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SpaceLiner - a Visionary Concept of an Ultra Fast Passenger Transport under Investigation in FAST20XX

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A couple of years ago DLR's launcher systems analysis division has proposed a visionary passenger transportation concept reaching the edges of space based on rocket propulsion. The paper describes the vision of the SpaceLiner and the latest technical lay-out of the configuration's preliminary design including its flight performance. The revolutionary ultrafast transport is now under investigation in the EU-funded study FAST20XX (Future high-Altitude high-Speed Transport 20XX) set off in 2009. The paper further outlines the intended research on this vehicle in the areas of structural design, advanced cooling and aerothermodynamics, and flight dynamic simulations.

Subscripts, Abbreviations

CAD	computer aided design
GLOW	Gross Lift-Off Mass
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MECO	Main Engine Cut Off
RLV	Reusable Launch Vehicle
TRL	Technology Readiness Level

I. Introduction

A strategic vision has been proposed by DLR which ultimately has the potential to enable sustainable low-cost space transportation to orbit. 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. 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.

A. Background and Motivation of the SpaceLiner Vision

Currently, the worldwide launcher sector including research and industry is running into a deep crisis.
An 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 [2] was an undertaking of NASA Marshall Space Flight Center (MSFC) and Futron Corporation designed to provide the best possible estimates of global launch vehicle demand for the next twenty years via the research, analysis and forecasting of current and future space markets and applications. 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

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businesses (particularly public space travel) there would be a rather rapid decline of the launch industry during the forecast period.

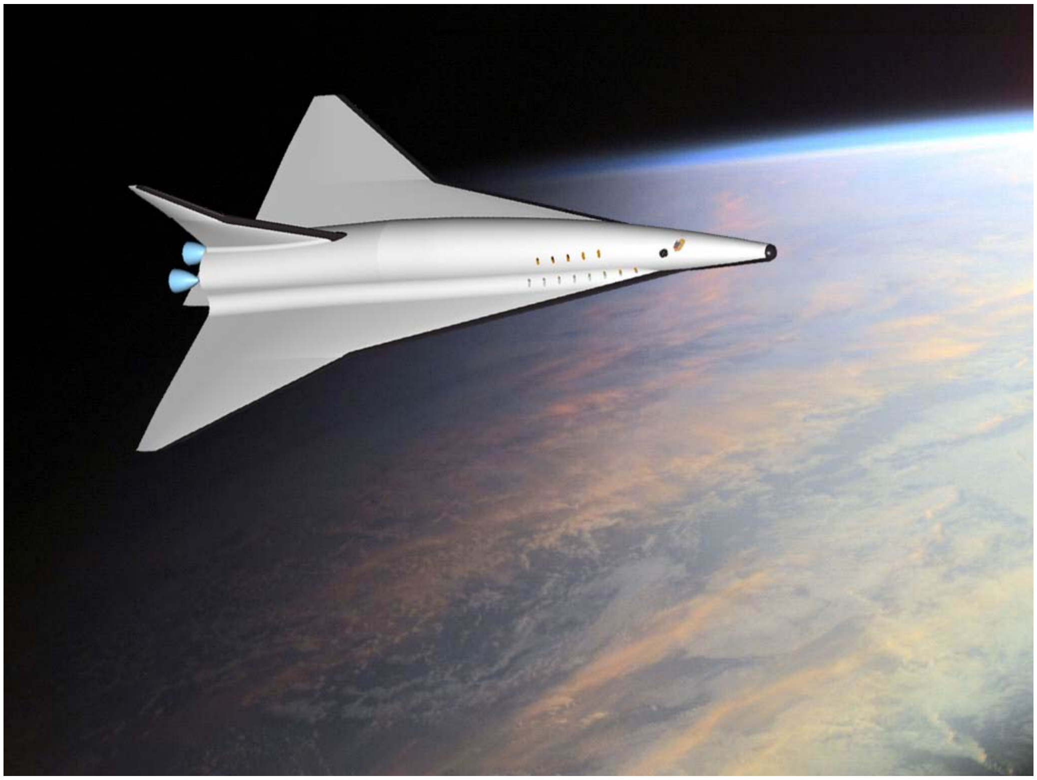

Figure 1: The SpaceLiner vision of a rocket-propelled intercontinental passenger transport, shown here in an artist's impression of the latest configuration, could push spaceflight further than any other credible scenario

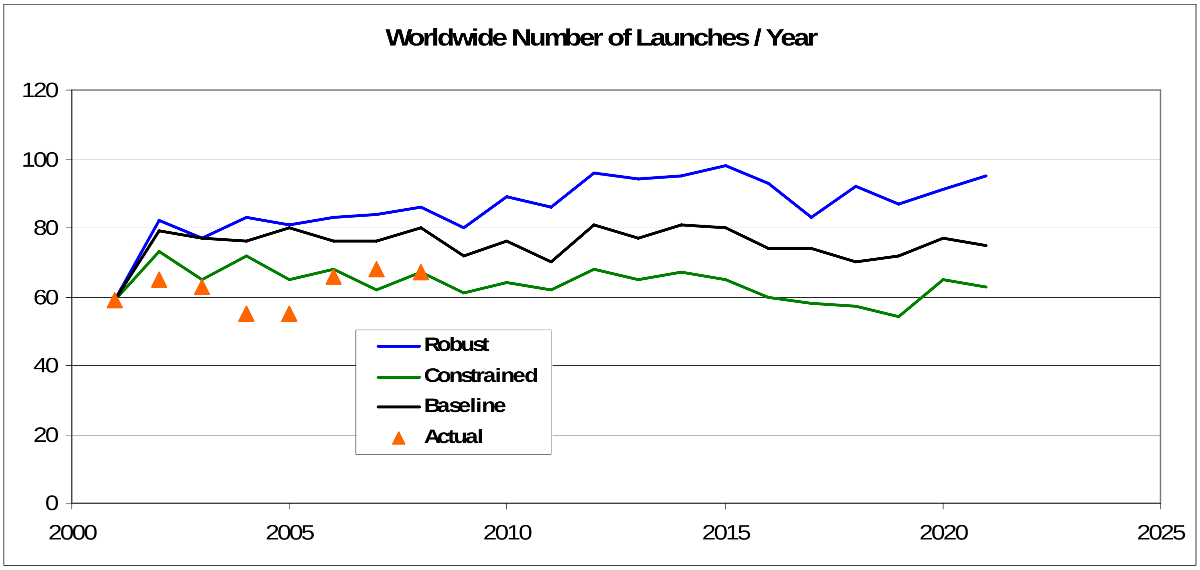

Figure 2: Baseline, Robust and Constrained Forecasts of worldwide number of launches per year for different ASCENT study [2] scenarios compared with actual number of launches

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. In 2007, for the first time, the

“Constrained” curve slightly exceeded and in 2008 exactly met the most pessimistic forecast. Thus, the development during the last 8 years demonstrates that without new applications the “Constrained” prognosis of ASCENT represents the upper limit of currently achievable yearly launch numbers.

The consequences for the development and operation for all kinds of launchers are catastrophic. 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.

Fortunately, the idea for a new application of spaceflight is gaining momentum: **The space tourism market.**
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. Another interesting intercontinental destination between Europe and North-West America could be reduced to flight times of about one hour [7].

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 airline’s 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.

B. Long-term Perspective of the SpaceLiner
Since the demise of Concorde operation, intercontinental travel is restricted to low-speed, subsonic, elongated multi-hour flight. The reasons for the commercial failures of Concorde and its Soviet counterpart Tu-144 can be seen in their relatively high cost but severely restricted range offering only a limited benefit for travelers. However, the public interest in hypersonic passenger airliners is still alive.

Conventional wisdom always assumes to operate these transport craft, depending on the flight Mach-number, by combined airbreathing turbo-jet-RAM-, or SCRAM-engines. Although these propulsion systems seem to be feasible in principle, their utilization is still quite far away in the future due to technical challenges, development-, and operational cost. The technical demonstration of SCRAM has reached the subscale level at best. The airbreathing vehicles are very sensitive to their achievable range and to environmental issues. Therefore, they might be severely restricted in the destinations they are able to actually serve. The potential RBCC / SCRAM propulsion of hypersonic aircraft has a low technology readiness level and the technical feasibility of such a large-scale propulsion system raises tremendous design challenges and is yet to be demonstrated [4].

An interesting alternative in the field of high-speed intercontinental passenger transport vehicles might be a rocket-propelled, suborbital craft. The functionality of rocket propulsion is a proven technology since decades and their performance characteristics are well known. Furthermore, a rocket powered RLV-concept like the SpaceLiner is more attractive because the flight durations are two to three times lower than those of even the most advanced airbreathing systems. It is to be recognized that travel times of any airliner are not identical to flight times. Additional times for commuting to the airport hub which offers the long-distance flight, check-in, security-check and those to be accounted for waiting and transfer are to be considered. A preliminary estimation of the expected travel time for a SpaceLiner passenger shows approximately 5 to 6 hours for ultra-long distances. This result corresponds to a reduction in the actual time needed for travelling between at least 75 % and 80 % compared to conventional subsonic airliner operation: Those reach about 23 hours for non-stop service and typically about 30 hours for single stop Europe-Australia flights.

In contrast to the first generation of SST, thus a substantial advantage in travel times and hence improved business case can be expected. Potentially interesting destinations and their respective flight distances following the orthodrome are listed in [9]. Airbus most recently recognized the interesting long-term potential of ultra-fast rocket-powered passenger planes [10]. A first assessment of the SpaceLiner's potential business case is described in the references 1, 3, and 6. A more detailed market analyses is currently ongoing in order to find out who might be interested in using the SpaceLiner in the future for travelling.

The environmental impact of the LOX-LH2 propelled SpaceLiner is relatively benign and seems to be much less critical than for airbreathing concepts. The rocket concept is releasing even less exhaust gases into the atmosphere than today's commercial airliners because the engines do not burn the air. Most of the flight trajectory is at a much higher altitude than for the airbreathing vehicles considerably reducing the noise impact on ground. Nevertheless, the 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. A first assessment of the logistics is described in [8].

II. Technical Development Status

First proposed in 2005 [1], the SpaceLiner is under constant development and the first major update has been published [7]. Within the FAST20XX project the next iteration loop has been initiated. A systematic investigation of different design and propulsion options is part of this work (see section III and ref. 12).

This "first generation" design has subsequently been used for more detailed studies, 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 [7].

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. Fuel rich staged combustion cycle engines with a moderate 16 MPa chamber pressure, 384.5 kg/s mass flow, and 437.6 s (booster) / 448 s (orbiter) I_{sp} in vacuum are assumed for the propulsion system. 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.

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 current characteristic SpaceLiner data in Table 1.

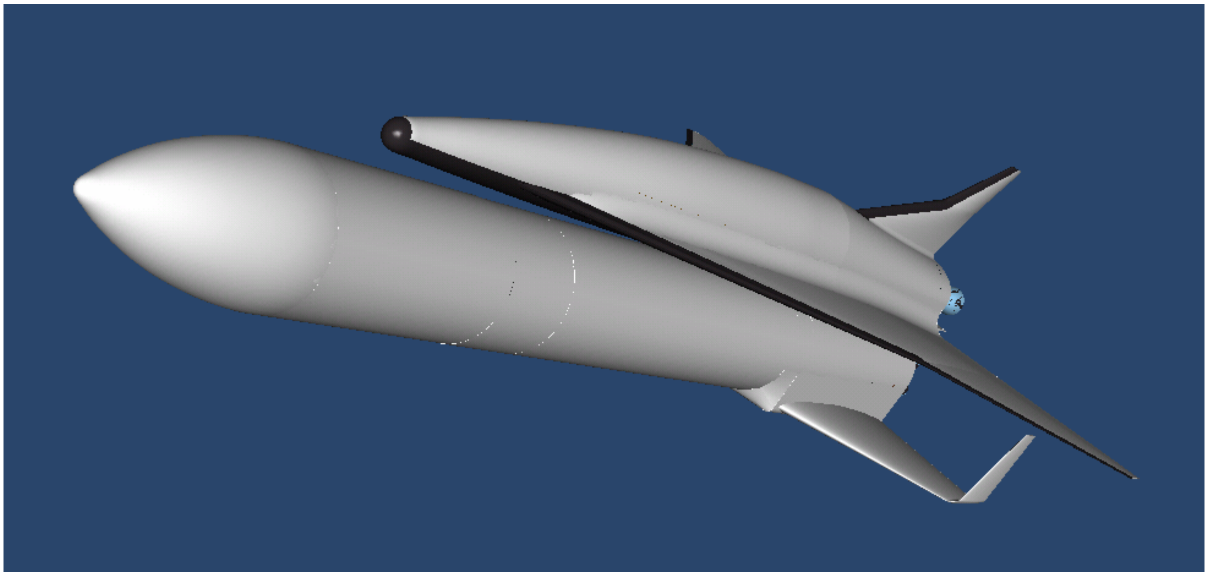

Figure 3: Latest geometry of generic rocket powered intercontinental passenger spaceplane SpaceLiner (top) with reusable booster (bottom)

	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

Table 1: SpaceLiner2 characteristic vehicle data (reference mission)

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 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 [7].

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 (compare [8]) 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, has been investigated for its suitability with the SpaceLiner2 configuration [7]. As has been found an elongated orbiter derivative could transport 100 passengers about 9000 km in one hour.

III. FAST20XX Research

The EU-funded FAST20XX (Future high-Altitude high-Speed Transport 20XX) multinational collaborative research project aims at providing a sound technological foundation for the industrial introduction of advanced high-altitude high-speed transportation in the medium term and in the longer term (SpaceLiner application) [11]. Note that no detailed vehicle design is planned in the study but the mastering of technologies required for any later development. The identified critical technologies will be investigated in depth by developing and applying dedicated analytical, numerical and experimental tools, while the legal/regulatory issues will be discussed with government or international authorities.

The high-energy concept SpaceLiner is intended to achieve a step change in ultra-fast long-haul passenger and freight transport. Although the basic performance data of the vertically launching and horizontally landing two-stage vehicle are undisputable, the eventual commercial realization is facing quite a lot of technical and operational challenges. The most important challenges are:

- High reliability and safety of hypersonic passenger flight
- Long life staged combustion cycle rocket engines
- Transpiration cooling to safely withstand a challenging aerothermal environment
- Fast turn-around times currently unknown in the launcher business

Some of these challenges characteristic for any high-energy transportation are addressed in the FAST20XX project. The work package 3 of FAST20XX looking at technologies for High-Energy Suborbital Transportation is organized in five different top-level lines, each one addressing a different technology to be developed and/or assessed:

- Mission Definition and System Analysis of the SpaceLiner (led by DLR SART as the creator of the concept)
- Heating, Flow and Flight Control (led by DLR's high-speed windtunnel division)
- Advanced Structures (led by Swedish research organization FOI)
- Low-Density Effects in Suborbital Flight (investigated by DLR and the Italian aeronautical research institution CIRA)
- Flight Dynamics and Safety (led by DEIMOS SPACE)

System Analyses

The system analyses work package is addressing the following subjects:

- Definition of the mission requirements for an ultrafast passenger transport (e.g. limits on acceleration during takeoff and descent, requirements on reusability and propulsion subsystem, safety issues etc).
- Establishment of a preliminary aerodynamic database in the hypersonic flight regime.
- Analysis of the flight profile and nominal flight trajectories for an ultrafast passenger transport.
- Sensitivity of vehicle and trajectory with respect to parameters which are of particular interest for the concept of this vehicle (e.g. L/D, wingload).
- Assessment of safeguard issues, crew safety aspects, including abort mission scenarios and associated requirements. The vehicle is designed for commercial passenger transportation. Therefore safety is of crucial importance. Thought must be given to safety systems and possible high risk flight phases must be defined.
- Generation of load cases and documentation of resp. loads for nominal and off-nominal conditions.
- Concept trade-off studies: Different vehicle concepts will be studied. For example different geometries will be investigated, to see what the effect of geometry is on aerodynamic heating, maximum obtainable range, weight, etc. Also, apart from the LOX-Hydrogen rocket engines, LOX-Kerosene engines for application on the booster stage will be investigated.
- Preliminary definition of SpaceLiner subsystems like:
    - Rescue subsystem
    - Passenger cabin subsystem
    - Propulsion and propellant supply subsystem
    - Active cooling subsystem and passive TPS
- CAD model establishment.
- Calculation of SpaceLiner masses and centre-of-gravity. After integration of the subsystems, the new COG of the vehicle is calculated and it is checked if the vehicle is still trimable.
- Cost assessment for development and operation.

A more detailed concept and trajectory optimization under the consideration of all relevant mission constraints and objectives followed by an extended analysis of sensitivity and safety aspects is performed using the *AeroSpace Trajectory Optimisation Software* ASTOS. This will include for example the following tasks: Simulation/-optimisation of the nominal case with 3-sigma deviations on the atmosphere and wind and the change in cross/-downrange due to 3-sigma deviations.

A critical assessment of different High-Speed Passenger Transports will be done on best available data and as far as possible on a similar technology basis. Hypersonic air-breathers of another EU-funded study LAPCAT with similar intercontinental range requirement will be compared with the SpaceLiner. Environmental issues will be discussed. Operational issues will also be addressed and the impact of horizontal-take-off vs. vertical take-off will be discussed.

Cooling Structure

The next important work package is the Cooling Structure design. The severe thermal loads in the nose and leading-edge regions of long-distance ultra-fast concepts require advanced active cooling. Novel and re-use friendly cooling systems will be needed which are robust and at the same time light-weight. Some promising techniques have been identified (fluid transpiration through porous material) for which the TRL will be significantly raised in the corresponding technology development activities. The objectives are to understand the related scientific and technological issues associated with the proposed transpiration cooling technology for extreme loaded structural areas while using porous CMC materials and structures. This includes the requirements assessment, choice and characterization of suitable candidate materials w.r.t chemical, thermal and mechanical durability, numerical analysis of temperature, pressure and flow (velocity) distribution within the active cooled structural wall material while taking into account porosity and permeability, phase change of the cooling fluid (boiling) and characterization of interaction phenomena in the structure/gas boundary layer. In addition, limits of selected ceramic heat protection material will be investigated to determine the range where active cooling concepts are definitely required.

In the frame of this work package such materials with transpiration cooling using water will be tested at flight similar conditions in the DLR arc heated facility L3K at heat flux rates up to 4 MW/m^2. The transition limit between active and passive oxidation is to be determined by VKI. It allows – together with the expected trajectory or the flight – the judgement if the TPS of the vehicle can be reused.

Flow control

The world-wide know how on how to keep supersonic/hypersonic boundary layers laminar is still small. However, the ability to stabilize a hypersonic boundary layer and increase the length of the laminar flow region is of critical importance in the hypersonic vehicle design. Early transition causes significant increases in heat transfer and skin friction. Higher heating requires a thermal protection system (TPS) with increased performance, active cooling, or trajectory modification. This translates into higher cost and weight of hypersonic vehicle in the case of increased TPS weight. With the still relatively low payload mass fraction, even small savings in TPS weight can provide a significant increase in passenger payload or range. Laminar flow control can help to meet such goals.

Advanced Structures

A structural model based on a conceptual design and preliminary construction is to be established in FAST20XX, using both metallic materials and modern advanced high-temperature resistant composite materials with possible cooling. The work will contribute also in a refined detailed simulation, including possible fluid-structure interaction at elevated temperature for some critical components of the orbiter. The simulations will be based on commercial finite element (FE) codes, FOI in-house unstructured CFD solver Edge, FOI in-house hp-FE computational structural mechanics (CSM) code Stripe and a coupled CFD–CSM methodology.
In a separate task, the small Austrian enterprise Orbspace analyses window designs and materials, as well as their size, number or location in the vehicle and their impact on vehicle structural mass. FE analysis of three generic windows conceptual designs shall provide a clearer understanding of the challenges and design difficulties.

GNC techniques

Latest results from control theory are already being transferred to flight application in the civil and military aeronautical domain suggesting their extension to the highly challenging atmospheric entry. The main challenge stems from the inherent uncertainty in the performance parameters of maneuverable re-entry vehicles which require the application of advanced robust flight mechanics methods for modeling, control design and certification process. A multidisciplinary approach is required to tackle the multi-variable, non-linear, time-varying and uncertain nature of the vehicle dynamics in all the steps of the GNC design process, from modeling, through GNC design and analysis, GNC verification and validation, till GNC functions certification. The planned activities of FAST20XX will lead to an increase up to TRL 3-4 of several key technologies in the GNC area (e.g. O/B trajectory optimization and re-planning, linear fractional transformation methods to represent the vehicle dynamics plant, robust GNC design techniques, O/B autonomous failure detection and identification (HMS-FDI) through robust estimation filters, novel worst case analysis methods during control certification process). The developed technologies will pave the way for their dual application to space transportation and aeronautics. The results of the proposed leading edge research in advanced optimization and control theory will be applicable to both sectors.

Worst-case conditions instead of a nominal reference scenario are used for the design of the subsystems. Trajectories in extreme conditions (maximum heat fluxes, maximum flight time, maximum g-loads…) are identified and calculated as a complement to the optimized reference trajectory. Either heuristic methods or optimization can be applied to compute those trajectories. It is used as an input to guide Monte Carlo simulations

Prerequisites for Flight Operations

Beyond the above listed research dedicated to technologies required by the high-speed concept SpaceLiner, the work package 4 in FAST20XX addresses the more general questions of Prerequisites for Flight Operations. This WP intends to state the pre-requisites that are needed to be able to fly, including safety, infrastructure needed, ground operations, medical aspects, legal aspects and certification, and environmental impact of flights. The objective is to have a solid foundation for designing vehicles and operations.

The work is broken into the following six top-level lines:

- Facilities and Ground Operations (led by Swedish Space Cooperation)
- Legal Aspects and Certification (led by Orbspace)
- Environment (led by Swedish Space Cooperation)
- Human Space Flight (led by DLR's aerospace medicine department) addressing g-induced as well as radiation issues etc.
- Safety & Business (led by Orbspace)
- Guidance, Navigation & Control Technologies (led by DEIMOS SPACE)

IV. Conclusion

Simulations show that an ultra fast rocket-propelled intercontinental passenger transport could one day flexibly serve the different passenger volumes on the major business routes of the world. The SpaceLiner concept, explicitly defined for this purpose, requires challenging technology but avoids any exotic equipment. Its size and performance are intentionally less demanding than well known Space Shuttle technology which is now more than 25 years old. However, some key technologies have to be improved, to make the SpaceLiner vision viable. The most important are:

- High reliability and safety
- Long life staged combustion cycle rocket engines
- Transpiration cooling to safely withstand a challenging aerothermal environment
- Fast turn-around times currently unknown in the launcher business

Some of these challenges characteristic for any high-energy transportation are addressed in the European research project FAST20XX which starts at the end of 2009 and runs for three years. An overview of the intended research subjects within this project related to the SpaceLiner concept is provided.

V. References

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Further updated information concerning the SART space transportation concepts is available at:
http://www.dlr.de/SART