary stage of the SpaceLiner investigation some uncertainty remains on the system aspects of the advanced active cooling technique. However, a realistic engineering relationship demonstrates the potential attractiveness of this innovative design.

5 CONCLUSION

A conceptual reusable winged rocket for very high-speed intercontinental passenger transport is proposed by DLR. 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. An elongated orbiter derivative could transport 100 passengers about 9000 km in one hour.

Rocket engines are well known in their performance characteristics but are also notorious in their low reliability and life time. Significant improvements in the latter fields as well as additional vehicle safety measures are indispensable for passenger flights of such concepts.

An atmospheric skipping trajectory is found technically attractive for the rocket plane after its MECO. It remains to be seen if the related alternating normal loads are acceptable for passenger comfort. For the SpaceLiner an orbit consisting of a singular ballistic arc followed by conventional re-entry exists as a backup to the skipping, which also avoids extreme thermal heat flow. However, this solution would considerably increase the size of the launcher.

The environmental impact of the LOX/LH2 powered rocket SpaceLiner seems to be much less critical than that of hypersonic airbreathing concepts. The engines do not pollute the atmosphere with nitrogen oxides because they do not use the air. A first estimation shows that the total exhaust gas mass is lower than for today’s large subsonic airliners on similar routes. If the hydrogen is gained from advanced solar processes, no CO_2 will be produced. Most of the flight trajectory is at a much higher altitude than for airbreathing vehicles, considerably reducing the noise impact on ground. Nevertheless, the SpaceLiner launch has to most likely be performed off-shore because usually no remote, unpopulated areas are found close to the business centers of the world. Consequently decoupling of the launch and landing site will create some logistical challenges. This is an important aspect because fast turn-around times currently unknown in the launcher business are required.

The temperature at leading edge areas during the most severe skipping conditions may rise to 3000 K if not adequately cooled by active means. Transpiration cooling can be an attractive countermeasure, but is poorly understood. Thus, DLR initiated a fundamental research campaign focusing on the critical issue of active transpiration cooling in the stagnation point. Three different nose cone models out of a porous aluminum-oxide material were tested in high enthalpy flow. A huge increase of cooling efficiency is observed when using water instead of using a gas as a coolant. DLR intends to extend this promising experimental research in transpiration cooling methods in the future.

Based on the experimental results the total SpaceLiner's water usage along its hypersonic flight is estimated in a preliminary system analysis. About 9.1 tons water are necessary to cool down the vehicle's nose and leading edges during the most severe trajectory points of a mission. The technical challenges of the SpaceLiner are formidable but also promising technologies are under investigation which will enable its technical feasibility and viability.

An ultra fast rocket-propelled intercontinental passenger transport could one day flexibly serve the different passenger volume on the major business routes of the world. The resulting launch rates per year would then be far in excess of any other credible access to space scenario. This form of space tourism, not only attracting the leisure market, would, as a byproduct, enable to considerably reduce the cost of space transportation to orbit.

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