HYPOTHESIS ON THE ENHANCING OF THE PROBABILITY OF SURVIVAL OF SPACE AND TRANSATMOSPHERIC VEHICLES IN SPACE DEBRIS AND MICROMETEOROIDS CONTAMINATED ENVIRONMENT

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Abstract

The portion of space surrounding the earth interested by man made flying crafts has become more and more polluted: on top of natural objects, man made debris circle the earth at different heights. Advanced design methodologies are now used for preliminary design. Within these frameworks various analysis can bring specific benefits. Evolving from similar uses in the aeronautical field, we have used the Zonal Analysis techniques at conceptual level to evaluate the risks of damages coming from impacts with debris, and so gather evidence for internal systems reallocation. The two cases in study are both conceptual design developed for research purposes at Politecnico di Torino: a trans-atmospheric vehicle and a micro satellite. The work presents the environment, the threat and the preliminary results of this research.

1 General Introduction

Space operations and on-orbit fragmentations have created a large number of man made, free flying, uncontrolled objects. Natural objects, meteoroids, are also present. The earth is completely enshrouded in a cloud of so called space debris. Figure 1 one shows a realistic view taken from a modelling software [1]. The meteoroids environment is fairly constant with time, while the man made debris environment has a more dynamic behaviour. The spatial distribution of catalogue orbits families is clustered around the standard data of launch latitudes and preferred altitudes and inclination bands. This, together with statistical evaluations on historical productions of man made objects, has provided forecasts and evaluations of impact spatial densities.

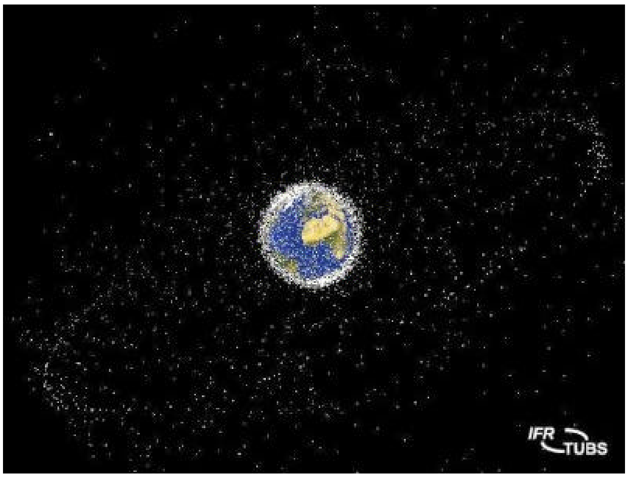

Figure 1: Model of spatial distribution of debris (Courtesy of IFR TUBS/ESA)

This environment can be extremely dangerous, because a 1 cm size fragment orbiting at speeds well above 28000 km/hour, or 8 km/second, could shatter a multi million dollars multi years development satellite. The physicist call the regime above said hypervelocity. No need for explosive when you have plenty of kinetic energy.

The design of spacecraft in our research group, the System Engineering Group working at DIASP (Politecnico di Torino), comes as a follow up to the design of aircraft, and hypersonic vehicles [2], [3], [4]. The main research aim is to develop more efficient, advanced and complete design methodologies. Among others two are the latest design research activities. One is the preliminary design of a sub-orbital technology demonstrator, another is the conceptual design of a micro satellite for earth observation.
The sub-orbital vehicle comes as an evolution of a recent study [5] aiming at participating at the X-Prize contest. The purpose was the design and implementation study of an advanced reusable launch vehicles to let the space tourism start.
The satellite is thought to be a micro satellite developed by a pool of universities. It would be placed in a Low Earth Orbit (LEO), around 900 km of height, and the experiments on board should be relative to earth observation. The conceptual layout has been defined and the outline of the proposed payloads identified.

As new tools are available they are added to the methodology. Among these new tools and evolving from previous knowledge is the Zonal Analysis (ZA) technique. In this context and relative to the particular threat ZA can be used to evaluate different architectural configurations and internal systems layout to ensure the most protection to minimize risks. This leads to the application of techniques similar to the ones of vulnerability and survivability, which are typical of fighter aircraft design, to assess the potential damages on the vehicle.

The maximum altitude reached by the trans-atmospheric demonstrator would be around 120 km, thus remaining significantly lower than the inferior limit for debris tracking and modelling. But, as this is an evolution, of a previous design, it will evolve into a Single Step To Orbit (SSTO) craft. So the analysis was intended to acquire confidence with the method on this specific applications.
The small satellite was chosen for the analysis because, even if the surface is small and so, given a certain level of threat, the flux of debris is low, the economic design does not allow for any kind of protection. Being so simple not much can be done as far as layout modification, but ideas can be developed for higher class crafts.

The purpose of this work is to show how the ZA techniques can be applied within the preliminary design methodology, in the two above mentioned different cases. In particular, having an initiating fault, not coming from internal failure but one generated from the outside, an impact.

2 Debris generation and environment characterization

The portion of space surrounding the earth, up to a certain distance from it, is “polluted” with natural objects and man made debris.
The former have origin and distribution either random or predictable through cosmic laws. The latter ones come from a variety of sources. We remind here some of the most important ones with a brief explanation each:

- in orbit fragmentation and collisions: in brief is what we can call explosion, it is due to various reasons and as of today records show approximately 160 events of such kind. Dimensions and directions of debris generated is variable and covers different orders of magnitude. About 100000 of the generated quantity are estimated to be still in Low Earth Orbit (LEO). One particular kind are the fragments due to collision between satellites. These are not yet a source with significant contribution to the overall population. 3 events have been recorded so far.

- Solid rocket motor firings: when firing solid rocket motors particles are expelled, in particular made of Al_2O_3 an liner or insulator. The particles size is normally less then 3 cm. There are high concentrations on Geo Transfer Orbits (GTO) and Geostationary Orbits (GEO). 50 % of the objects larger than 1 cm are at LEO altitudes.
- Coolant release of nuclear reactors in space: these events generate mainly droplets of NaK used as coolant in nuclear reactors. Particles of coolant are released during the ejection of the reaction core. It is necessary to open the coolant loop during the ejection of the core.
- Surface degradation: it is due to a multitude of factors among which are atomic oxygen and impinging radiation.

3 Survivability: overview of the problem

In this context survivability can be defined as the capability of a spacecraft to withstand the natural and man-made hostile environment. Natural are the meteoroids, man-made is the bountiful harvest of objects generated in various ways from man-made crafts.
Before giving a brief overview of survivability, we would like to emphasize two very important points [6]. First, when the craft is foreseen will operate in an environment posing threats, survivability must be seriously considered. This means by everybody during the early stages of design. And this fits perfectly well with our researches on the preliminary design and other research works, pushing the importance of early analysis. As per other features, implemented thanks to engineering specialties, survivability features, can be best incorporated during the early phases. Retrofitting in some cases might be impossible, always expensive. Second point, the people working on these features must work in close cooperation with the rest of the design team. They should be able to read the design across all areas and suggest improvements.

3.1 Damage mechanisms

A damage mechanism can be assumed as the physical description of the tangible instrument or measurable quantity that will inflict the damage upon the craft. According to the general classification the most part of the debris in orbit can be classified as fragments, while some should be addressed as penetrators. One damage mechanism can initiate several damage processes. If we want to enhance the survivability of our crafts we will need to know the nature of the damage process and the terminal effects caused by the damage mechanisms. For our application the traditional mechanisms apply with very large margins, as we are in the hypervelocity impact field.
Given the dimension and shape of most of the debris we have considered only fragments and/or penetrators. The worst case assumed for the impact includes having wall stresses and interaction of the fragment cloud with pressure gas. Hence the processes identified are as follows:

- Stress concentration around the impact hole that can induce front side failures.
- Ablation and deceleration mechanisms reduce the kinetic energy of the fragments. Under certain conditions, the fragments energy can be completely consumed up [7].
- Rear wall cratering and perforation of the fragments can initiate crack growth due to the stress magnification and cause subsequently rear side failure.
- Shockwaves are transmitted from the projectile-target interface into the pressure gas (case of pressure vessels only). Bow waves of the individual fragments add up to a strong gas shock wave, which impacts the rear wall and can cause rear side failures.

4 Zonal Analysis for spacecrafts

The forethoughts of Zonal Analysis come from two basic considerations we have made during the development of design methodologies [8].
Digital Mock Ups (DMU) are a relevant part of the design process of new aircraft. And they have proved extremely powerful and versatile. It has now migrated to the design of space re-usable vehicles and satellites.

From previous experiences we have realised how inadequate FTA is to predict or discover a certain class of safety threats. The limits are due to the fact that is unable to catch the multiple effects of failures. That is failures that propagates to adjacent systems, causing other systems failures. These failures, can hence be seen as induced failures due to the installation of several subsystems, interacting within the main system.

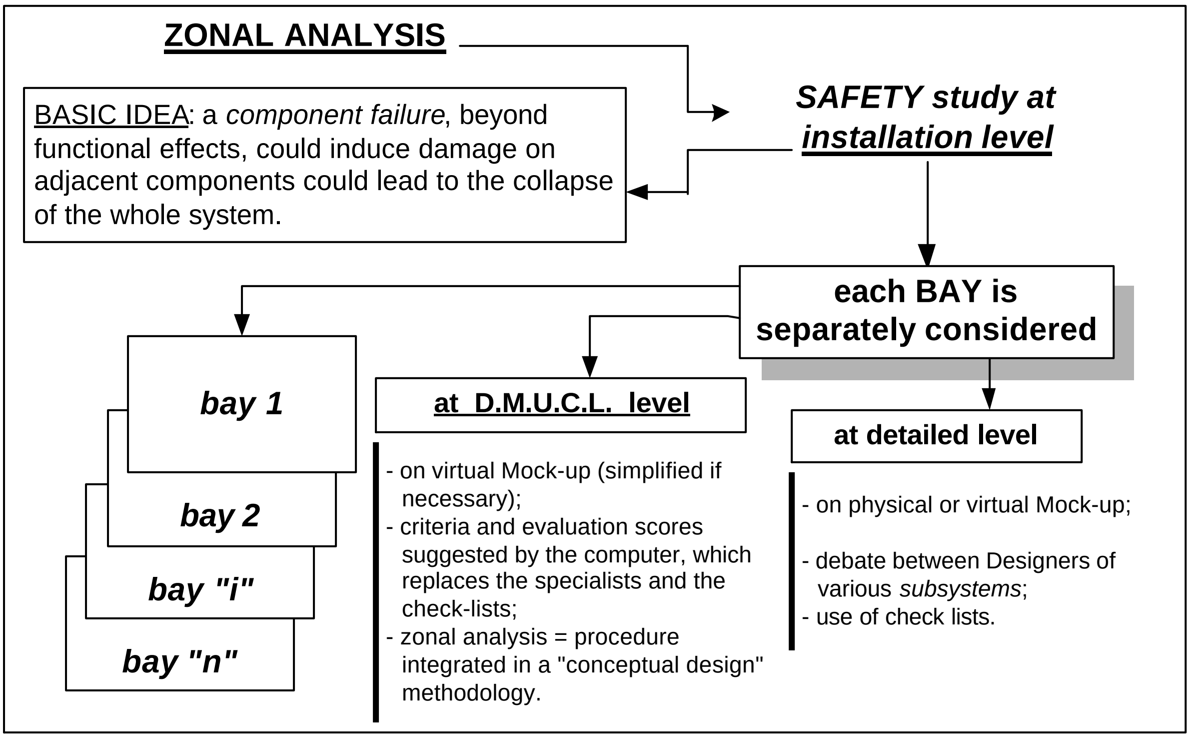

Figure 2: ZA at the traditional level of detail and in the context of Conceptual Design

The importance of the installation regards in particular those systems which count a great number of components in a confined volume. This is typical of spacecrafts where many subsystems share the same accommodation volumes. This would eventually lead to cross damaging. Not taking into account this kind of failures may lead to wrong results in a preliminary analysis focused on functional aspects, for example by underestimating the number of redundancies needed or by inducing unexpected failures.
So far, ZA techniques have been developed and used on aircraft mock-ups, and then on prototypes, consisting in a visual check by a team comprehensive of designers of all subsystems present in such a zone
CAD tools now available, offer the possibility to perform a safety zone analysis from DMU, thereby greatly enhancing the ability to anticipate failures.
The work carried out so far in our research has taken the preliminary safety analysis at installation level to the early phase of conceptual design. Figure 2 reports an overall scheme of these concepts.
As specialists are not involved at the conceptual design stage, it is impossible to

carry out ZA in a traditional way, so we devised a different procedure to evaluate the potential hazards.
Main steps are as follows:

a. Subdivision of the spacecraft in several zones. This is done by CAD, "cutting" the spacecraft in different parts. It is possible to draw out information on equipments/modules placed in the different zones, from DMU views, as shown in figures 5 and 6 for the trans-atmospheric vehicle.
b. The definition of the equipment/module risk level. The operation is performed by the designers using their engineering judgement, taking into account the following:
   - ✓ Probability of dynamic mechanical failures;
   - ✓ Presence of explosion sources;
   - ✓ Presence of corrosive liquids;
   - ✓ Presence of high pressure vessels or pipes;
   - ✓ Presence of electrical devices;
   - ✓ Equipment duty cycle.

   Each of the aforesaid aspects receive a score (“equipment risk score”).
c. The definition of the zone risk level: this could be obtained by summing the equipment risk score and the zone basic risk score (obtained with a procedure similar to the previous one, which takes into account temperature, vibration and shock level, probability of external hits, applicable to the whole zone).
d. A “delta zone risk score” (Ärisk) is added to previous sum. This score takes into account the induced risk due to the adjacent zones.

The whole procedure to perform the Zonal Analysis at Conceptual level is summarised in figure 3, showing how the evaluation of “risk by installation” can be obtained.

Table 1 is an example of the coefficients, scores criteria and other data needed to carry out the aforesaid procedure

5 Application and results

The ZA has been performed on the two preliminary designs available in our research group.
The very low level of definition of the two designs has not allowed us to pinpoint modification or radical changes. Basically it has been applied to verify the compatibility with the two design and have a preliminary idea of which could be the bay at highest risk.
As it was expected the situation is slightly different in the two subject, but the principles remain the same.

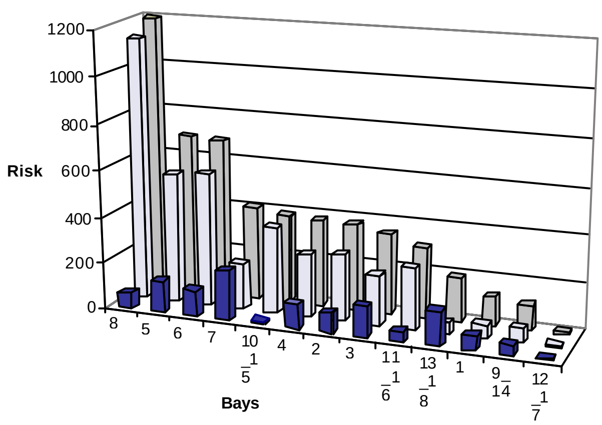

Figure 4 Pareto plot for risk levels

At the end of the process a visualization of the risk levels results can be done by means of Pareto plot of the bays risk scores, see figure 4. Each bay is shown with the components divided into categories. This allows a quick resume of the concentration of risks.
Obviously, high risk concentrations have to be avoided, by changing the layout in the DMU. Different layouts will undergo again the procedure and the final results will give the designer information about:

- ✓ Quality level reached;
- ✓ Necessity of further improvement;
- ✓ Indication of which areas offer the possibility of improvement.

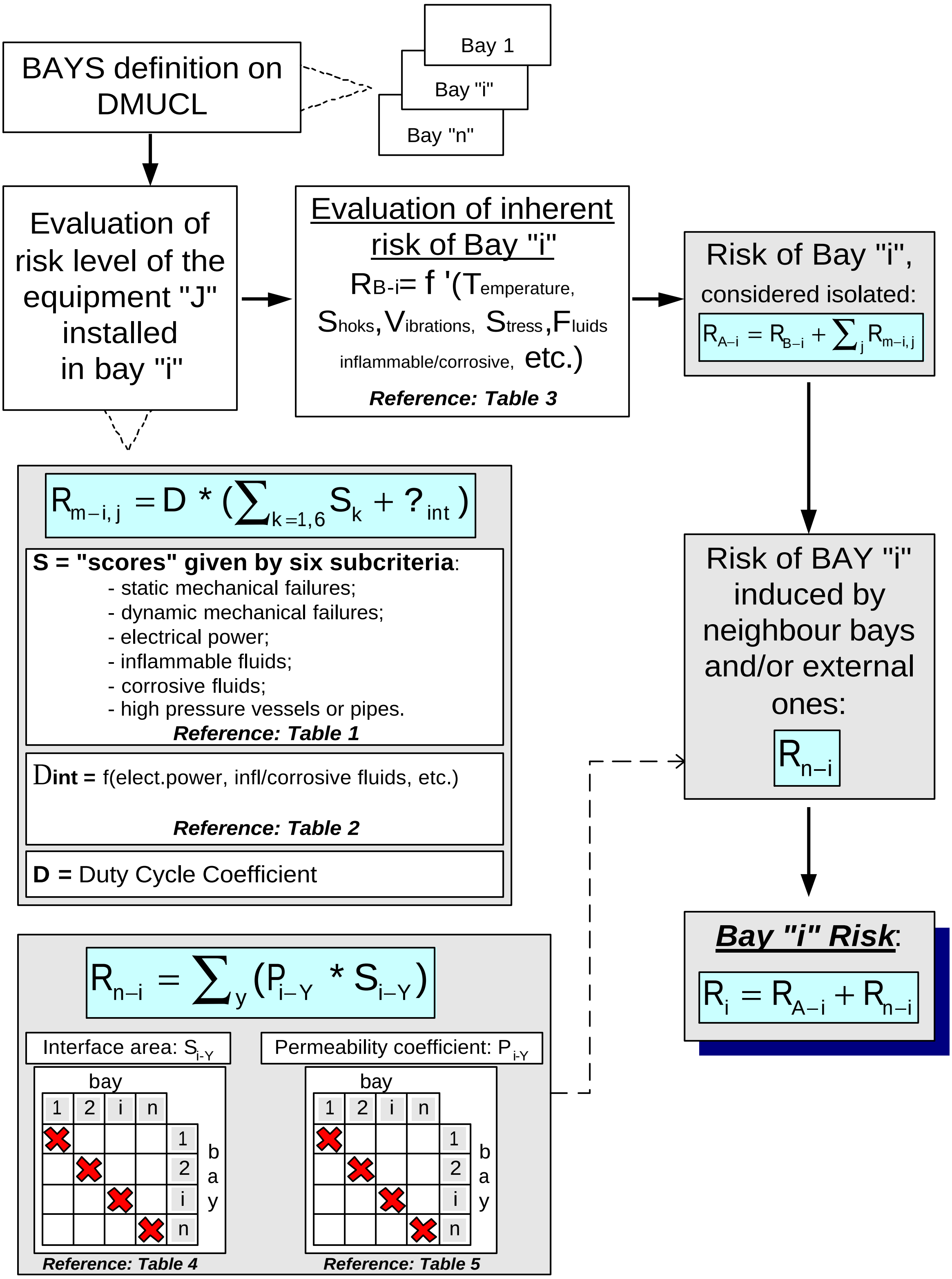

Figure 3 Schematics for performing Zonal Analysis

Table 1 Example

Mechanical breakdown due to static failures	Thermal stress			Relative action				Forces or torques exchanged		
	None	Low	High	None	Rotation	Misc.	Friction	Low	Medium	High
	0	1	2	0	1	2	3	1	2	3

5.1 Analysis of trans-atmospheric vehicle

The trans-atmospheric vehicle is shown in figures 5 and 6. The design at the time we performed the analysis called for an overall length of about 40 meters and overall span of about 18 meters. The propulsion elements are thought to be a mix of turbofans and rockets. The vehicle would take off horizontally and use the turbofan as propulsion up to the altitude of flight refuelling. These operations are conducted at about 9000 meters and at a speed of Mach 0.8. Fuel consists of LOX. After refuelling it propels itself up using the rockets. For this stage the maximum altitude attainable is estimated at 120 km. In the future version it should reach the insertion in LEO. During flight at high altitude the air-breathing engines would be sealed off via dedicated vanes. Subsequently, after payload release, if any, or tourist time if manned with passengers, it descends to lower flight levels, until reaching an adequate altitude for engine restart. This would ultimately allow full manoeuvring capability for approach and landing.

The preliminary zonal analysis has highlighted that the highest risk would be yielded by the large centre body part, where the LH_2 tanks are located. The structural loads have not been assessed yet, but in order to retain the shape and sustain the stresses during manoeuvred flight the large centre portion will need particular structural design. The choices are locked for this particular detail and no options were foreseen as available as of the preliminary design. Still referring to figure 4 We notice that the fuel tanks might be modified in order not to increase excessively the weight due to internal stiffeners or similar structures. So we have increased, slightly the volumes to accommodate spherical or ellipsoidal tanks. The level of risks due to impact on systems(controls, etc.) has been deemed, at this stage relatively low, since they are distributed all over the fuselage but in areas still very likely to be modified. Zone 10 is suitable for equipment, because, as of now, there is no room for fuel under pressure. Another possible choice is to move JP4 fuel tanks from zone 2 to zone 10, considering the advantage to have jet engines near their specific fuel. Third choice would be placing the landing gear in zone 10, but for the moment no configuration was defined for landing gears.

5.2 Analysis of small satellite

The micro satellite was meant to be developed by a pool of universities, where each member would have brought its proper specific knowledge. We assumed the task of the preliminary design. Unfortunately due to early suspension of the program we were not able to finalize the conceptual phase and so we used for the analysis a very didactical configuration as shown in figure 7 already subdivided for ZA. The satellite was thought for a Earth observation mission, orbiting in LEO at an altitude of no more 900 km. The mass was estimated preliminarily to be within 25 kg. The overall structure was still under screening from different possibilities. The only preliminary results we have achieved have suggested to protect at best the optical instruments.

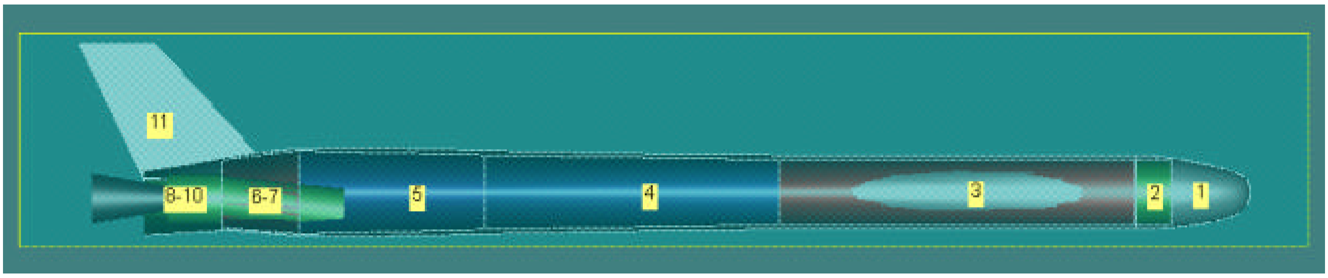

Figure 5 Side view, bay subdivision for ZA on the trans-atmospheric vehicle

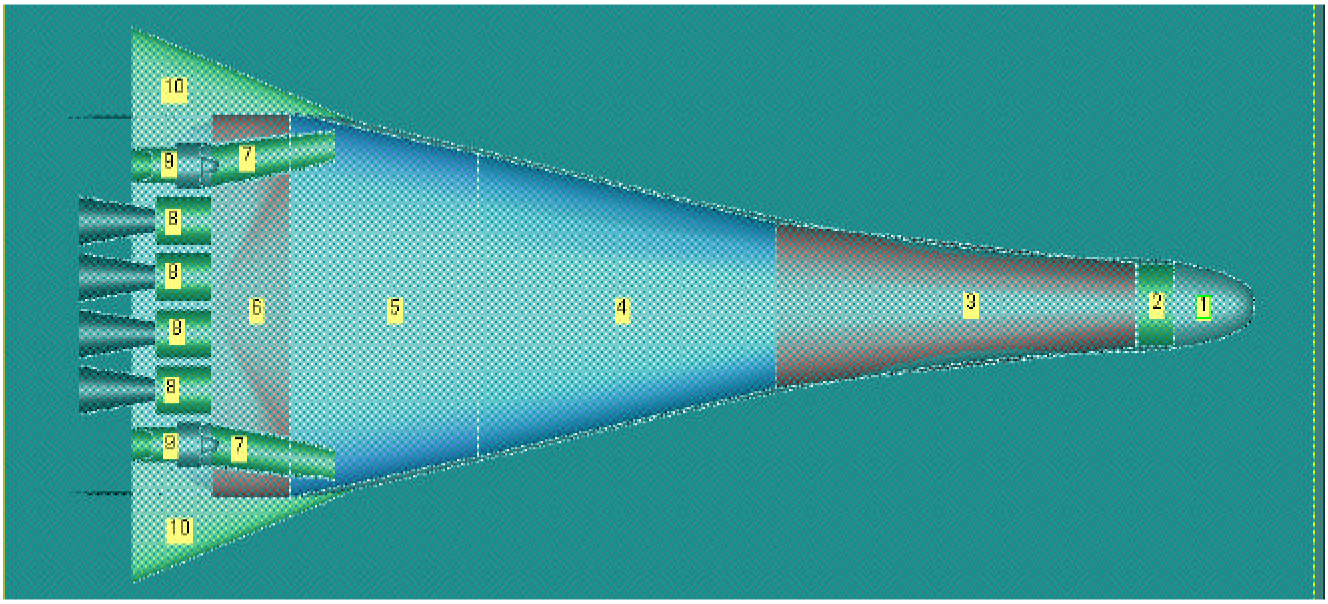

Figure 6 Top view, bay subdivision for ZA on the trans-atmospheric vehicle

The radiator panel, shown in figure between the equipment has been seen reducing the risks on the external side. Unfortunately the low level details configuration did not allow more analysis.

6 Summary

The original research program originating this work has now been suspended, so no further results can be shown, but the preliminary dispositions.

Nevertheless the main objective has been achieved: evaluate the effectiveness of ZA outside its traditional, for us, field of application. And in particular the possibility to implement it in our methodology for preliminary design of space vehicles. The results are encouraging, it is effective at our level of definition. It is valuable for giving directions to the design for survivability in a contaminated environment. The preliminary design, taking into account the output of the analysis, might steer the layout of some critical systems.

Originally the scope was broader, in the sense of modelling trajectory of impact. If resumed, the research will cover the internal disposition and the most probable hit directions.

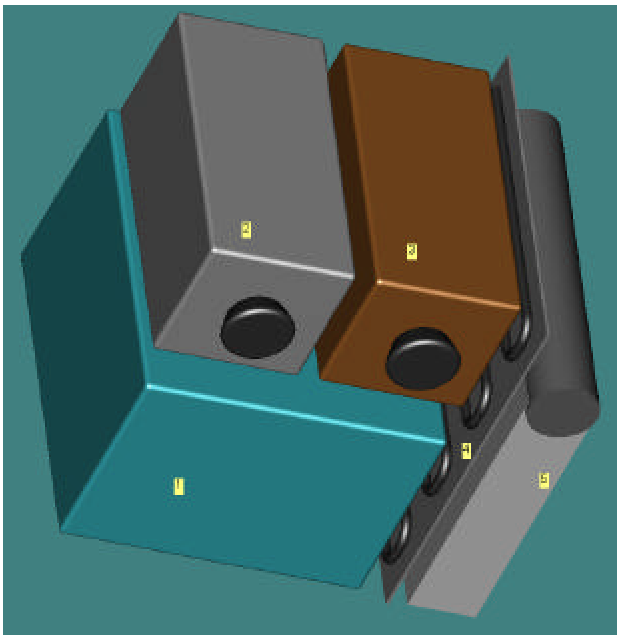

Figure 7 Bay subdivision for small satellite payload module.

Deeper analysis if deemed worthwhile, will cross risk analysis techniques and Monte Carlo simulation with ZA.

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