REDUCING THE VULNERABILITY OF SPACE SYSTEMS TO SMALL DEBRIS PARTICLES

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ABSTRACT

The European funded FP7 project, ReVuS, aims to define design solutions that will reduce the vulnerability of future low Earth orbit (LEO) satellites to the small- and medium-sized debris.
An assessment of the vulnerability of two representative LEO satellites to these debris has allowed to evaluate the failure probability for the entire satellite, and to identify the critical areas and equipment on the satellites. It appears that the most significant contribution to this probability of failure comes from the debris in the range 2 to 5mm.
Potential solutions to minimise the vulnerability of the satellite have been identified, both at system and architecture levels.
The use of shielding protection is one of the main solutions, to protect the critical equipment, possibly the critical areas. Shielding configurations are based on shielding bricks. Tests have been performed to evaluate the characteristics of these shielding bricks and the performances of a set of shielding configurations. An assessment of the proposed solutions is on-going, to evaluate the gain in terms of vulnerability and the impacts on the satellite.

1 INTRODUCTION

The number of debris in space is continuously increasing**,** especially as a result of the collisions that have occurred in the past few years**.** Thus the presence of debris could become an increasing risk for the survivability of space assets. Indeed, the probability for a satellite to collide with orbital debris, although very low, could become non negligible.

For the purpose of this project, the following assumptions regarding the different sizes of debris and their relevance with respect to the analyses have been made:

- Debris size larger than 10cm (large size debris): it is assumed that they can be detected, catalogued and tracked from ground: collisions can be predicted, avoidance manoeuvres can be performed.
- Debris size from 0.1 to 10 cm (small size debris) cannot be tracked, so that collision with a satellite cannot be predicted and could generate critical damage, such as the loss of a part of the mission or the loss of the de-orbit capability of the satellite, and could generate additional debris. Indeed, the energy of such debris particles is high enough to penetrate the satellite structure and constitutes a risk for internal mounted units.
- Debris size below 0.1 cm: the energy carried out by this debris is low enough to be absorbed by the structure materials. However, such debris particles could be a threat for external mounted units such as sensors, antennas, solar arrays, pending on their size and location.

In order to mitigate this risk, the "Survive" approach, related to the medium size debris that cannot be tracked, consists in defining design rules to minimise the effects of debris impacts on the satellite and its mission.

2 OVERALL REVUS PROJECT

The ReVuS project is an answer to the *Survive* approach. It is a European FP7 project, funded by the European Union, which started in March 2011. It aims

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to define design solutions in order to reduce the vulnerability of future LEO satellites to small-sized debris. A debris size range of 0.1mm to 5 cm is targeted.

2.1 Project Logic

The project follows a three-step approach, as illustrated in Fig 1:

- the vulnerability analysis, to evaluate the effects of a collision of a satellite in LEO with small size debris, the potential damage and the critical parts of the satellite, the risk of mission degradation.
- the identification and analysis of potential solutions at system level, and at satellite architecture level, with a focus on the shielding concepts and shielding materials.
- the resiliency analysis, aiming at evaluating the resiliency of the selected solutions with respect to debris impact and at proposing design rules and standards.

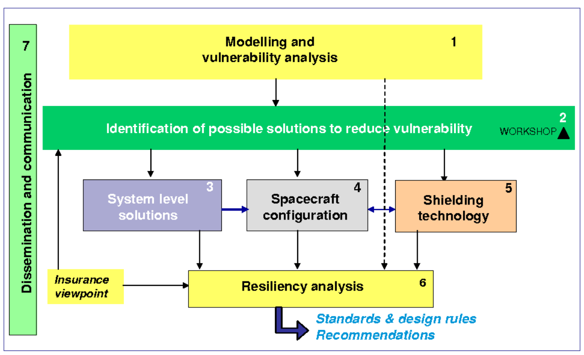

Figure 1: Logic of the ReVuS project

2.2 Partnerships

The ReVuS project is carried out by a consortium, led by Astrium SAS and gathering the expertise of 9 partners from Universities, SME and large enterprises:

- Astrium SAS is leading the activities on the system level solutions, the resiliency analysis of proposed solutions and the shielding material definition and tests, and participates to the shielding concepts
- Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V., (EMI) for the shielding aspects (shielding architecture and test of shielding materials), and satellite damage assessment
- Technische Universität Braunschweig brings its knowledge on the debris environment modelling (MASTER) to generate the flux distribution
- University of Southampton for their knowledge on the debris environment modelling (DAMAGE) to evaluate the candidate shielding protections
- University of Leicester to analyse the distributed architectures as a system level solution
- Astrium GmbH in charge of the vulnerability analysis and spacecraft configuration
- PHS Space Ltd for satellite damage assessment and definition of standard design and rules
- TenCate Advanced Composites BV to define and produce the shielding materials
- Hiscox Assurance Services to bring the insurer's point of view
- Astri Polska Sp Z.o.o for the communications and the dissemination of the results

3 VULNERABILITY ANALYSIS

As shown in Fig 2, the vulnerability analysis is based on the use of the impact risk assessment SHIELD3 tool:

- To evaluate the probabilities of penetration of small debris particles in the satellite and in the equipment
- To determine the failure probability for all equipment parts considered.

The results of this vulnerability analysis are presented in detail in [1].

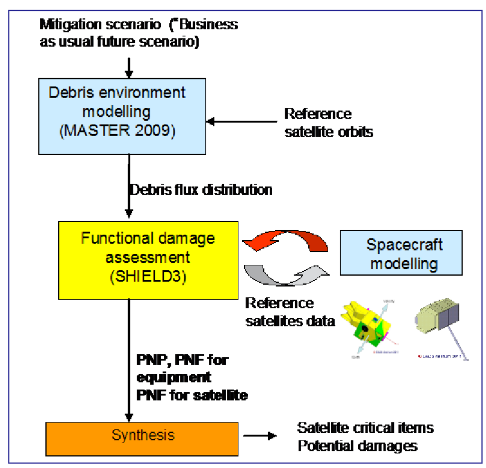

Figure 2: Approach for vulnerability analysis

Two reference satellites, an Earth Observation optical satellite and an Earth Observation radar satellite, have been taken into account. They have different configurations and different orbit altitude (the optical satellite has a deployed solar array and is located at 820 km altitude while the radar satellite has a rigid body mounted solar array and is located at 515 km altitude).

The SHIELD tool relies on information about the design of the satellite and on the directional distribution of the flux of debris on the satellites computed using the MASTER 2009 environment model.

The SHIELD tool has used these input data to determine the impact and failure probabilities for all equipment considered. By combining this with information on the redundancy concepts and the criticality of specific equipment, a debris impact-related failure probability for the entire mission has been derived.

This analysis has been done for the Business-As-Usual (BAU) scenario as implemented in the MASTER-2009 (Meteoroid and Space Debris Terrestrial Environment Reference) model. This scenario assumes that current practices are to continue into the future. The period used for the analysis will be the 10 years following January 1st, 2020.

An evaluation of the flux of debris impacting, and of the flux of debris penetrating the reference satellites on their different faces has been done for successive ranges of particles diameter. It appears that:

- debris below 1mm diameter has a high probability of impact, but only few penetrate the satellite, so that the effects on equipment are very low.
- Debris particles with a diameter in the range (1-10mm) impact and penetrate the satellites 100 times more often than debris particles in the range (10-50mm).
- The risk of being impacted or penetrated by small debris is much higher at 800 km than at 500 km
- The radar satellite presents a very low vulnerability to small debris, with a high Probability of Non Failure (PNF) due to its cylindrical shape, with axis along velocity vector and rigid body mounted solar arrays, and its low altitude (515 km) outside the zones where the density of debris particles is high.

The penetration of a debris particle in the satellite, and in equipment could lead to three types of potential damages: the loss of the mission, that could result from penetration of debris in the tank (with a risk of explosion or only leakage depending on particle size and impact conditions), or in a non externally redundant equipment (in the case of internally redundant equipment, the level of failure depends on the internal architecture); the degradation of performances of the satellites, resulting from the loss of resources like battery, the degradation of solar cells, radiators, loss of payload equipment, tank leakage, etc; the reduction of the satellite reliability (loss of redundant equipment).

Exposed functional surfaces, which are not protected, such as solar arrays, are in general designed to tolerate a debris impact flux. Such surfaces are thus not considered in the evaluation of probability of failure.

The SHIELD tool has evaluated the probability of penetration of satellite equipment by the debris particles (including those that have penetrated equipment inside the satellite). Then, taking into account the effects of the redundancy concepts, in particular the fact that the equipment has an internal or an external redundancy, an evaluation of the probability of non failure of the satellite has been derived. Fig 3 illustrates the probability of failure of the reference satellites as a function of the diameter of debris particles. This is only applicable to the two reference satellites as the result depends highly on the size of satellite, its orbit, its layout (deployed or rigid body mounted solar arrays, etc). These figures cannot be taken as general/average numbers. However, it appears that the debris of size between 2 and 4 mm are the main contributors to the probability of failure (due to debris impact) of the satellite.

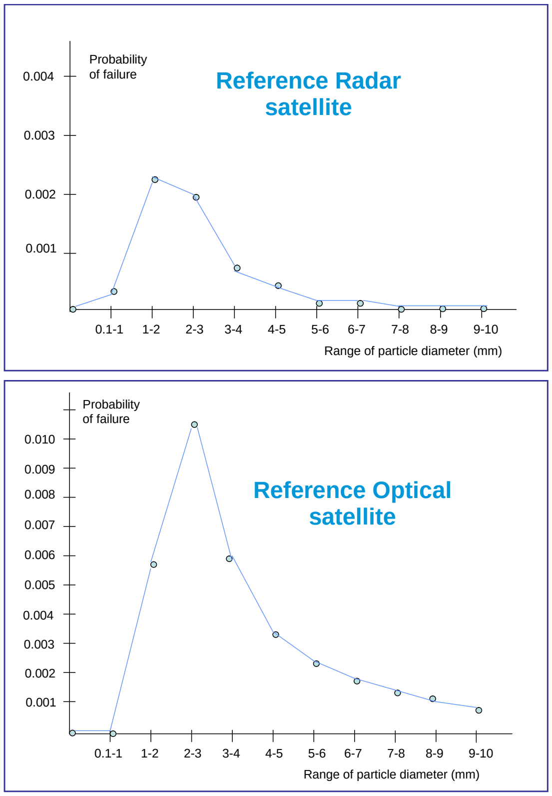

Figure 3: Illustration of Probability of failure as a function of debris size for the two reference satellites

4 POTENTIAL SOLUTIONS

The vulnerability analysis shows that the effects of particle penetration on the satellite equipment are not identical and depend on the satellite configuration equipment location etc. Thus, for each satellite, there are equipment with the highest risk of penetration, (externally mounted electronic equipment, payload or platform, internally mounted equipment located close to the front face, the tubing and the harness) which could result in the reduction or the loss of the mission, and the equipment with catastrophic consequences if a particle penetrates, such as tanks and batteries (depending on the technology).

Based on the results of the vulnerability analysis, two main categories of solutions (Fig 4) have been defined: solutions at system level, and solutions at satellite architecture level, which includes the shielding solutions.

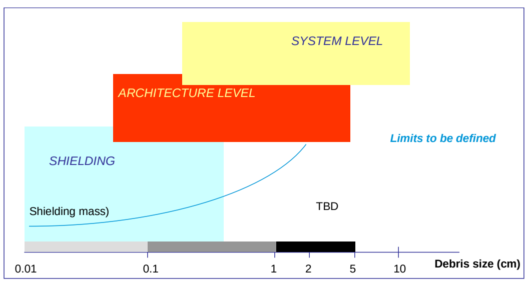

Figure 4: Categories of solutions

The system level solutions can take into account the full range of debris size. An example is the fractionated satellite concept, which consists in sharing some functions of a satellite (communications with ground, computing capability, payloads, etc) on modules forming a cluster, based on wireless communications and interconnecting network. With an adequate distance between the modules, a collision with debris could lead to the loss of a module, but not the complete mission. Another example is the distributed system concept, which will adapt the principles of existing terrestrial wireless to distributed space system architectures. Possible concepts of operations are also part of the system level solutions.

At spacecraft architecture level, several types of solutions can be considered, such as:

- Adequate equipment location and physical segregation of the redundancies
- Review of architecture of subsystems, such as solar arrays electrical architecture, propulsion configuration, harness configuration, etc
- Shielding of the spacecraft: different strategies of shielding can be considered. However, their impact on the spacecraft is different in terms of accommodation and satellite performance (mass, thermal behaviour, electrical properties, RF properties), and is a criterion of evaluation of the shielding strategies.

These solutions will be evaluated with respect to their accommodation on the spacecraft and the impacts on the spacecraft configuration in terms of mass, launcher interface, propellant budget, thermal behaviour, etc.

5 SHIELDING ASPECTS

5.1 Shielding Concepts

The shielding solution will have a significant impact on the mass and on the layout of the satellite. Thus, it will rather be used at equipment level, for those items experiencing the highest risk. The analysis of the reference satellites, and also of the current and future LEO satellites, shows that various basic configurations of equipment can be defined according to their location in the satellite for equipment having a risk of failure due to debris. Tens of configurations have been identified. Some examples are shown in Fig 5.

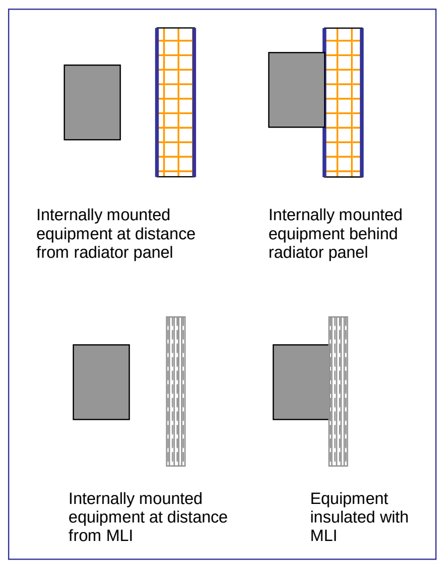

Figure 5: Examples of equipment basic configuration

A review of the occurrence of these configurations on various current LEO satellites has led to the identification and selection of the most frequently used.

A set of preliminary shielding concepts have been defined for each of the selected basic configuration. They include conservative concepts (with increased material thicknesses to protect against particles of 3 to 4 mm, but no additional layers and no change of material) and innovative concepts (with new material and/or additional layers). Each shielding concept is characterised by the number of layers (in general, a multi-wall is better than a thicker wall), the thickness and materials of layers, and the spacing between layers. Each shielding concept has an impact on the performance of the satellite (e.g. mass, volume, structure and thermal performances, integration effort and manufacturing cost).

The required objective of the shielding is to reduce the probability of failure of the satellite (due to debris) by half. As shown in Fig 6, this objective could be achieved at satellite level when all items (taking into account redundancy scheme) are protected against debris in the size range of 3 to 4 mm.

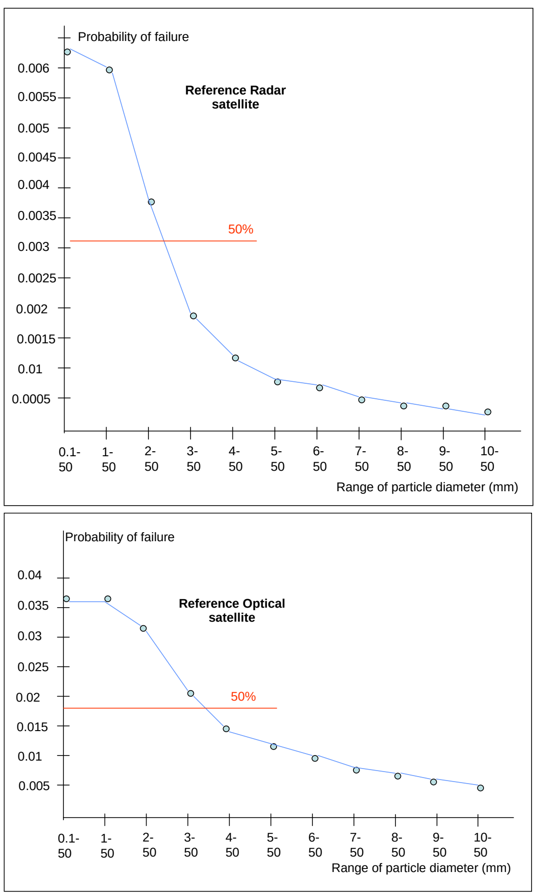

Figure 6: Cumulative probability of failure as function of particle diameter for the two reference satellites

They can be implemented locally (in the vicinity of an especially vulnerable item), or more widely, in order to protect a large area of the spacecraft. In some cases they can be added to conventional structures or implemented during the manufacturing of structural items (for example sandwich panels) or thermal items (MLI).

More than twenty shielding concepts have been defined. To achieve this variety of concepts, a number of shielding bricks were identified and applied to the basic configurations: reinforced MLI, reinforced sandwich panels (Al or CFRP), reinforced equipment box and intermediate layers. These bricks can be mixed to define an efficient shielding solution, such as for instance reinforced MLI plus reinforced panel.

The evaluation of the performance of the candidate shielding concepts has led to plan a campaign of tests, in two phases:

- Preliminary tests, done at brick level. All the identified shielding bricks have been tested in order to compare different materials and class the different bricks. The results have been used to review and update the shielding concepts.
- Optimisation tests and tests of selected shielding concepts. The optimisation tests aim to optimise parameters such as the spacing between layers.

These tests are being performed at Fraunhofer EMI's two-stage light-gas guns [2] at 7 km/s.

5.2 Shielding Tests

Experimental evaluation of the shielding concepts is currently on-going. So far, the major part of the preliminary tests are conducted and analysed.

The aim of the first test campaign is to evaluate promising shielding components identified during the study. The shielding components are placed within a set-up that is representative for their occurrence within a spacecraft: multi-layer insulation (MLI) and sandwich panel samples are placed at the outermost location and impacted directly, whereas intermediate layer samples are placed with some spacing behind a bumper. The targets are impacted with nominally identical impact conditions above their ballistic limit. Behind each target, witness plates are placed. The first witness plate behind the target (WP1) is considered somewhat representative for module walls.

Figs. 7 and 8 show a sandwich panel target (featuring aluminium foam as core) before and after impact testing. Fig. 9 shows high-speed video images from the impact test on this target. As can be seen especially from the later images, this type of sandwich panel produces a great number of fragments that are ejected inside the spacecraft. This is a non-desirable effect.

Figure 7: Sandwich panel target before impact testing (sample 2.6, experiment 5376).

Figure 8: Sandwich panel target after impact testing (sample 2.6, experiment 5376).

As all targets are different, comparison of their performance is nontrivial. In the approach taken within the ReVuS project, the penetration capability of the most damaging fragment impacting the witness plate simulating the module wall (WP1) is estimated. This penetration capability is a measure for the quality of the investigated sample. This parameter describes both the sample's ability to disperse the fragment cloud over a larger area, and (especially for intermediate layer samples) to decrease a fragment cloud's energy.

The penetration capability is given in terms of the penetrated areal density of the shield. This number includes the (nominal) areal density of all layers that would have been necessary to stop the impacting particle. The module wall (represented by WP1 in the experiments) is calculated from the perforation capability of the most damaging fragment as identified by the procedure outlined above, using the Cour-Palais damage equation.

Using this number, different shield types can be compared against each other. Fig. 10 shows an example plot for Al sandwich panel targets. As can be seen from the graph, samples 2.3 and 2.6 are the most lightweight to stop the impacting particle.

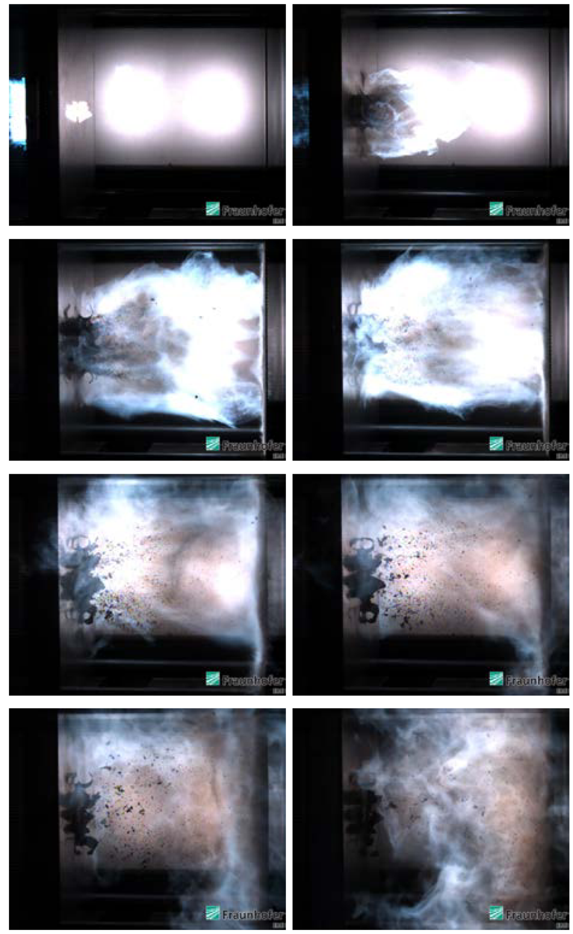

Figure 9: High-speed video image sequence from sandwich panel impact testing. Image times with respect to impact are 13μs, 88μs, 347μs, 495μs, 791μs, 1106μs, 1606μs and 3199μs.

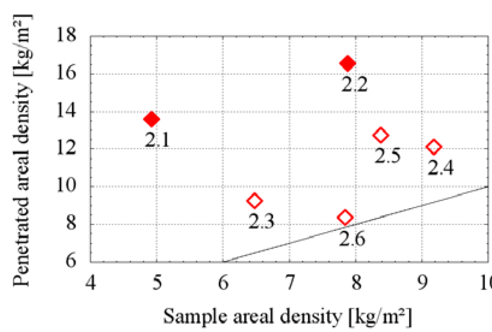

Figure 10: Penetrated areal density plotted vs. sample areal density for the Al sandwich panel targets. Filled symbols indicate WP1 perforation. Solid line is identity. All tests have nominally identical impact parameters (diameter 5 mm Al sphere at 7 km/s).

A paper dedicated to the preliminary tests is presented at this conference as well [3].

6 ASSESSMENT OF POTENTIAL SOLUTIONS

An assessment of these potential solutions with respect to impacts with small size debris will be done in order to evaluate their benefits with respect to existing architectures and to compare the performances of these solutions. In particular, the interest of combining several solutions will also be assessed.

As an example, an analysis of the implementation on the representative radar satellite of three possible solutions has been done with the SHIELD tool [4]. These solutions are based on the use of shielding configurations to protect some critical equipment and some areas, and the use of architecture level solutions (typically equipment relocation). Fig 11 shows that each of the solutions has fulfilled the required objective.

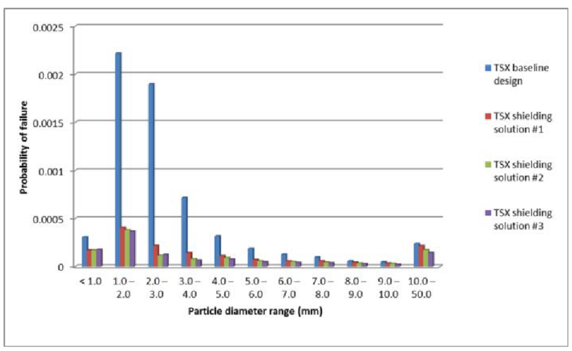

Figure 11: Failure probability vs. impactor size for each of the radar satellite solutions

Ultimately, this assessment should lead to design rules for the future spacecraft and to recommendations and guidelines for reducing the vulnerability of spacecraft to on-orbit collisions in the future debris environment, which address protection solutions during design and operation.

7 CONCLUSIONS

The ReVuS project is defining and assessing different solutions, at system level and at satellite architecture level, that could be implemented to reduce the vulnerability of satellites to small debris, and thus to avoid or minimise any degradation of the mission. The shielding of critical satellite elements appears to be one of the most promising solutions. The vulnerability analysis of two reference satellite has shown that the particles inducing the highest probability of failure of the satellite have sizes in the range 2 to 4 mm. This is mainly due to their high fluxes as compared to particle with size above 1 cm. The shielding of the equipment will be sized against this size of particles. Solutions at architecture and system levels will take into account the larger size of debris up to 5 cm.

Within this project, innovative shielding concepts using new materials have been defined and are tested.

The ReVuS project will allow the elaborating of new design rules to increase the robustness of European satellites in the growing population of small debris.

8 ACKNOWLEDGEMENTS

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