DESIGN FOR CONTAINMENT TECHNIQUES TO REDUCE SPACECRAFT RE-ENTRY FOOTPRINT

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ABSTRACT

Clean Space is an ESA initiative to address the technological challenges in reaching sustainability of space activities on Earth and in orbit. Its purpose is to guarantee the safety of the human population and future space activities. Under this initiative, different solutions, such as Design for Demise (D4D) and debris removal, are studied.

Design for Containment (D4C) is the design of spacecraft systems using methods that keep harmful objects under control or within limits, so as to reduce the number of impacting fragments on ground during re-entry events. While potentially increasing the impact mass, the lower number of fragments may significantly reduce the overall casualty risk. These methods could render future un-controlled re-entry missions compliant to the space debris mitigation guidelines without major design changes, that could put them at cost or schedule risk. In this paper, the system level investigations, simulation results and first findings of the on-going ESA funded study "Containment Techniques to Reduce Spacecraft Re-Entry Footprint" (also called the D4C study) are presented. The study aims to identify and validate promising containment techniques and to provide an update to the current material database for re-entry models (ESTIMATE). Feedback to the ESA guidelines for demise verification (DIVE) will also be a valuable outcome.

The project uses the following approach:

- First, an assessment of containment methods is performed based on a literature review and preliminary re-entry simulations of several different satellite missions as study cases.
- Then, more detailed simulations are conducted. They allow a trade-off between the different previously identified containment methods.
- A test plan and prototypes of the best containment methods are defined, and predictive simulations of the entry flight are conducted.
- Finally, the prototypes are tested according to the test plan and the results are analyzed to derive conclusions on the tested containment methods. Based on these results, modelling recommendations and updates to the DIVE document and the ESTIMATE database are proposed.

1. INTRODUCTION

With a current rate between 100 and 150 launches per year [1], some of which inject over 30 satellites into orbit at once, and assuming a mean number of four to five break-ups per year, the number of objects in space is expected to increase steadily. As a consequence, the probability of casualty due to the re-entry of space debris is also expected to increase. The most effective short-term means for reducing the space debris growth rate is through the prevention of in-orbit explosions (via passivation of space objects at the end of their operational life) and collisions (via collision avoidance manoeuvres while the objects are still active). Strict compliance with post-mission disposal guidelines is the most effective long-term means of stabilising the space debris environment at a safe level.

According to these guidelines, low earth orbit (LEO) missions may perform an uncontrolled re-entry, provided their re-entry casualty risk estimation remains under a certain limit. The time between the end of the mission and the uncontrolled re-entry may be up to 25 years. This disposal method requires the satellite to strongly limit the casualty area on ground as well as to passivate power, communications and propulsion systems at the end of the mission for reduction of on-orbit explosion risks. In order to reduce this casualty area, spacecraft design can rely on both Design for Demise and Design for Containment techniques.

Design for Demise is the design of space system hardware that will intentionally burn up – or ‘ablate’ – during an atmospheric re-entry in order to reduce both the number, mass and size of surviving parts that reach the ground and hence the associated casualty risk. However, several parts of the spacecraft may, due to performance requirements or long development cycles (e.g. optical instruments, large mechanisms, etc.), not be suitable to be made demisable by change of materials or design. During re-entry, each of these elements may generate debris surviving the re-entry, thereby significantly increasing the on-ground casualty risk.

Design for Containment, the subject of the study addressed herein, attempts to reduce this casualty risk by using specific hardware or design principles to maintain several critical elements as single object. This way, the probability of collision with a human is reduced by reducing the number of independent fragments reaching ground. In some cases, this may be enough to render a mission feasible within the cost and schedule as it may avoid major design changes.

The objective of this study is to identify and validate containment techniques that can be broadly applied to spacecraft critical elements to reduce the ground risk.

For this scope, the approach followed in this study is first to assess and trade-off different containment concepts, through re-entry analysis and system aspects evaluations, and second to develop prototypes of the containment methods to be tested in a relevant re-entry environment.

The results of this study are also intended to provide both an update to the current material database for re-entry models (ESA ESTIMATE) and feedback to the ESA guidelines for demise verification (DIVE, Demise Verification Guidelines for Analysing and Testing the Demise of Man-Made Space Objects During Re-entry).

2. IDENTIFICATION OF CRITICAL ELEMENTS

The elements subject to the application of design for containment methods are the ones that survive atmospheric re-entry. These so-called critical elements can be identified by re-entry simulation using dedicated software such as DRAMA or SCARAB. In this study, two types of LEO satellites have been chosen and their critical payload and platform elements have been identified through re-entry simulation of three real satellite study cases: Sentinel 1, ROSE-L, and a High Resolution (HR) Earth Observation (EO) small satellite.

LEO platforms usually include several equipment items that do not demise well or that contain elements that do not demise. These are typically reaction wheels (RW) parts (steel fly wheels and ball bearing units), magnetorquers, large electronic boxes, titanium propellant tanks or valves and star tracker parts (mostly lenses and titanium inserts).

In addition to these elements, the overall demise process of radar satellites can be highly impacted by the shape and size of their Synthetic Aperture Radar (SAR) antenna, as found in the analysis of the Sentinel 1 and ROSE-L study cases. The antenna can thereby indirectly impact other items with its ballistic coefficient or shielding effects or, depending on its substrate material, break into numerous fragments that may survive re-entry.

The high-resolution optical instruments that can be found on Earth Observation satellites also have numerous not-demisable elements such as mirrors made out of ceramic materials, optical fixings made out of invar or titanium, ceramic truss structures and titanium feet, as found in the analysis of the Earth Observation satellite study case.

Some of these objects reach the ground because their material (titanium, ceramic) never reaches its melting temperature. Others do not demise because they are sheltered by other elements and therefore not exposed to the harsh environment of the re-entry.

3. DESIGN FOR CONTAINMENT TECHNIQUES

3.1. Containment Techniques classification

In order to contain the critical elements found in the study cases, and in LEO satellites in general, a number of techniques has been identified in the first part of the study.

The D4C techniques have been classified in four families listed by order of magnitude of design impact regarding usual design. The methodology suggests then to try one method after the other. Several methods under these techniques can be cumulated in order to meet the final objective.

3.1.1. D4C Technique: REGROUP

This technique deals with the architecture/accommodation change with respect to the standard design in order to regroup re-entry debris. This modification may be applicable: for the entire mission (flight architecture change), or only for the re-entry phase of the mission (adaptative change at end of life).

3.1.2. D4C Technique: ATTACH

This technique summarizes all methods for joining several surviving elements. This includes the addition of new specific joining elements (such as tethers, brackets) and other necessary design changes to make the attachment effective (such as change of shape or materials).

3.1.3 D4C Technique: PROTECT

This technique includes all methods that involve the modification or the addition of a specific protection to prevent the exposure of certain elements to the heat flux. Such specific protection can be of different natures:

- Coating, paint, specific treatment,
- Covering tissue or material or
- Mechanical shield assembly (deployable, inflatable…).

3.1.4. D4C Technique: ENCAPSULATE

This technique deals with the implementation of a dedicated device to enclose elements surviving the re-entry (mechanical containment). This technique may be achieved:

- Via a partial encapsulation (allowing the exposure of contained elements to the hot flow) or

- Via total encapsulation (not allowing the exposure of internal elements).

3.2. Enabling Technologies

In this section, a review of the most recurring enabling technologies that could be used to manufacture the previously mentioned D4C techniques is given.

The main technology is related to implementation of thermal protection system (TPS) materials as raw materials or within protection devices.

3.2.1. Ceramics

Different types of ceramics made in Europe could be envisaged:

- Sintered SiC produced in France,
- Sintered Si3N4 produced in Germany,
- SiSiC produced in Germany,
- HBCeSiC produced in Germany and
- C/C produced in France and Germany.

3.2.2. Metal Alloys

The most interesting metals for containment techniques are the ones with high melting temperatures, reasonable prices and availability as semi-finished product. This category mainly includes:

- Titanium (1670°C), the most widely used high melting temperature metal in the aerospace industry.
- Tungsten (3400°C), the highest melting point metal, making it the go-to metal for high-temperature applications, such as light bulb filaments, welding electrodes and furnace heating elements.
- Molybdenum (2620°C), primarily used to alloy with other metals, is relatively lightweight. It is used in superalloys for jet engines.
- Tantalum (2980°C), which is used for high temperature, corrosion resistant alloys, e.g. in vacuum furnace parts.

3.2.3. Ablative Materials

Many different examples for use of ablative materials exist or have existed; the main flight demonstrations in Europe were performed during the re-entry of inter-planetary probes and industry and research follow the needs of extra-terrestrial and earth re-entry probes.

US ablative references mostly refer today to Phenolic-Impregnated Carbon Ablator (PICA) and have been used for several Mars rover missions.

Due to the lack of European ablative reference to comply with high velocity earth re-entry, several research programs have been funded to address this need.

3.2.4. Flexible Thermal Protection

A solution similar to the use of ablative TPS would be encapsulating the non-demisable elements by a ceramic fiber based net or envelope. Different materials could be used. Alumina-silicate fiber fabrics are well known and sometimes used inside rocket thruster nozzles. The melting point of the resistant fibers is above 1800°C. Other fibers, such as pure alumina fibers, can be stable up to 2000°C and more.

An alternative investigated in the scope of D4C is the use of mechanisms to adapt the system architecture to a different one implementing further regrouping, protection, encapsulation or closure. This actuation can be commanded at end of life or the regrouping mechanism may act autonomous through thermally activated shape memory alloys based actuators.

3.3. Applicability to the study cases

After identification of possible containment techniques and their enabling technologies, their applicability to the selected study cases has been analyzed. This analysis has been later used to assist the trade-off between the different techniques, presented in section 4.

3.3.1. Radar Satellite Study Case

The radar satellite study case provides several potential applications for containment. In the “regroup” and “attach” categories, it would be possible to change the satellite’s architecture to group and attach the reaction wheels and the propellant tank to form a single block. This could be done through a rigid attachment between the components or by a tether solution to keep non demisable items together. The bus module fragments could also be attached through a titanium bracket or any other non-demisable joint. Another containment concept that may be worth investigating for this kind of satellite is based on keeping the main structure (central cylinder and panels) and the SAR antenna connected for as long as possible. This way, the improved ballistic coefficient of the assembly may enhance its overall demise.Since the objective here is not to just keep ground fragments together but to improve the overall demise, the challenge in this concept lays in avoiding additional fragments by the structural parts applied to maintain parts together. Furthermore it must be ensured that no previously non-critical items further inside the structure become critical due to shielding effects. For this concept Steel brackets could be used since it does resist re-entry to a certain level but still has a potential to demise (in contrary to Titanium for example which never demises).

3.3.1. Optical Satellite Study Case

For the optical satellite study case, a possible D4C solution would be the total encapsulation of the instrument via a thin titanium shell. The drawback of this idea is the addition of a dedicated titanium shell that has no role for flight in the opto-mechanical assembly. An alternative design could be based upon a ceramic structural baffle that substitutes the current structure, which is based on ceramic lames holding the upper mirror above the lower one. An improvement of the capsule may be achieved by protecting it with an ablator. A partial encapsulation that uses a dense mesh instead of the Titanium baffle solution would be possible as well. In all these cases, the containment needs a closing system that would be activated at the end of life or during early re-entry.

The implementation of the specific attachment method also seems interesting for this study case. The critical elements could be joined using a non-demisable wire. For this purpose, the instrument's structural ceramic lames could have small holes at the top and the bottom to allow the passage of the non-demisable tether. The RW supports would have to be re-designed to become non-demisable (by changing their material to Titanium, for example), and the wire could pass across their already existing holes. The cover of the RW would have to be redesigned to be non-demisable and hold the internal elements or a custom cage around the whole RW could be designed for this purpose. The wire would be made of a high melting temperature material and would be protected and channeled with specific supports to avoid obstructing the instrument's Field of View. A wire connecting the problematic elements would give a single surviving object under the hypothesis that the ceramic lames are most likely to break into two pieces at maximum. However, the length of this wire might become relatively long and the Debris Casualty Area (DCA) of the single fragment may be high. A combination of both ideas – the encapsulation of the instrument, and the attachment of only the RWs – may be a better solution.

4. PRELIMINARY TRADE-OFF

4.1. Trade-off criteria

In order to assess and perform the selection of the most promising containment concepts, the following criteria have been identified:

I. Applicability of the Containment Concepts

A. Applicability for future Missions

A prediction of the suitability of the containment method for future missions.

B. Applicability of the same method to different spacecraft

A prediction of the possibility to use the same containment method for various equipment items. A method is considered to be less beneficial if applicable for only one type of equipment or a single spacecraft.

C. Programmatic aspects (Technology Readiness Level, Development cost and risks)

An assessment of the aspects that could impact the development of the containment method.

II. Benefits of the Method

A. Casualty Area (DCA) Reduction

A quantification of the difference in casualty area due to the application of the containment method, obtained by simulations and eventual post-processing.

B. Kinetic energy (KE)

A quantification of the difference in kinetic energy due to the application of the containment method, obtained by simulations and eventual post-processing.

C. Reliability (or confidence level)

An assessment of the robustness of the DCA and KE reduction to small parameter variations, or the amplitude of the method's working conditions.

III. Design and system impacts

A. Accommodation

A description of the accommodation impacts induced by the application of the containment method, such as the addition of new elements, the displacement of existing ones, the perturbation of sensors Field of View…

B. Mass

A quantification of the difference in the system's mass due to the implementation of the containment method, including all necessary changes, such as holes and material changes.

C. Costs

The estimated direct cost of the flight hardware associated to the containment method. This includes tethers, brackets, protections, the cost increase due to material changes etc., but excludes development costs, tooling, and others.

D. Manufacturing complexity

A description of any difficulties that may be found during the production of the containment method associated hardware, such as material handling or machining difficulties.

E. Structural, thermal, electromagnetic implications

A description of any impacts that the containment method could have on a structural, thermal, electromagnetic or other level, such as increased or decreased strength, heat dissipation or absorption, electromagnetic interference, cleanliness concerns etc.

F. System Reliability

A qualitative assessment of the reliability impacts of the containment method on the system, e.g. due to the addition of mechanisms or environmental dependencies.

IV. Modelling Aspects

A. Modelling Effort

A description of the potential modelling approach and the data needed for modelling.

B. Current DRAMA modelling limitations

A description of the difficulties that may be encountered in the numerical modelling of the containment method.

C. Confidence in modelling approach

An assessment of the level of representativeness of reality in reach through the numerical modelling and simulation of the containment method.

V. Testing Aspects

A. Test sample representativeness

The assessment of the representativeness of the test samples for the flight hardware is mainly based on the simplifications applied to the test hardware. Ideally, real flight hardware is used for the experimental simulation. Typical simplification that reduce the representativeness are simplification of the shape or the lack of coating and material treatment.

B. Test sample procurement

A description of the containment method test sample procurement approach and the potential problems that have to be dealt with, e.g. the long lead times or strict export regulations.

C. Test sample cost

An estimation of the cost of the test setup for experimental verification of the containment method . This includes the costs of the samples, holders and the required intrusive instrumentation.

D. Test facility compatibility

A verification of the wind tunnel constraints that can prohibit testing of the test sample or achievability of the desired test conditions. The most important limitations are the possible size of the test sample and the ability to produce a test environment that is representative for the entry flight. This can be a binary criterion, but limited compatibility that requires adaptation of the test sample or setup (e.g. downsizing) is also possible.

4.2. Trade-off evaluation

This section presents some of the outcomes of the first trade-off evaluation performed according to the previously mentioned criteria, and mainly based on the analysis of the study cases.

The most **applicable** containment methods have been found to be those based on the regrouping and attachment of critical elements, and those based on encapsulation. The regrouping and attaching strategy is applicable for most satellites as it is a solution suitable for many kinds of critical elements, such as reaction wheels, propellant tanks and small structures. Encapsulation has been found most interesting for optical satellites, as they typically have telescopes that are composed of numerous ceramic and/or glass parts. The encapsulation approach can also be envisaged to retain general small objects that come loose during reentry, such as reaction wheels or other internal objects.

In terms of **benefits**, the specific attachment has been found to be the most beneficial in DRAMA simulations. Casualty Area reductions due to the application of this method go from 0,7m² for the simplest RW attachment case up to 30m² for an optimized case seeking ballistic coefficient increase. Taking into account the most realistic DRAMA simulation results, the casualty area can be expected to decrease by 1 to 2,5 m² using this method on reaction wheels, tanks and small structural parts. The encapsulation of a telescope has shown to decrease casualty area by 10 m² in a DRAMA simulation that is considered plausible. In terms of kinetic energy, the specific attachment using tethers is the least penalizing due to its low mass penalty. An increase of the ground impact energy in the order of 5kJ is to be expected for the attachment of unmodified elements. Several tens of kJ are to be expected if aluminum objects are changed to Titanium in order to ensure they do not come loose. Encapsulation is found to be very penalizing in terms of kinetic energy (several tens of kJ as well), but an improvement of this result could be reached through partial encapsulation based on cages or nets. These open solutions would allow flow penetration with a subsequent heating of the contained parts. This can lead to a partial demise and thus a reduction of the mass reaching ground.

In terms of **system** impacts, the architecture change, whenever it is possible and sufficient to avoid demise, has been found to be the most beneficial, as it implies no additional mass and cost and does not change the reliability of the system. In opposition, the so-called adaptative change, where elements would change their position at the end of life via a dedicated mechanism, is found to be complex and to have an undesired impact on mass, cost and reliability. Tether solutions and specific attachments in general are found to increase mass and cost by the addition of new elements and the potential material change of existing ones, but are usually found easy to accommodate and have no impact on reliability. Some of these material changes could increase the strength of the assemblies, having a positive impact, but the piercing of holes into elements could reduce their strength or create points of stress accumulation. Protections in blanket or coating format are evaluated to have mild system impacts but also limited benefits, so they are considered as a complement to other methods rather than an independent containment solution. Protective shields based on mechanisms or inflatable systems have been found to be very penalizing in terms of mass, cost and complexity, and out of scope for containment purposes. Finally, total encapsulation is the most penalizing in terms of accommodation and mass. The capsule imagined for the Earth Observation study case could add from 10 to 20 kg to the system depending on its material. Its addition would require the repositioning of several other equipment and its closing cover is very likely to obstruct the field of view of other sensors. Moreover, the closing system is expected to have a negative impact on reliability due to the addition of a new mechanism. The partial encapsulation alternative to encapsulation (cages and nets) is however found to mitigate some of the negative mass impact, and would be easy to accommodate around small equipment such as RWs.

The **simulation** of the architecture and material change methods pose no particular issue and the usual DRAMA modelling approach can be used with a good level of confidence. Tether-based solutions can be modelled in DRAMA as rigid connections between elements with some limitations, e.g. loops cannot be created, movement and forces are disregarded, links will be assumed to have zero length and the aerodynamic properties of the compound object cannot be included. These limitations are mainly due to the fact that the simulation of detailed containment technique designs goes beyond the purpose for which the DRAMA software was developed – connections were originally meant for the satellite’s external appendices [2]. Alternatively, the benefits of such attachments in terms of casualty area could be obtained using post-processing. Protections could be modelled using parent-child relationships in DRAMA, however their representativeness would be low for very thin protections and complex shapes, so the confidence in the results would be limited. Encapsulation can be modelled in DRAMA through parent-child relationships without any particular limitations and with a good confidence level, however partial encapsulation is more challenging. A post-processing approach could be used, but the reentry phenomena associated with this technique are not known and only a very low confidence level could be attributed to the results. Though, as long as the internal parts stay contained, the uncertainties would only affect the landing mass and not the casualty area.

When it comes to **testing**, one of the main limitations is the potential size of the test setup. For the architecture change technique, for example, reduced scale models of the system would have to be made. These would be hard to manufacture to a good level of representativeness and the scaling gives a non-representative temperature distribution. In the case of tethers, the major limitation is the missing or non-realistic dynamic behavior. A sample of a tethered assembly with flight characteristics could be tested, but the relative movement of the parts it connects could not be reproduced realistically in a test on ground. In contrast, the testing of other rigid attachments such as non demisable brackets could have a good representativeness using a rotating set up and an intelligent sample design. When it comes to protections and capsules, the testing of material coupons and layered samples would be possible, but the testing of a real size assembly would be limited to very small applications. A major limitation in the testing of ablators is the fact that the transient nature of the aerothermal environment and loads cannot be fully rebuilt. Solid cage solutions could be tested well within the size limitations, but the testing of nets is more challenging due to the difficulties in testing flexible components as mentioned for the tether solution.

5. FIRST CONCLUSIONS

The chosen study cases (Sentinel 1, ROSE-L and a High Resolution Earth Observation satellite) represent two kinds of LEO satellites (radar and optical earth observation). These study cases have allowed the analysis of a variety of containment methods. The consideration of their applicability, benefits, system impacts, simulation, and testing aspects has served as input for a preliminary trade-off between the containment methods.

These inputs have been compiled in a multi-criteria analysis table which, using a rating system, has provided a first idea of the most promising D4C methods. The results of this first iteration are found in line with expectations and encouraging with respect to the potential of these techniques.

The consortium has decided to keep focus on the following methods, covering at least 3 families, during the next part of the project:

- The architecture change concept will represent the regroup concept family.
- The specific attachment and change of interfaces are considered of similar nature and will represent the attach concept. Some changes of design could complement them as it has been mentioned for the attachment of RWs.
- The effects of total encapsulation being better known, the consortium will focus on partial encapsulation for the encapsulate idea.

6. FUTURE WORKS

The most promising D4C techniques identified in the frame of the trade-off will be simulated with the ESA SCARAB software on system/spacecraft level. As study case for application of these techniques a model derived from the ROSE-L satellite has been selected. This is an L-band SAR satellite.

Three different containment scenarios will be analyzed. The simulations will provide information about the break-up and demise process during re-entry and allow a characterization of the predicted surviving fragments. A critical comparison with the results obtained for the unmodified scenario, i.e. without any D4C or D4D techniques applied, will give the baseline for quantifying the effectiveness of the simulated techniques.

Some D4C techniques will be challenging with regards to the simple aero-thermodynamic algorithms incorporated in SCARAB. For example, the flow field around, inside and behind a containing mesh or cage cannot be simulated in SCARAB, as the tool does not simulate the flow field. A solution to this is the introduction of simplifications such as a specific ratio of the outer heat load reaching the contained parts. High-fidelity simulation would require CFD simulations that model the flow field. These are prohibitively expensive for the complete entry flight of complex objects. Therefore, the SCARAB simulation results will be verified by and calibrated against the test results.

Two test campaigns in the LBK high enthalpy wind tunnels will be performed within this activity. The purpose of the first test campaign, which takes place in the less powerful L2K facility, is designed to test the feasibility of the fundamental concept (e.g. just a tether without any motion). The second test campaign, which will be conducted in the larger L3K facility, is designed to test and demonstrate the complete containment concepts (e.g. a free-moving component that is joined to a fixated one by a tether).

The first campaign is highly important to the success of the activity, as this also acts as a screening test campaign. This allows the enabling technologies for the containment concepts to be tested and verified. For example, a tether concept requires demonstration that the tether itself will survive the re-entry intact as well as demonstration that the tether will remain attached to the contained objects that it is intended to keep together. Thus, the screening tests will be used for testing possible materials, such as oxidic fibers for flexible links, high temperature metallic rods for hard links, and the connections of these links to the components of interest. Performing these tests at relatively small scales allows the heat flux levels of L2K to be sufficient whilst determining the demise behavior of the containment concepts. The intention is to demise the concepts in order to understand the limits of the concept and its implementation.

The concepts which are successful in the screening tests will then be applied in a more realistic mock-up of the complete concept in order to demonstrate successful containment of the full concept at a realistic scale.

10. REFERENCES

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