PASSENGER CAPSULE FOR THE SPACELINER

C. Bauer, A. Kopp, T. Schwanekamp, V. Clark, N. Garbers
German Aerospace Centre (DLR), Space Launcher System Analysis (SART),
Institute of Space Systems, Robert-Hooke-Strasse 7, 28359 Bremen

Abstract

Since 2005, the SpaceLiner concept has been under investigation by the DLR-SART group. The goal of this hypersonic space plane concept is to fly 50 passengers within 90 minutes from Australia to Western Europe. A dedicated capsule concept will provide regular conveniences to the passengers during the nominal mission and will protect the passengers during an emergency situation. This capsule needs to be able to fly autonomously and safely back to the ground. Within this paper, first an overview of previously used and currently in-use escape systems of manned spaceflight will be presented, e.g. escape towers and ejection seats. Afterwards, two ideas of the SpaceLiner capsule concept will be presented. Finally, both concepts will be compared regarding geometry, mass, aerodynamic coefficients, and the integration/separation process.

1. INTRODUCTION

Since 2005, the DLR-SART group has worked on the SpaceLiner concept which is a hypersonic, passenger transportation, point-to-point system. The goal is to transport 50 passengers plus two crew members in 90 minutes from Australia to Western Europe [1], [2].

During this mission, the SpaceLiner to be subjected to very high thermal and structural loads which could present a risk to the lives of the passengers. An additional threat is that whilst on the launch pad, liquid hydrogen (LH2) and liquid oxygen (LOX) will be inside the tanks. These are just two of the reasons why a dedicated rescue system is needed to protect the untrained passengers travelling with the SpaceLiner.

However, the passengers are not to undergo a special training before flight. The idea is to have a capsule rescue system which also acts as a cabin during the nominal mission.

The requirements for such a hybrid capsule system (rescue vehicle and cabin) are challenging because they need to cover the nominal flight requirements as well as the off-nominal flight conditions.

For the nominal flight the preliminary requirements are:

- Enough space for 50 passengers plus two crew members
- Seating as conventional passenger aircraft
- Adequate and comfortable environment (temperature, pressure)
- Boarding and de-boarding has to occur when the capsule is horizontal on the ground
- Quick and reliable integration into the SpaceLiner orbiter before launch and quick and reliable removal after landing

For the off-nominal flight the preliminary requirements are:

- Autonomous ejection and flight back to Earth through the entire mission
- Landing in many environments (water, land, ice)
- Fast and un-aided evacuation possibility
- Minimize the injury and loss of life of passengers, crew
- Minimize the injury and loss of life of ground-inhabitants and damage of ground-buildings
- Maximum allowed acceleration of 12 g_0 for 2 s in n_x, and 3 g_0 in n_z

These requirements are currently preliminary requirements and it is quite possible that during the project further requirements will be made and the above mentioned requirements will be changed.

With these requirements in mind, two different capsule concepts were investigated and the preliminary results are presented within this paper.

A preliminary investigation of different capsule geometries has been conducted and on this basis, the here presented alternative capsule concepts have been modified.

First a short introduction of used and proposed crew escape systems is given, followed by the presentation of the baseline capsule. Second an introduction of an alternative capsule concept is given. For both concepts, the aerodynamics, the mass data, and the preliminary flight trajectories will be presented as well as the integration/removal options of the capsule will briefly be discussed.

Lastly, both concepts will be compared with each other so that the advantages and disadvantaged are made clearly.

2. BACKGROUND INFORMATION OF CREW ESCAPE SYSTEMS

The launch abort and aborts during the early phases of the ascent are most critical because the tanks are completely full with explosive fuel. If at this stages of the mission a failure occurs, not only the crew on board, but also people on the ground are in danger. Therefore, since the beginning of human space flight, studies of escape systems have been undertaken, and to some extent implemented. For the launch abort, two different approaches for escape systems were or are still in use: escape towers (Mercury, Apollo, Soyuz, Orion, and the Chinese Shenzhou) [4], [5], [6] and ejection seats (military supersonic planes, Vostok, Gemini, and Shuttle) [5], [7].

Escape towers are mounted at the top of the spacecraft and have their own rocket motors or rocket engines. The escape towers pull the crew capsule/compartment away from the danger zone, to a safe altitude at which point the parachute can be deployed. Thus, a soft landing of the crew capsule/crew compartment a safe distance from the danger zone can be assured.

During a nominal launch and ascent phase, the escape towers are jettisoned to reduce the mass of the accelerating and rising rocket.

Ejection seats are used for rocket planes throughout the entire mission and for others (e.g. Vostok and Gemini) during launch and early mission abort. Ejection seats were also implemented in the early Space Shuttle testing phase, but they were removed for the operational flights [5].

For the Gemini missions and the Shuttle Program, escape systems were removed due to financial and design technical reasons [5].

3. BASELINE CAPSULE

Figure 1 displays the integrated baseline capsule of the SpaceLiner. The capsule sits in the front section of the SpaceLiner orbiter, followed by the liquid oxygen tank (LOX) and the liquid hydrogen tank (LH2). Figure 2 shows the preliminary structural design of the capsule: a pressurized cabin and an aerodynamic shell.

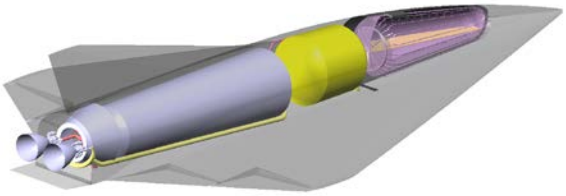

Figure 1: SpaceLiner with the baseline capsule integrated

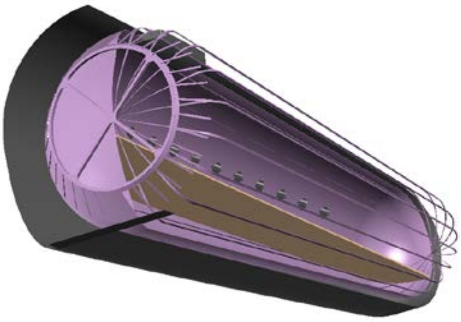

Figure 2: Preliminary structural design of the baseline capsule

The capsule has two purposes: during the nominal mission, the capsule is the passenger cabin where the passengers have their seats and all conveniences. However, during the case of an emergency, when the capsule is about to be separated, the capsule is the emergency escape vehicle which will bring the passengers safely back to the ground.

A rough preliminary interior layout is shown in Figure 3. The stairs are necessary because the passengers embark the SpaceLiner while the capsule is horizontal on the ground. Thus, the passengers can walk without additional help to their seats. After boarding is completed, the stairs are folded and stored. The stairs are also needed after landing for the passengers to leave the capsule through the main door.

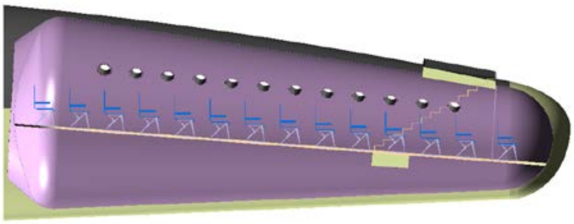

Figure 3: Side view of the baseline capsule

3.1. Mass budget of the baseline capsule

The mass budget of the baseline capsule includes the mass of the structure, masses of all subsystems, masses for the propulsion systems, and masses of the thermal protection system (TPS).

The masses for the subsystems include all subsystems needed to ensure a safe return flight (parachutes, swimmer, pressurizer), subsystems needed for the passengers' convenience (in-flight entertainment), and subsystems which are necessary equipment for nominal flight and for abort missions such as electronics, avionics, and hydraulics.

The propulsion group consists of the separation system, the retro-rockets, the RCS engines, and the pitch motor plus the fuel needed for these motors and engines.

The TPS group includes the masses of the thermal protection of the capsule during nominal mission as well as during off-nominal missions. [8]. The peculiarity of the TPS for the baseline capsule is that the upper part of the capsule's TPS is the orbiter's TPS. In other words, the upper surface part of the capsule is during nominal missions the surface of the orbiter. Thus, a requirement for the TPS is that the TPS of the upper surface part of the capsule is able to withstand the heat loads during an off-nominal mission as well as the heat loads during the nominal mission.

In Table 1, the preliminary masses of the mentioned groups are shown. The subsystems group has with 17.6 t the highest mass compared to the other groups. With all the mentioned values, the baseline capsule has a mass of 36.5 t.

Table 1: List of the masses for the baseline capsule

	Mass [t]
Structure	9.2
Subsystems	11.2
Passengers and luggage	6.4
Propulsion	4.9
TPS	4.8
Total mass	36.5

Subsonic, transonic, and supersonic regime (0.2<M<3.8)

For the case of abort on the launch pad, and for the final approach of the abort trajectories, the subsonic, transonic, and low supersonic Mach number are especially important. The lift coefficient for the baseline capsule is presented in Figure 4, the drag coefficient can be seen in Figure 5, and Figure 6 shows the glide ratio (L/D). The glide ratio for the baseline capsule in this regarded Mach number regime is around one which can be expected for such a capsule geometry. The reference area for these following values is 10 m^2.

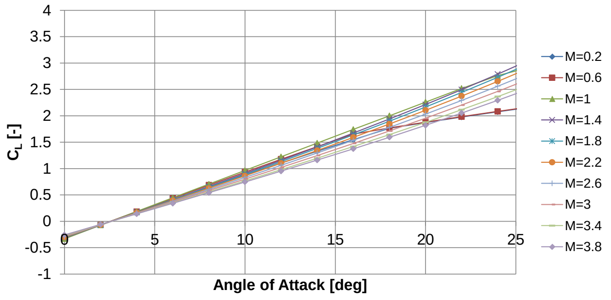

Figure 4: Lift coefficient c_L for 0<M<3.8

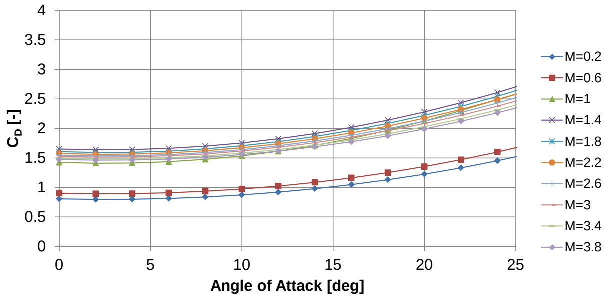

Figure 5: Drag coefficient c_D 0<M<3.8

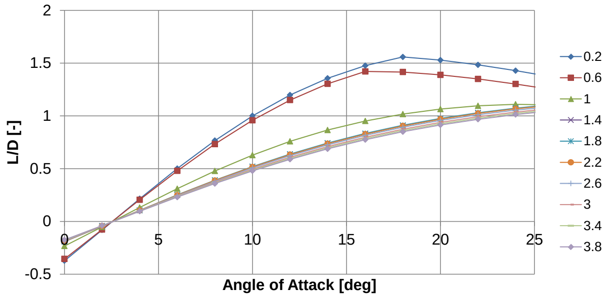

Figure 6: Glide ratio for 0<M<3.8

Hypersonic regime (M<4)

The aerodynamic of the hypersonic regime presented here is pre-trimmed. That means that the momentum coefficient are always around zero and thus, the capsule is in a trimmable state.

Figure 7 displays the lift coefficient, Figure 8 shows the drag coefficient, and the glide ratio can be seen in Figure 9 with values of slightly above one.

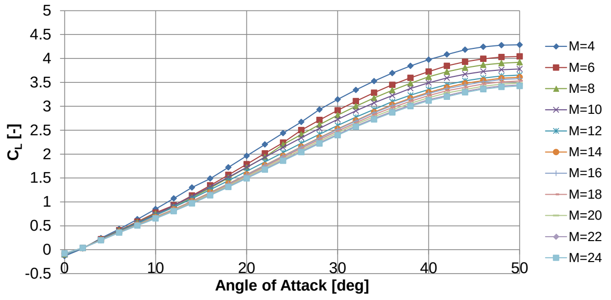

Figure 7: Lift coefficient c_L for M>4

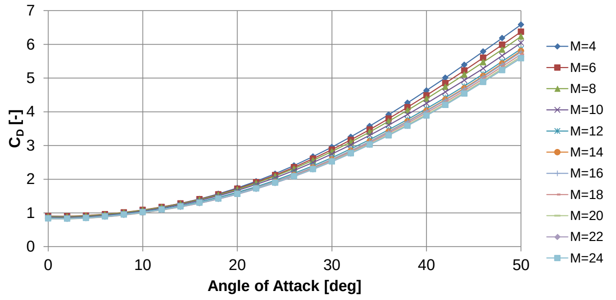

Figure 8: Drag coefficient c_D for M>4

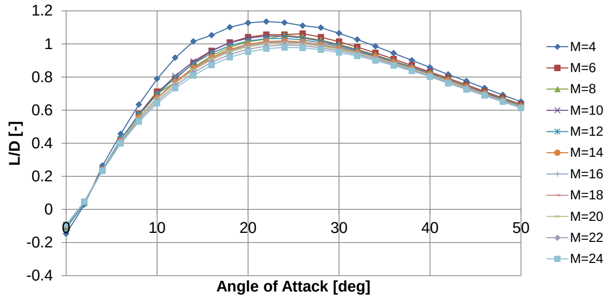

Figure 9: Glide ratio for M>4

3.2. Ejection trajectories of the baseline capsule concept

In this section, four ejection trajectories will be presented for the following abort cases:

- Launch pad
- Nominal booster separation
- Nominal highest altitude
- Nominal main engine cut-off (MECO)

The assumption for the following trajectories is that no interaction between the vehicles is taken into account. Only the capsule and its re-entry trajectories are considered.

Abort at launch Pad

The ejection of the capsule of the launch pad is challenging since the orbiter and the booster are in a vertical position and completely loaded with fuel. The separation motors must accelerate the capsule such that the danger zone is left behind and that the landing parachutes are able to inflate properly. That means that a certain altitude and a certain distance from the exploding fuel need to be reached. It is assumed that the structure of the capsule can withstand a blast wave of 60 kPa, and consequently the capsule must be 289 m away from the launch pad when hit by the blast wave of the exploding fuel tanks [9]. Hence, an investigation was carried out and the conclusion was that five solid rocket motors (SRM) are sufficient to provide the required thrust for the launch pad abort.

With these above mentioned requirements in mind, the launch pad trajectory is calculated. The altitude over time is shown in Figure 10.

The capsule reaches a maximum altitude of over 1.4 km, so that the parachutes can be safely deployed and eventually, the capsule can land softly. Furthermore, the analysis confirmed that the capsule reaches the safe distance within the required time and the maximum allowed loads.

Figure 11 displays the maximum loads occurring during the short abort flight. The maximum loads in x directions are under 12 g_0.

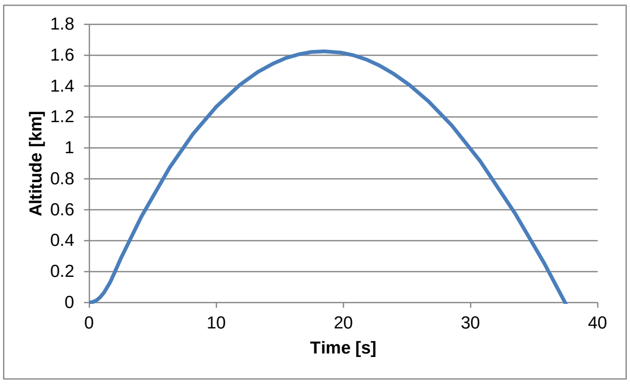

Figure 10: Altitude over time for abort at the launch pad

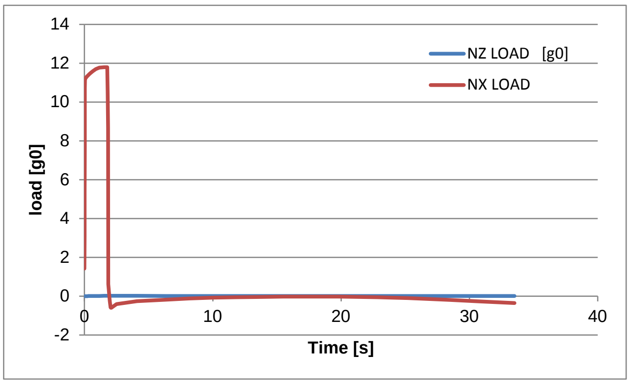

Figure 11: Loads over time for abort at launch pad

Abort at nominal booster separation

The capsule is assumed to contain five SRMs attached as discussed in the previous section. However, it needs to be carefully confirmed that this is compliant with the acceleration load requirements. If all five SRMs were to be fired at the same time, the maximum acceleration loads would exceed the stated limits. The proposed solution is to first fire four SRMs and 2 s later start the remaining SRM. This allows the capsule to reach a safe distance while remaining within the load requirements.

The altitude where the booster separation occurs during a nominal flight is at 73.1 km with the velocity of 3.7 km/s.

Figure 12 presents altitude over time for the abort at nominal booster separation. This re-entry flight is quite smooth without large skips in the atmosphere. Figure 13 shows the Mach number characteristic over the time for the descent trajectory of the capsule. The Mach number decreases without major jumps or peaks. In Figure 14 the loads which occur during the descent are presented. The highest loads (n_x) occur at the separation and are below the limit of 12 g_0. After the highest loads at the separation occurred, the loads stay well below 3 g_0 for the remaining flight.

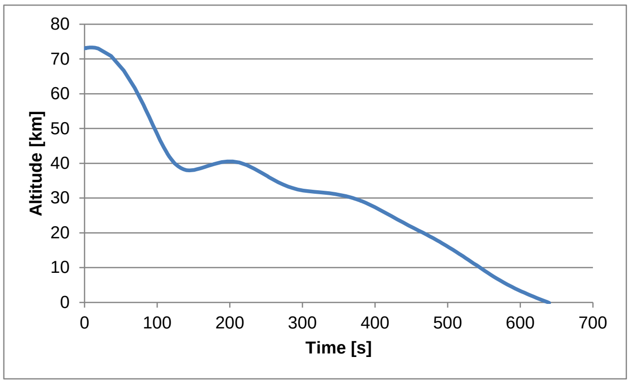

Figure 12: Altitude over time for abort at nominal booster separation

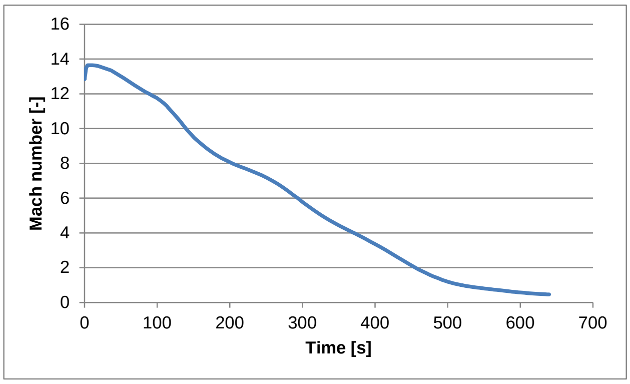

Figure 13: Mach number over time for abort at booster separation

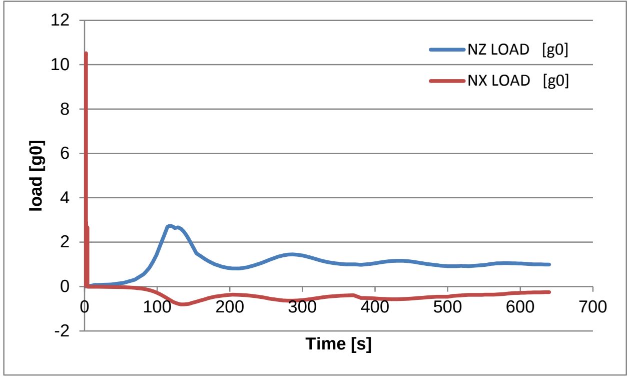

Figure 14: Loads over time for abort at booster separation

Abort at nominal highest altitude

This abort case was chosen because the orbiter has reached its highest altitude but is still accelerating. Thus, it is crucial to understand the flight of the capsule after a separation from the accelerating orbiter. However, only the capsule trajectory is considered within this paper.

The altitude where in the nominal mission the highest altitude is reached is at 73.4 km and the initial velocity is 4.0 km/s.

Figure 15 shows the altitude over the time of the re-entry trajectory of the capsule. This trajectory is also without skipping and decreases gently back to the ground.

Figure 16 presents the Mach number gradient over time. The Mach number decreases steadily throughout the flight.

Figure 17 presents the loads characteristics and the highest loads by far occur at the separation. During the remaining time, the loads do not exceed 2.5 g_0 in z-direction nor -2 g_0 in x-direction.

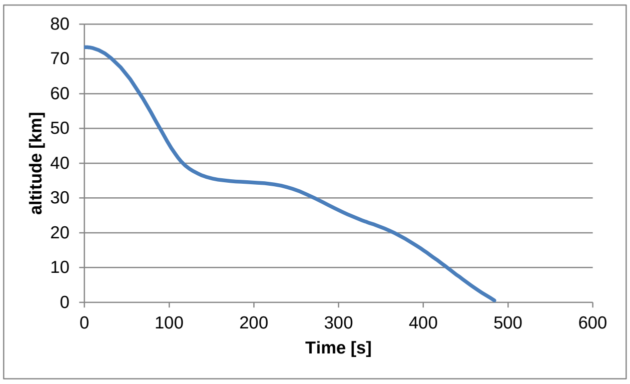

Figure 15: Altitude over time for abort at nominal highest altitude

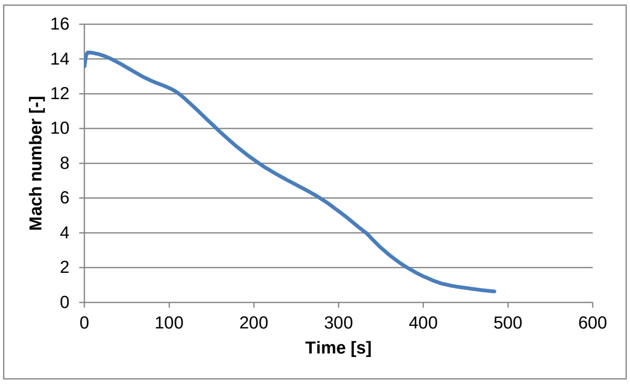

Figure 16: Mach number over time for abort at nominal highest altitude

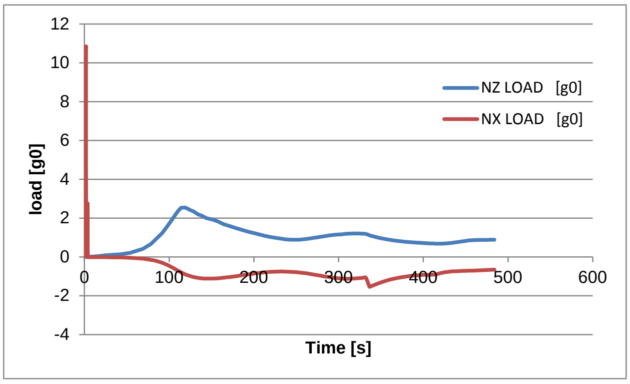

Figure 17: Loads over time for abort at nominal highest altitude

<u>Abort at nominal MECO</u>

This abort case was chosen due to its occurrence at the highest nominal velocity during the nominal flight of the SpaceLiner.

The altitude where in the nominal mission, MECO occurs is at 70.3 km and the initial velocity is 7.5 km/s.

Figure 18 shows the altitude over the time of the re-entry trajectory of the capsule. Due to the high initial velocity, the capsule has a long flight time of about 2200 s.

Figure 19 presents the Mach number gradient over the time and Figure 20 presents the loads characteristics and the highest loads by far occur at the separation. During the remaining flight time, the loads do not exceed 1.5 g_0 in z-direction nor -0.5 g_0 in x-direction.

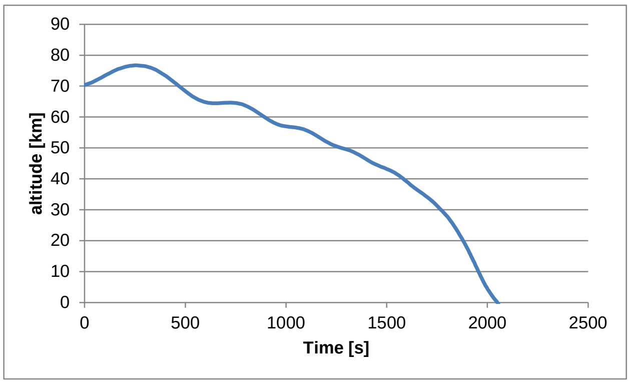

Figure 18: Altitude over time for abort at nominal MECO

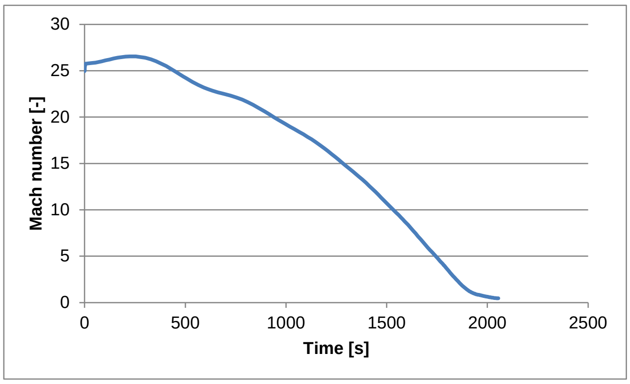

Figure 19: Mach number over time for abort at nominal MECO

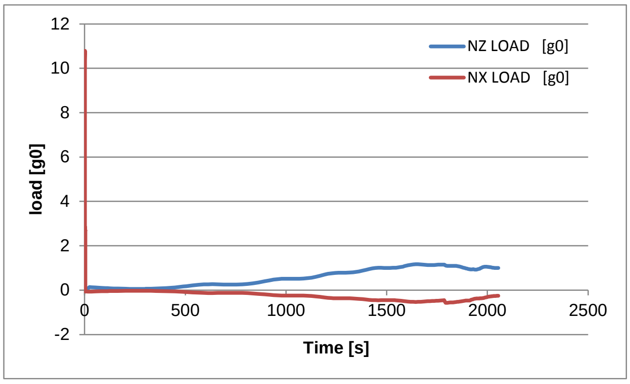

Figure 20: Loads over time for abort at nominal MECO

3.3. Integration / Removal of the baseline capsules

The integration of the capsule shortly before launch of the SpaceLiner is a very complex procedure and it is one of the most important procedures of the concept from on operational point of view since the integration will need to be made on a daily basis. Therefore, we have to ensure that this sequence has a short duration (the preliminary assumption is less than 10 minutes) and that this sequence is reliable. In other words, the design of the mechanical interfaces between orbiter and capsule need to be designed such that in the case of an emergency, a quick separation is ensured.

The preliminary separation sequence is shown in Figure 21. First, the capsule is moved forward, second the capsule is rotated, and finally the capsule is, during further rotation, accelerated forward.

However, Figure 21 also points out the critical situation when separation will occur: that other elements of the orbiter will need to be jettisoned before the capsule can be used as an escape vehicle. For example, during the forward movement, elements in front of the capsule need to be moved out of the way, and during the rotation, elements of the upper part of the orbiter will need to be removed to ensure a successful separation. Furthermore, jettison of elements on the side of the orbiter would also be necessary for capsule separation.

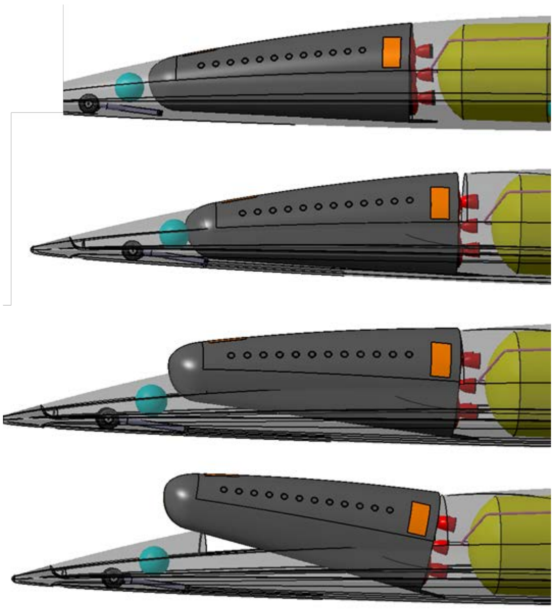

Figure 21: Separation sequence of the baseline capsule

4. ALTERNATIVE CAPSULE CONCEPT

Another capsule concept is that the escape vehicle makes up the entire front section of the orbiter. In Figure 22, the blue color indicates the escape vehicle.

This capsule concept has the same requirements as the baseline capsule.

The major geometrical difference to the baseline capsule is the wing section which also needs be separated in a case of emergency because it is thought to be a quicker integration and separation process.

The advantage of having a wing is that lift is provided and that means the cross range of the capsule can be increased. Figure 23 shows the alternative capsule concept after the separation has occurred.

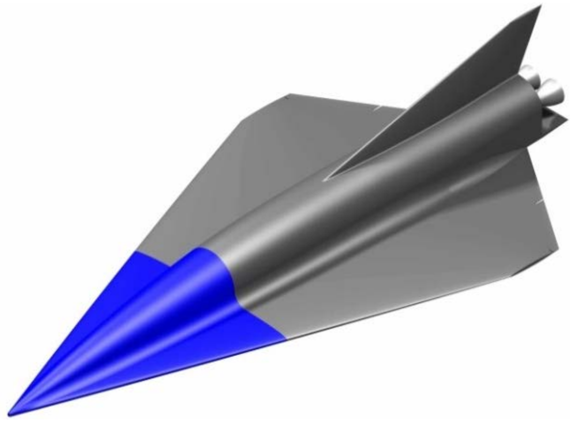

Figure 22: SpaceLiner with an alternative capsule concept

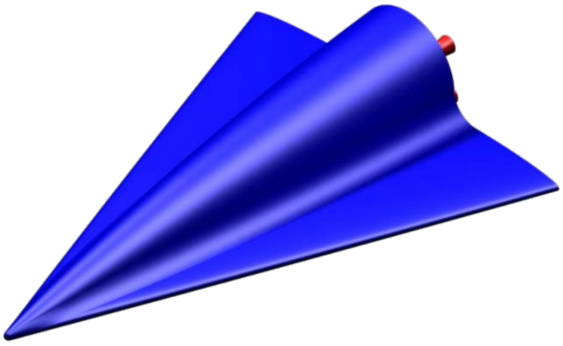

Figure 23: Alternative capsule

4.1. Mass budget of the alternative capsule concept

The preliminary mass budget for this alternative capsule concept can be seen in Table 2. The breakdown of the masses is the same as for the baseline capsule: structure, subsystems, propulsion, and TPS. With all of these masses, the total lift-off mass of this alternative capsule concept is 66.3 t.

Table 2: List of the masses for the alternative capsule concept

	Mass [t]
Structure	24.7
Subsystems	13.2
Passengers and luggage	6.4
Propulsion	8.2
TPS	13.8
Total mass	66.3

4.2. Aerodynamics of the alternative capsule concept

The aerodynamic data for the alternative capsule concept has a similar approach as the baseline capsule. First, aerodynamics of the subsonic and the supersonic (0.2<M<3.4) are shown. Second, the hypersonic aerodynamic is presented (M>4). The alternative capsule concept is trimmable with the deflection of the body flap between 10° angle of attack (AoA) and 30° AoA. Therefore, the following diagrams are shown within this range.

Subsonic, transonic, and supersonic regime (0.2<M<3.4)

The lift coefficient for the alternative capsule concept is shown in Figure 24, with the calculated values landing between ~5 for 10° AoA and ~36 for 30° AoA. Figure 25 presents the drag coefficient, and in Figure 26 the glide ratio can be seen. The glide ratio is the highest, at an AoA of 10°, with a value between 3 and 4 for the supersonic Mach numbers, and a value of ~6 for subsonic Mach number.

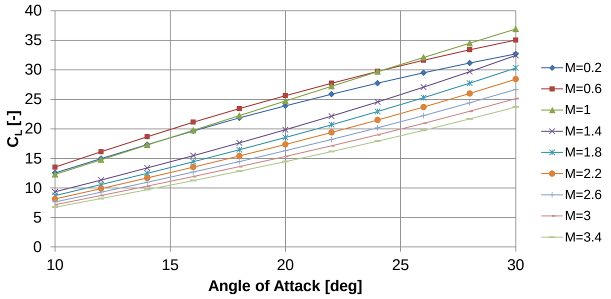

Figure 24: Lift coefficient c_L for 0.2<M<3.4

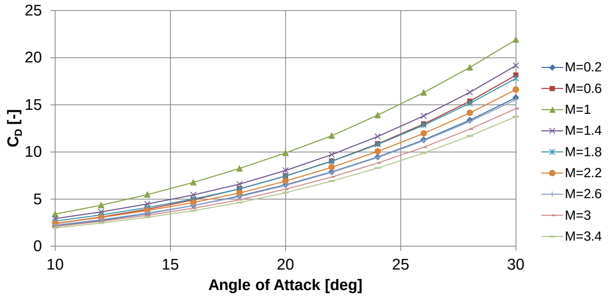

Figure 25: Drag coefficient c_D 0.2<M<3.4

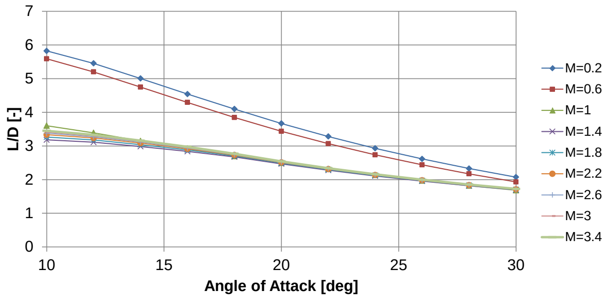

Figure 26: Glide ratio for 0.2<M<3.4

Hypersonic regime (M<4)

Figure 27 shows the lift coefficient for the hypersonic Mach number regime. In Figure 28 the drag coefficient are displayed, and Figure 29 presents the glide ratio of the alternative capsule for Mach numbers between 4 and 24. For the hypersonic regime, like in the subsonic, transonic, and supersonic regime, the glide ratios are the highest at 10° AoA with a value between 2 and 3.5 depending on the Mach number. The trend is that the higher the Mach number, the lower the glide ratio.

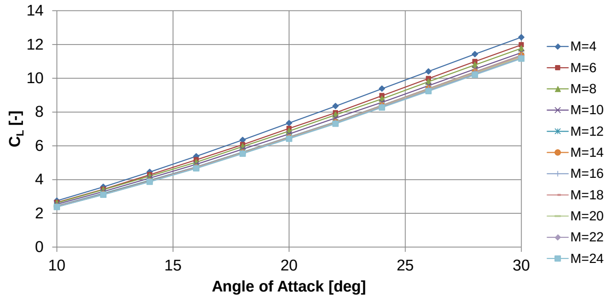

Figure 27: Lift coefficient c_L for M>4

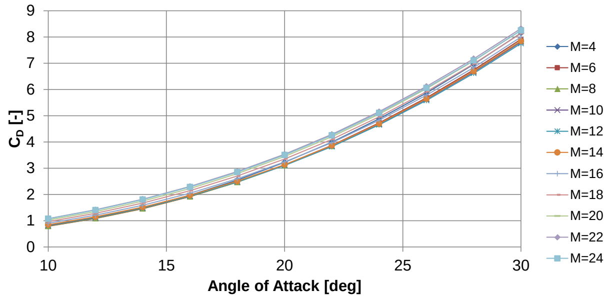

Figure 28: Drag coefficient c_D M>4

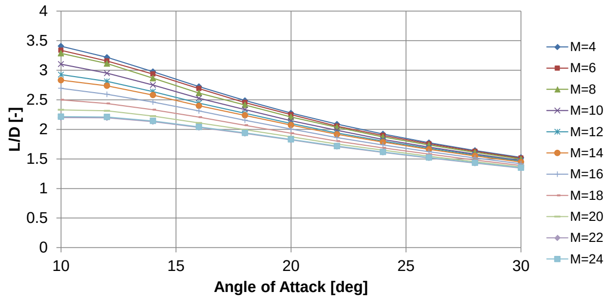

Figure 29: Glide ratio for M>4

4.3. Ejection trajectories of the alternative capsule concept

The requirements in each case are the same as in section 3.3. The investigated cases for the alternative capsule concept are also the same except for the use of the five SRMs. For this alternative capsule concept, all five SRMs are fired at the same time for all emergency cases.

Abort at launch Pad

The abort at launch pad is one of the most important cases due to the high masses of explosive fuel.
For the alternative capsule concept, the flight trajectory for the abort at launch pad can be seen in Figure 30 and the occurring loads are presented in Figure 31. The covered distance of the capsule within the first 2.5 s is more than the required 289 m.

The loads occurring during this abort case are well below the requirement of staying below 12 g_0 in n_x and 3 g_0 in n_z.

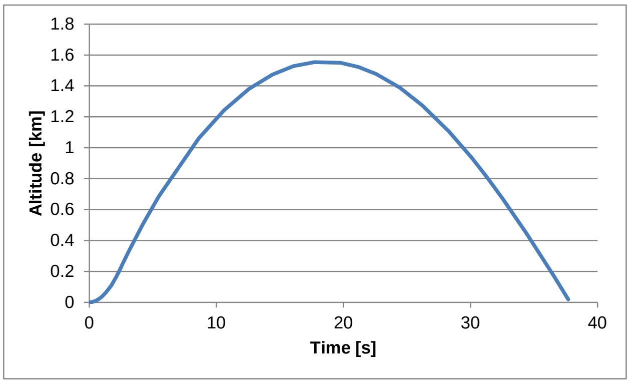

Figure 30: Altitude over time for abort at the launch pad

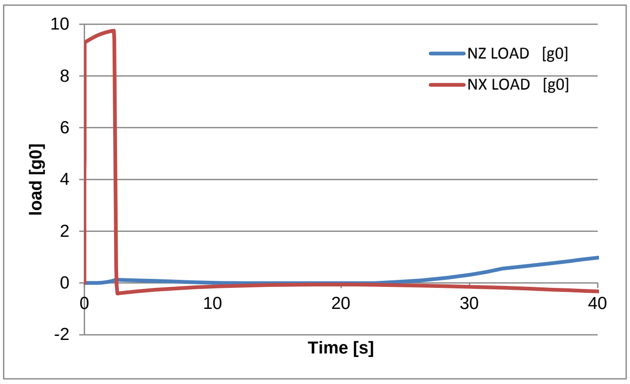

Figure 31: Loads over time for abort at the launch pad

Abort at nominal booster separation

The trajectory of the alternative capsule concept is presented in Figure 32. Figure 33 shows the Mach number over the flight time and in Figure 34 the occurring loads during the flight are presented.

The trajectory, in Figure 32, shows some slight skipping during descent but the final approach is smooth.

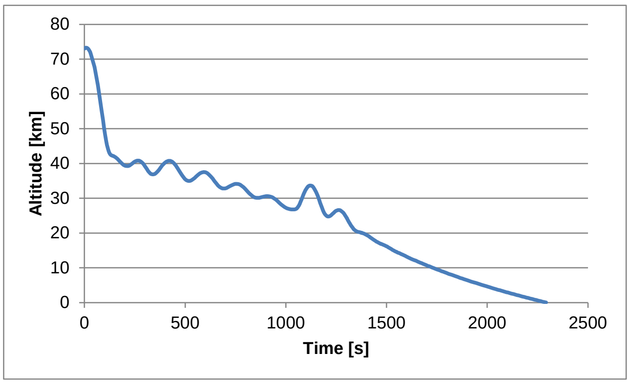

Figure 32: Altitude over time for abort at booster separation

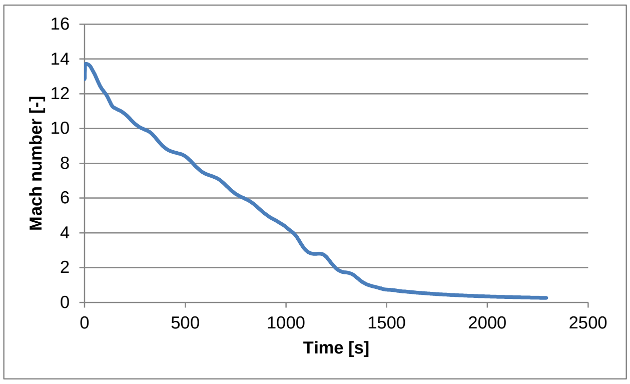

Figure 33: Mach number over time for abort at booster separation

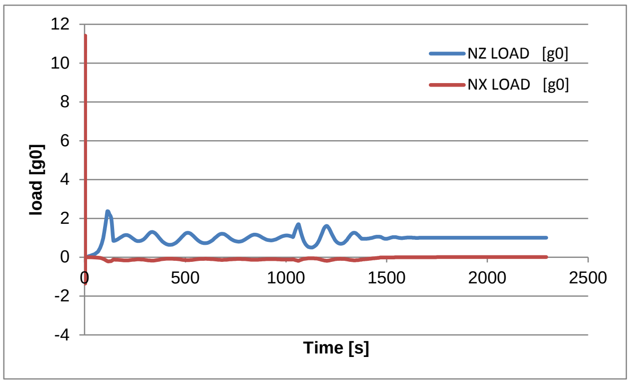

Figure 34: Loads over time for abort at booster separation

Abort at nominal highest altitude

Figure 35 displays the trajectory of the alternative capsule concept for the abort at highest altitude, Figure 36 presents the Mach number over the flight time, and in Figure 37 the occurring loads during the flight are shown.

The trajectory includes some slight skips during descent, but again the Mach number decreases gently over the flight time, and the loads are below the required limits.

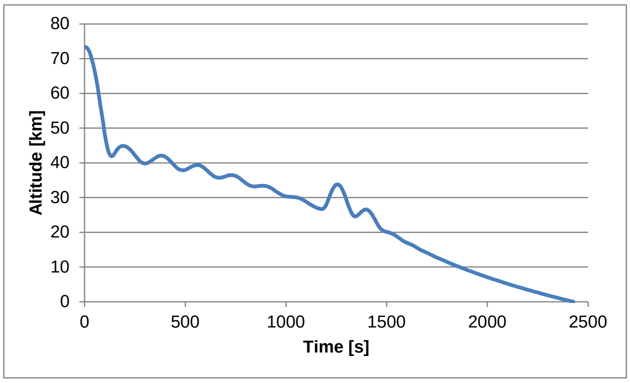

Figure 35: Altitude over time for abort highest altitude

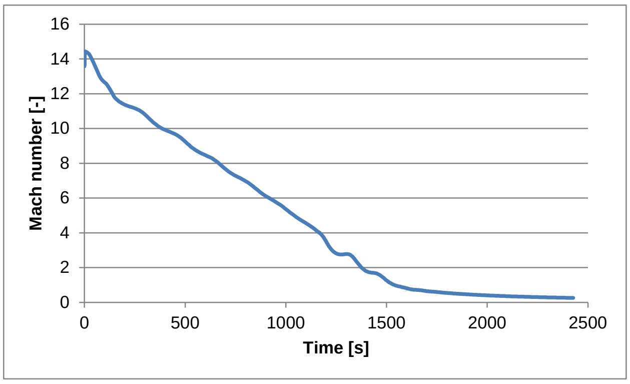

Figure 36: Mach number over time for abort at highest altitude

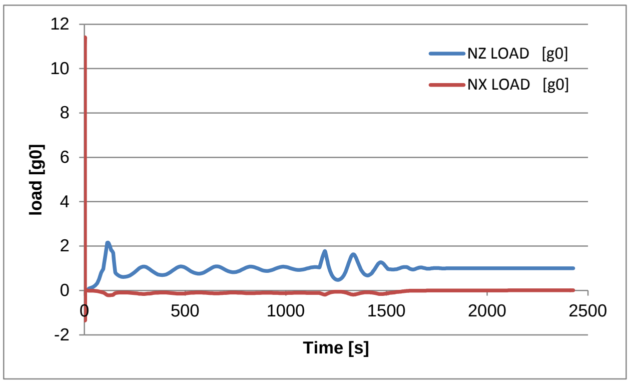

Figure 37: Loads over time for abort at highest altitude

Abort at nominal MECO

The trajectory for the abort at MECO of the alternative capsule concept is displayed in Figure 38, in Figure 39 the Mach number over the time is presented, and Figure 40 presents the loads occurring during this abort flight.

The trajectory is smooth and has only slight skips, whilst the Mach number first increases and then afterwards decreases. The loads remain well below the limits throughout the flight.

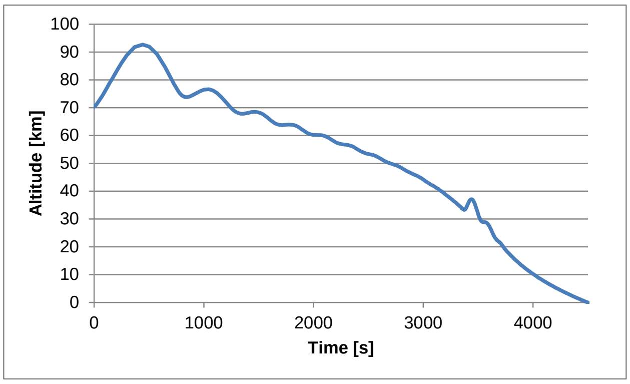

Figure 38: Altitude over time for abort at MECO

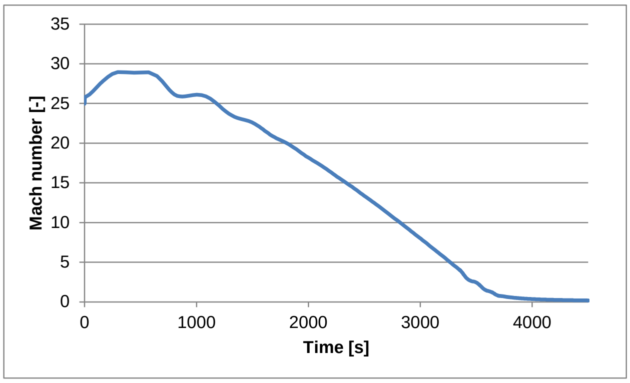

Figure 39: Mach number over time for abort at MECO

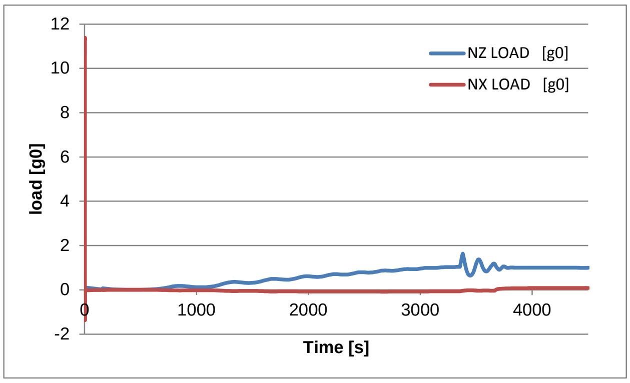

Figure 40: Loads over time for abort at MECO

4.4. Integration / Removal of the alternative capsule concept

The integration and the removal of the alternative concept are quite simple: the capsule sits in front of the LOX tank. Basically, the whole nose section of the orbiter is the escape vehicle.

Before launch, the alternative capsule is connected to the orbiter in similar fashion to the upper stage of a conventional rocket. The mechanical interfaces between orbiter and capsule must be similar to the interfaces between stages of conventional launchers. This means that the capsule must be able to be locked during the nominal mission, yet easy and quick to unlock in the case of capsule separation.

Figure 41 displays the preliminary separation: the capsule is accelerated away from the orbiter without any rotational movements.

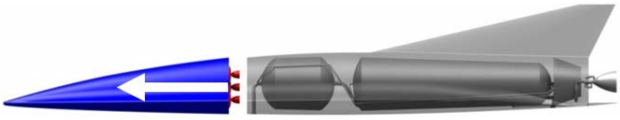

Figure 41: Separation of the alternative capsule concept

5. COMPARISON OF THE TWO PRESENTED CONCEPTS

After the presentation of the results for both capsule concepts, the comparison and the assessments of the results is now presented. Table 3 shows the comparison of both concepts.

The baseline capsule is integrated into the orbiter whereas the alternative capsule is attached to the front of the orbiter. This attachment can be seen as a stage when comparing with conventional rockets. The advantage of the baseline capsule is hence if a separation is needed due to TPS failure on the lower side of the orbiter, the baseline capsule has an additional TPS which will continue to protect the capsule.

The baseline capsule has a mass of 36.5 t compared with a mass of 66.3 t for the alternative capsule. These values are only for the capsules. However, when estimating the mass of the whole SpaceLiner concept, the difference between the masses may not be significant.

The primary difference in the aerodynamics of the concepts is the differences in the glide ratios (L/D). For the baseline capsule, the glide ratios are low compared to the glide ratios of the alternative capsule. This means that the flight range is larger for the alternative capsule and thus, the flight times are also longer for the alternative capsule.

Furthermore, the integration and the separation process of the baseline capsule are significantly more complex. Additional panels need to be attached after integration and jettisoned before the capsule can be separated. Due to the project requirements, the integration process shall be less than 10 minutes and the separation process must be less than 2.5 s.

In conclusion, the final decision which capsule system will be used, requires more analysis and data. Both concepts need to be further studied to come to a final conclusion.

Table 3: Overview of the two presented concepts

	Baseline capsule	Alternative capsule
Geometry	Integrated into the orbiter	Attached to the orbiter
Mass	36.5 t	66.3 t
Aerodynamics	Low L/D (glide ratio)	High L/D (glide ratio)
Trajectories	Shorter flight times	Longer flight times
Integration/ Separation	complex	simple

6. CONCLUSION

Within this paper, a short overview of previously used and still in-use crew escape systems was given. This was followed by presentations of the baseline capsule design and an alternative capsule concept. These presentations included the introduction of the geometry, the preliminary mass estimation, aerodynamics, trajectories, and the ideas of integration and separation for each capsule concept. Finally, both capsule concepts were compared with each other.

A capsule should increase the safety of the passengers. At this point in time, the final decision as to which concept shall be used for the SpaceLiner is still under investigation.

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

[2] Sippel, M., Promising roadmap alternatives for the SpaceLiner, Acta Astronautica, Vol. 66,No. 11-12, pp. 1652-1658,2010

[3] Becker, M., Rettungskapsel-Design und Integration für das Hyperschallverkehrsflugzeug SpaceLiner, SART-TN-001/2014

[4] McCarthy Jr., J. F.; Dodds, J. I.; CROWDER, R. S., Development of the Apollo launch escape system, Journal of Spacecraft, Vol. 5, No. 8, August 1968

[5] Musgrave, G. E.; Larsen, A. M.; Sgobba, T., Safety Design on Space Systems, Elsevier 2009

[6] Maloney, K., Launch pad Escape System Design (Human Spaceflight), KSC-2011-096

[7] Ray, Jr. H. A., Burns F. T., Development and qualification of Gemini escape system, NASA TN D-4031, 1967

[8] Garbers, N., Latest version of the SpaceLiner's TPS with TOP, SART-TN-026/2013

[9] Johannsson, M., Capsule Rescue Motors for SpaceLiner 7.1, SART-TN-018/2012