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CABIN ESCAPE SYSTEM: A WAY TO ENSURE CREW SAFETY DURING SUBORBITAL FLIGHTS

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Abstract

This paper deals with the conceptual design of a cabin escape system to be implemented on a spaceplane aimed at performing suborbital parabolic flights. After the identification of the reasons why an escape system is so interesting for this type of vehicle, a design methodology and the related support tool-chain are proposed and applied to the definition of an escape system for a single stage suborbital transportation system taken as reference case study. During the design process, specific attention is paid to the impact of onboard systems integration on the vehicle architecture and on the cabin escape system layout. Furthermore, the possibility of exploiting this system during the different phases of the mission has been evaluated and eventually, a preliminary impact risk analysis is reported.

1 General Introduction

Suborbital flights are becoming very interesting for a noticeable number of stakeholders thanks to their wide range of possible applications they could offer: from touristic experiences to scientific experiments in microgravity conditions. However, this increasing demand is in contrast with the lack of well-defined international regulations. Only few national efforts could be observed, like for example the FAA initiatives about space transportation system in US [1], the UK proposals for spaceplane and related operations [2] and the Italian initiative lead by ENAC (Italian National Airworthiness Agency) [3]. The imbalance between market and regulation forces the designer developing solutions with an ever higher level of safety in order to maintain or increase the public consensus and, as direct consequence, to create more profits (i.e. to sell higher number of tickets for parabolic flights). In this context, this paper proposes a way to enhance the safety level of an innovative suborbital single stage vehicle suggesting the implementation of a cabin escape system.

In the past, several examples of emergency and rescue systems have been envisaged and proposed for both space vehicles [4] and aircraft [5]. In particular, after Space Shuttle disasters, the need for an emergency system able to guarantee crew survivability in case of very severe mishaps all along the mission was strongly supported by different parties encouraging in depth-studies [6] [7]. Since the beginning of the space race era, and even more in the current attempt of space transport commercialization, the need for developing innovative solutions for the crew survival is first of all an attempt perform since the conceptual design stage, to diminish the risk of loss of lives during flights related to this kind of applications. It is worth to notice that the need of detaching a part of a spaceplane can deeply affect the architecture of the spaceplane as well as the its inertial characteristics, handling qualities, in-flight performances, costs and time of all product life cycle's phases. Indeed, the desire of guaranteeing the survivability of the crew, once the emergency pod is detached from the main vehicle, forces the designer to accommodate within the volume located for the escape systems all the vital equipment.

After this introduction aimed at revealing the major motivations in carry on this study, Section 2 provides a brief overview on suborbital vehicles and missions, presenting also the reference vehicle. Section 3 suggests a conceptual design methodology to face with the design of a cabin escape system and its integration in the reference case study. Then, Section 4 summarizes the main achievements of the design process and eventually, the results of a preliminary risk analysis are reported.

2 Suborbital flights: an overview

In the last decades, the high speed of development of new advanced technologies, in different engineering fields, is pushing even more the humankind to reach the edge of space. In parallel to the design, development and operation of new Earth-To-Orbit transportation systems, there is an increasing demand for suborbital transportation systems [8]. In fact, the capability of carrying passengers up to a meaningful target altitude is seen as a promising near-future routine service able to guarantee a high level of profits to allow microgravity experience and an amazing view of our planet. On the one hand, from a technical and scientific point of view, the development of a suborbital transportation system is regarded as an intermediate and necessary step of a longer time vision roadmap aimed at developing reusable Earth-To-Orbit transportation systems (from a “space” point of view) or at designing a hypersonic spaceplane (from an “aeronautical” point of view). Suborbital flights are currently very popular and interesting for wide variety of missions and purposes for which they could be exploited. Indeed, considering the lower level of complexity with respect to orbital re-entry missions or hypersonic point-to-point flights, suborbital vehicles could also be envisaged as perfect test-bed for innovative hypersonic technologies or microgravity experiments.

On the other hand, from a touristic point of view, there is an increasing demand from private users to enjoy a suborbital flight, experiencing microgravity for brief periods and appreciating the Earth curvature surrounded by the dark sky, feeling like to be an astronaut.

Giving a close look at suborbital vehicles, the following aspects deserve to be carefully analyzed. Firstly, the propulsion system has to be recognized to be a leading technology for the design of these vehicles. In particular, the level of maturity of the propulsive technologies, sequence of ignition and the operative modes should be properly investigated. Secondly, aerothermodynamics related topics should be properly addressed, especially to correctly foresee the behavior during the re-entry phase. Besides of the fact that the re-entry is less demanding with respect to directly re-entering objects, because of the lower altitude from which the final maneuver is initiated, it is wise to evaluate and control the overall heat fluxes. Last but absolutely not least, the safety. This is a leading concept of the paper and it has been crucial for both the development of the methodology and for carrying out the design of the mission and the vehicle. Indeed, it is very important to notice that safety regards not only passengers, i.e. who pay a ticket for a suborbital flight, or the scientists and astronauts that could perform scientific activities, but also ground employers working in the launch site and all inhabitants of those areas flown over by the spaceplane. Any kind of injuries shall be avoided.

2.3 Reference Case-Study

All along this article the authors will refer to the reference case study introduced in this section. It was the result of a pre-feasibility study commissioned to Altec S.p.A. by private Malaysian Stakeholders. Politecnico di Torino, and in particular the research team to which the authors belong to, together with Thales Alenia Space Italy, were in charge of performing the mission analysis and system design of a suborbital vehicle. In particular, after a careful analysis of the stakeholders’ needs and expectations, the following mission statement was elicited:

The mission shall allow regular flight services to enable 4 flight participants at a time to reach 100 km to experience a period of microgravity and an amazing view of the Earth. The spacecraft shall perform a vertical take off from a sea-based or land-based platform and a vertical landing on the same site. Moreover, the additional capability to perform an un-crewed mission shall be considered.

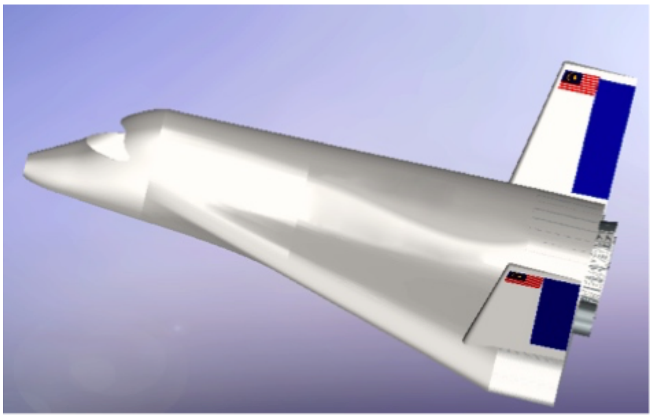


Fig. 1 CAD of the spaceplane selected for the case study

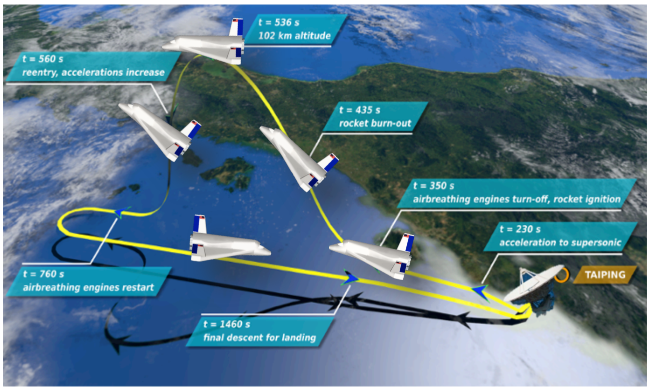


Fig. 2 Schematic view of the mission for the case study.

Fig. 1 reports a CAD drawing of the external shape of the vehicle that as a Take Off Mass of around 25000 kg. In addition, Fig. 2 provides the reader with a pictorial view of the mission trajectory highlighting the major events and related timeframe. For additional details about the design process that led to this configuration and mission concept, read the following references [9], [10], [11] and [12].

3 The need for a crew escape system in suborbital vehicles

Considering space manned missions, it is immediate to think about systems able to guarantee the crew and flight participants survival. But why, for aeronautical missions, this is quite taken for granted? In order to understand the reason why astronaut crews should have an escape option and airliners passenger do not, some safety numerical evaluations have been performed [13] considering the Risk of Loss of Life during flight as Figure of Merits.

Tab. 1: Risk of Loss of Life for different kind of aerial transportation systems

Type of flight	Risk of Loss of Life During Flight
Commercial Airplane	$1/10^6$ flight hours
Military Aircraft	$1/10^5$ flight hours
Combat in a military jet Aircraft	$1/10^4$ flight hours
Human Spaceflight	$1/10^2$ flight hours

The results of the Safety and Mission Assurance Directorate of NASA are reported in Tab. 1.

Despite of the high number of under-development studies all around the world, considering their experimental level of this vehicles, it is convenient to currently assume as reference value, the estimation characterizing the Human Spaceflight. However, it is important to reach a higher level of safety (pointing to commercial aviation as a target) in order to enhance the public consensus. Starting from a analyses of the main reasons why Considering the main factors for which suborbital flight are still too risky, it could be notice that the major role is played by several aspects. First of all, the low System Readiness Level plays a fundamental role. This parameter depends not only on the TRL (Technology Readiness Level) but also on the way in which the different components are integrated within the system. In addition, the limited number of flight hours with respect to the other categories, the very hazardous environment in which the vehicle is operated and the restricted possibilities of carrying out flight tests are the major causes of the high level of risk. Unfortunately, the need for developing ad-hoc systems to be used only in case of emergency represents an unavoidable increment in complexity and weight and in the past it has been avoided preferring additional levels of redundancy.

Since the beginning of the design process for the reference case study, trade off analysis between risk and cost has been performed in order to select the optimal strategy for guaranteeing crew survivability. Considering the specific case of suborbital flights, taking into account the short duration of the mission, the limited number of passengers and the need to host non-trained people, the authors after the evaluation of other safety solutions like, ejectable seats or escaping pods, crew escape system has been envisaged since the beginning.

Under this hypothesis, the probability of crew survival is enhanced like demonstrated with the following formula.

$$P_{crew\ survival} = 1 - (P_{primary\ failure})(P_{rescue\ failure})$$

where:

$P_{crew\ survival}$ is the probability of survivability for the crew;

$P_{primary\ failure}$ is the probability for the vehicle to experience a failure requiring a crew escape system.

$P_{rescue\ failure}$ is the probability that the rescue system and related procedures fail in their mission.

This is the general statistical formula that could be adopted to evaluate the crew survival but it is important to notice that depending on the safety approach, it can slightly vary. For example, in case of future transportation systems able to carry a high number of passengers and thus requiring more than a flight to complete the rescuing or more rescue systems operated in parallel, the formula can be modified as follows:

$$P_{crew\ survival} = 1 - (1 - P_{primary\ success})[1 - (P_{rescue\ success})^{n^\circ\ requested\ flight}]$$

where:

$P_{crew\ survival}$ is the probability of survivability for the crew;

$P_{primary\ success}$ is the probability for the vehicle complete a mission successfully.

$P_{rescue\ success}$ is the probability that a rescue activity is completely positively.

4 Conceptual Design of cabin escape system

Once that the need for developing an escape system has been clearly demonstrated and reported in Section 3, it is important to envisage a feasible technical solution. As it has been above mentioned, considering the high level of impact of this system on the entire mission, from the concept of operations to the vehicle layout, it is important to consider the need of crew survival since the very beginning of the design activities. For this reason, this subsection aims at showing the way in which the design of the escape systems should be carried out in parallel to the vehicle architecture definition and system sizing.

Fig. 3 shows the different steps of the conceptual design methodology based on a Systems Engineering approach. In particular, starting from the analysis of the Stakeholders and related expectations, with the support of the market forecasts and taking into account the possible constraints coming from the regulation of the countries in which the mission will be performed, the main objectives of the mission could be carried out [14] and [15].

This is the starting point from which a functional analysis has been developed. Indeed the methodology proposes to look at the product starting from the functional point of view at first. The results of this phase are the Functional Tree and a first list of functional requirements. Then, through the exploitation of a function/device matrix, it is possible to find out the main products able to carry out these functions. The main output of this phase can be summarized in a Product Tree.

Once the main subsystems and components have been identified, it is important to evaluate the different mission phases in which they can be exploited and the way in which they can be integrated on-board the vehicle.

In order to support this methodology, a precise tool chain consisting of commercial and had-hoc homemade software has been conceived and exploited. This tool chain aims at automatizing the overall process, easing the iterations to select the optimal solutions and allowing a complete traceability between design choices and related requirements.

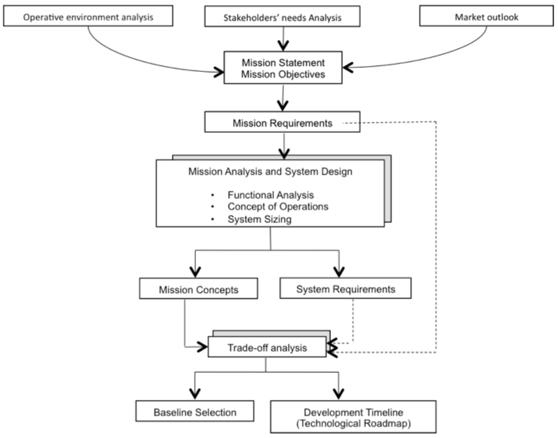


Fig. 3 Workflow of the conceptual design methodology

Indeed, this tool chain comprehends also CAD software and mission and flight simulators that will help in verifying the integration and the feasibility of the solutions.

4.2 Cabin Escape for a Suborbital Vehicle

Focusing on the development of a cabin escape system for a vehicle able to perform suborbital parabolic flights, the main goal is:

- Enable crew survivability.

Then, depending on the stakeholders' needs, different functionalities could be foreseen.

As it has been mentioned above, the design of the escape system has been carried out together with the definition of the spacecraft. In particular, the selection of a winged body solution with a dual primary propulsion system was chosen after several iterations of the methodology in the attempt to fulfill all the stakeholders requirements. The entire process that led the authors to the definition of the entire configuration is reported in [9] [12]. Fig. 5 and Fig.6 report the main results of functional analysis carried out in order to define the escape system.

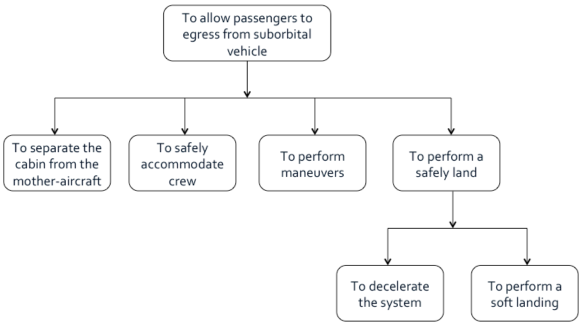
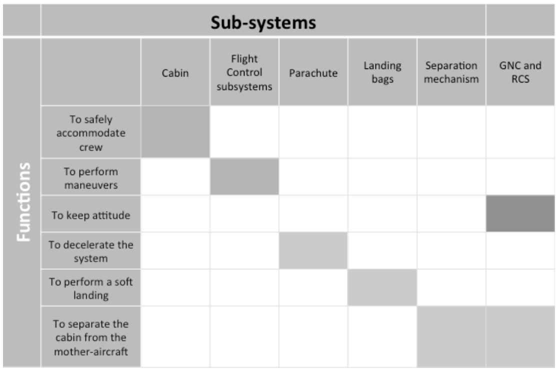


Fig. 4 Functional Tree for the Escape System



		Sub-systems					
		Cabin	Flight Control subsystems	Parachute	Landing bags	Separation mechanism	GNC and RCS
Functions	To safely accommodate crew	▨					
	To perform maneuvers		▨				
	To keep attitude						▨
	To decelerate the system			▨			
	To perform a soft landing				▨		
	To separate the cabin from the mother-aircraft					▨	▨

Fig. 5 Function-Device Matrix of the Escape System

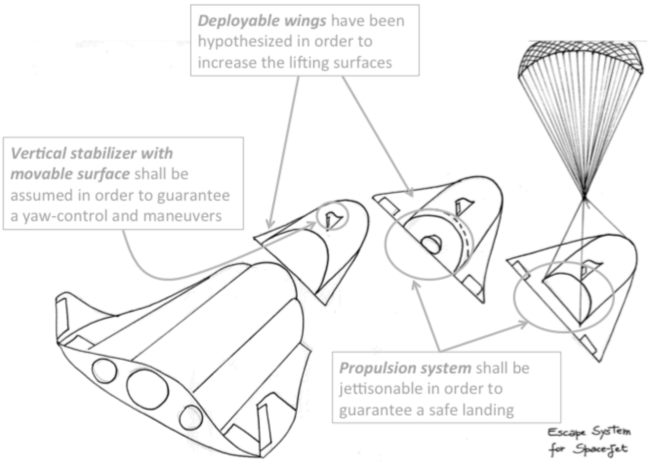


Fig. 7 Detail of the escape system

In the following paragraphs, a brief description of the subsystems required to be installed within the detachable part of the spacecraft is reported.

4.2.1 Crew accommodation

At a first glance, it is possible to notice that the cabin has been placed as far as possible from the propulsion system. In particular, the presence of a rocket engine increase the risk of hazardous events determined by the degree of explosiveness of the propellants stored on-board. Following this criterion, the crew compartment has been placed in the fore fuselage. This solution can allow the separation of this part from the main structure of the aircraft as shown in Fig. 7.

The Crew Compartment is the core of the cabin escape system. It is of cylindrical shape that avoids structural complexities and maximizes the available volume. The minimum room to host the passengers, which guarantees them to enjoy floating in microgravity, has been accurately evaluated taking into account both aeronautical and space regulations. Moreover, different seats configurations have been envisaged to select the best compromise between comfort during flight, encumbrance and the capability of been stored or at least reduced in volume during the microgravity experience.

Remembering that one of the stakeholders' expectations was to guarantee an amazing view of the Earth, it could appear strange the absence of windows (a part from the security hatch). Indeed, considering the demanding mission profile, the external structural loads and the need for avoiding additional weight, it was decided to provide the external visibility exploiting virtual reality subsystem consisting of a series of externally mounted cameras and O-Led panels covering the overall internal surface. In this way, the passengers can feel like flying freely in the sky. Psychological effects of this kind of systems have already been evaluated.

4.2.2 Structures and mechanisms

The forepart of the fuselage, i.e. the one that composes the escape system shall be considered as an entire and unique element able to sustain the structural and thermal loads both in nominal and emergency scenario (i.e. when it is detached.) The need for an escape system implies an additional structural element in correspondence to the possible separation section. In particular, depending on the maneuverability characteristics required for this system, a small rocket and related tanks should be accommodated in this part.

Behind the crew compartment the separation mechanism shall be installed. In particular, for this kind of application, mechanically initiated pyrotechnic devices have been used. In space applications, a mechanically initiated explosive device could be very simple equipment activated by a spring loaded firing pin that strikes a common percussion primer. A blow that causes metal deformation, which then pinches a small amount of a pressure sensitive pyrotechnic material between the deformation and an internal anvil, strikes this percussion primer, or cap. The sensitive powder then ignites, setting off the explosive train.

A proper controller should be in depth- studied in order to evaluate the firing condition, (typically an out-of-nominal set of parameters) depending on the mission phase. In this way, the escape system could be safely separated from the rest of the spacecraft in relatively short time and avoiding additional complexities.

In order to guarantee a limited maneuverability also to the escape system, rear flap shall also be detached exploiting a similar mechanism. It is worth to notice that all these design choices deeply affect not only the architecture of the spacecraft but also its development and construction and this is the main reason for which it is important to proceed following a methodology able to take into account and trace all these aspects since the beginning of the design process.

4.2.3 Propulsion subsystem, GNC and RCS

The need for guaranteeing a complete maneuverability of the escape system, once it is detached as well as the need for reaching specific landing site or avoiding populated impact areas force the designers to envisage an embedded rocket propulsion system with related feeding and propellant subsystem. This high level requirement has a noticeable impact on the weight and complexity of the overall transportation system. This is the main reason for which this alternative has been suspended at the moment, in favor of a simpler and lighter Guidance, Navigation and Controlled subsystem (GNC) and Reaction Control System (RCS) based on innovative electric thrusters. In this second alternative, thrusters have been envisaged in order to allow attitude control during the re-entry phase. It is important to notice that in the nose of the vehicle at least four couples of thrusters should already be present to guarantee controllability of the entire configuration in nominal condition. This means that in order to be exploitable also for the control of the escape system, tanks and related subsystems should be installed in the aft part of the fuselage.

4.2.4 Descent and Landing subsystems

The Descent and Landing subsystems should provide an adequate deceleration to the crew escape system during the re-entry phase and guarantee a proper impact load attenuation during the touch down or the splash down. In particular, considering that mission profiles for suborbital vehicles tend to overflown maritime areas, in order to avoid spacecraft or escape system sinking, inflatable bags will be added.

4.2.5 ECLSS

The Environmental Control and Life Support System is typical of manned space system and it aims at satisfying crew's needs and providing resources for their activities. This system shall provide the crew compartment with the proper pressurized environment, controlling temperature, pressure and air composition and avoiding any type of contaminations. The overall system could require too volume to be host within the forward part of the fuselage. Considering that in worst scenario, the vehicle could come back on Earth in less than 30 minutes, it could be sufficient to guarantee that the escape system is totally sealed and as redundancy, each passenger could be equipped with a proper small oxygen tank.

Considering the environment in which the spaceplane will operate and the early stage of development of this kind of transportation systems and the associated SRL, the use of light suits is suggested. They are not so bulky but they can provide an additional redundancy level and they can also be directly connected through proper umbilical to centralized ECLSS control and fluid distribution unit. In future, when these vehicles will have accumulated a certain amount of flight hours, the use of suits could also be avoided.

Furthermore, considering the short duration of these missions, no galleys for food have been envisaged but in case of touristic flights, the idea of the stakeholders was to equip each participant with a proper bag containing gifts and snacks.

4.3 Concept of operations

As it is clearly shown in Fig. 3, the design process consists of several activities that are related to each other and, for this reason, the best practice suggests carrying them out in parallel. In particular, in order to support the system sizing and architecture definition, the concept of operations shall be sketched. In this specific context, after the definition of the several mission phases for a nominal scenario, possible hazardous conditions and failure events should be detected and the possibility of the exploitation of the escape system shall be evaluated. In case it is not possible to use the escape system, other solutions are suggested.

4.3.1 Take-off and Landing

In space engineering handbooks related to safety, the first mission phase analyzed is the so-called "Prelaunch and Ascent Escape" because it usually refers to mission starting from a launch pad in a spaceport. However, in this case, we should refer to take off phase because our vehicle should be able to perform a vertical take off (in an Harrier-like mode and not tail sitting) and is not supposed to lift off from a dedicated spaceport. The major safety related problems concern the on-ground clearance area to prevent fire outbreaks due to risk of explosion of the stored propellant. This is currently the main driver for the design of spaceports for supporting suborbital vehicles operations. It is crystal clear that during this phase it is not possible to envisage egress systems like the ones already exploited for example by Space Shuttle or during the Apollo or Gemini Missions [6]. For the first one, in case of a serious malfunctioning occurring during prelaunch phase, the Shuttle was disconnected from the support infrastructure, the hatch was opened and the astronauts were able to leave the crew compartment by means of very simple slide wires. As far as Apollo mission are concerned, launch abort rocket system and ejection seats ensured flyaway capabilities. In case of Gemini spacecraft ejection seats were employed and due to the noticeable advantages in terms of weight reduction and similarities with respect to existing solutions adopted in military aircraft, this alternative was also exploited in the first Space Shuttle missions. Unfortunately, all these solutions are not suitable for the reference vehicle addressed in this paper because it is not performing a vertical tail sitting lift off and there is not the minimum required separation between crew compartment and ground.

If serious hazards are detected when the vehicle is on-ground, only inflatable slipway starting from the hatch could be envisaged to allow a fast egress.

If the vehicle is in terrain proximity but the take off maneuver has already been started, the escape system could be theoretically exploited only in case the thrusters system has been sized in order to shoot the cabin at an altitude sufficient to start a controlled descent.

The possibility of using such a device at very low altitudes implies a remarkable widening of the on-ground clearance and forces the operators to select launch sites mainly in costal or desert regions characterized by a very low habitants density.

4.3.2 Air-breathing powered climb

During this phase, the spaceplane is designed to operate like a traditional aircraft but at the end of this phase, supersonic speeds could be reached. In case of one engine inoperative condition, the vehicle is able to safely return to the starting spaceport and perform an emergency landing. From the one hand this means that during this phase, escape system will be used only in case of serious risk of explosion or in case of two inoperative engines. Depending on the altitude of the separation, different trajectories and operations should be planned in order to avoid injuries to the people that are on ground. Moreover, in case of emergency landing of the entire spaceplane, additional problems related to land with full propellant tanks can arise. Emergency jettisoning will be performed before reaching ground.

4.3.3 Rocket powered climb and Microgravity period

During this phase, the spacecraft is at a sufficiently high altitude to allow safety operations for the escape system in case of serious hazards. The detachment of the escape system is the only possibility to save the crew. Indeed, the environment would not allow survival with simple seat ejection also if properly wearing the suit.

4.3.4 Re-entry and Descent

Re-entry is considered to be the most dangerous part of the mission because of the high thermal and structural loads. However, during this phase, the risk coming from the presence of propellant on-board diminishes and so, also pure un-powered gliding could be feasible, as sketched in Fig. 8. However, up to a certain altitude, the use of the escape system will enhance the survivability of the crew.

Fig. 8 Un-powered gliding in case of emergency during re-entry and descent

4.4 Impact area and debris mitigation

Together with the previous analysis, the evaluation of the impact area for the possible debris generated by a spacecraft explosion has been carried out exploiting proprietary software of Thales Alenia Space Italia.

Moreover, three different cases with different mishaps have been considered, all happening at top of the parabolic profile.

For the evaluation of the re-entry risk the figures to be assessed are:

- Casualty area of the fragments reaching the ground.
- Footprint of the reentering fragments (if the initial coordinates of the re-entry interface are defined).

The casualty area of a surviving fragment k leading to a casualty if a person is struck, is defined as:

$$A_{C,k} = [\sqrt{A_{i,k}} + \sqrt{A_h}]^2$$

where:

A_i is the average projected area of the fragment surviving the re-entry

A_h cross-section of a human, which is conventionally defined equal to 0,36 m^2 according to the NASA Safety Standard NSS 1740.14

The total casualty area (A_c) of the re-entry is the sum of the casualty area of all surviving fragments ($A_{c,k}$):

$$A_C = \sum_{i=1}^{N} A_{C,k}$$

As explained above, since the vehicle design is at its early stages, only the external dimension of the vehicle and the dimension of few internal components (e.g.: tanks) are defined.

Therefore at this stage of the design is not possible to evaluate the casualty area, (total casualty area can be evaluated only knowing the dimensions of all the vehicle impacting fragments), and the associated casualty risk. An estimation of these parameters will be performed when the internal equipment, will be defined more in detail.

With currently available information it was possible to estimate the minimum and maximum impact points, i.e. the linear extension of the footprint that would be affected by fragments impacts.

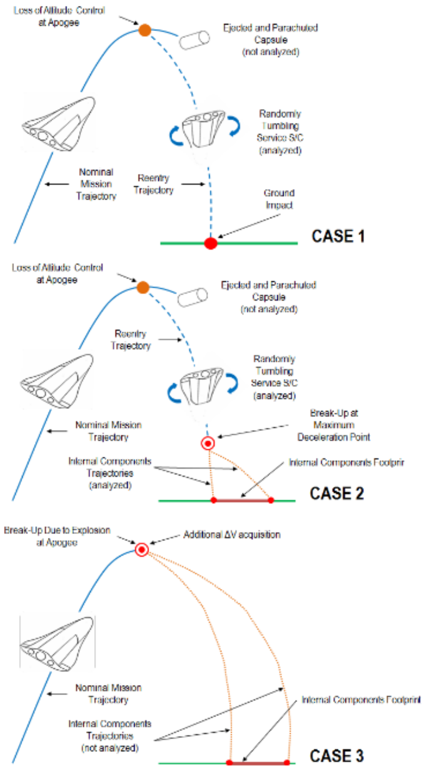


Fig. 9 Reference case studies for debris mitigation

The footprint extension (minimum and maximum downrange) depends on the trajectory evolution of the components with opposite ballistic behavior: the lighter and largest object and the heaviest and smallest object. For the reference aircraft, the following objects have been have been respectively defined as the LH2 tank (“light and large” object) and a linear actuator (“heavy and small” object).

As shown in Fig. 9, three different cases have been simulated.

- Case 1: loss of attitude control at the trajectory apogee: escape system is ejected and the rest of the spacecraft randomly tumbles until the impact on ground.
- Case 2: loss of attitude control at the trajectory apogee: escape system is ejected and the rest of the spacecraft randomly tumbles until reaching the maximum admitted deceleration rate. Overcoming this limit causes the fragmentation of the vehicle and the internal components are released and reach the ground.
- Case 3: Catastrophic explosion at the trajectory apogee without any possibility of detaching the escape system. All the internal components acquire an additional ΔV (due to the shoot of the explosion), whose effect must be evaluated for different directions. This catastrophic scenario has been evaluated in a qualitative way but deeper analyses will be performed in more advanced design stages.

Please notice that for case 1 and case 2, since the capsule is supposed to be equipped with a parachute, only the service vehicle re-entry has been simulated. Some results are reported in Fig. 10.

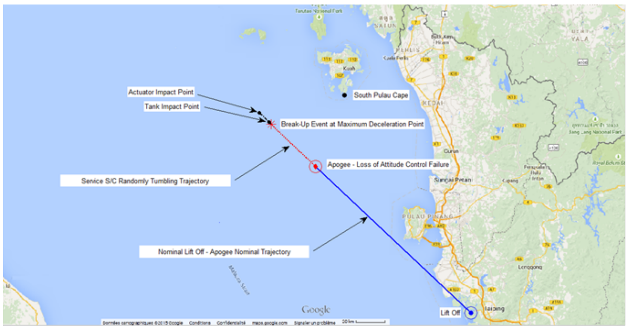


Fig. 10 Analysis of debris trajectory

3 Conclusion

This paper reveals the importance of developing a cabin escape system in order to enhance the safety level of suborbital flights. A proper conceptual design methodology and related support tool-chain are proposed enhancing traceability of requirements all along the design process. In particular, this article shows the design of an escape system for a Single Stage To Orbit able to carry 4 passengers up to the Karman Line to experience microgravity condition. An overview of the different operative conditions of this escape system is reported together with an impact risk analysis that will drive the spaceport design and location. In future, this cabin escape concept will be in depth-analyzed and additional numerical simulation will be carried out in order to precisely propagate the expected trajectory in all the possible out of nominal conditions.

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