AN OVERVIEW OF DESIGN FOR DEMISE TECHNOLOGIES

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ABSTRACT

Due to the high cost and mission architecture implications of controlled re-entry, the development of Design for Demise technologies has been progressing steadily in the past years. These are technologies intentionally designed to disintegrate more than their traditional counterparts or in general to reduce the casualty area during the re-entry in Earth's atmosphere. The objective of this paper is to provide an overview of the technologies that were developed with the support of the ESA Clean Space initiative. Lesson learnt from past studies and knowledge gaps that could be addressed in the future will be pointed out.

Keywords: re-entry; design for demise; space debris mitigation; casualty risk.

1. INTRODUCTION

Since the European Space Agency started to comply with ISO standards regarding space debris mitigation (see [22],[15] and [17]) spacecrafts in Low Earth Orbit (LEO) are required to leave the protected zone within 25 years and re-enter the Earth's atmosphere through uncontrolled re-entry, if the on-ground casualty risk is lower than 1 in 10,000, or through controlled re-entry, if the risk is higher than this threshold. Having to perform a controlled re-entry has a dramatic impact on the spacecraft design and on the mission cost. For this reason, many mid-large platforms that would not comply with the risk threshold using traditional technologies, have started trying to embed Design for Demise (D4D) technologies in their spacecraft architecture.

There are various methods to enhance the demise of a satellite or of a piece of equipment, such as minimising the required heat (*e.g.* change the material), maximising the available heat (*e.g.* increasing the local heat flux by changing the shape), optimising the heat transfer (*e.g.* early break-up) and minimising the casualty area (*e.g.* keeping the fragments together using containment techniques). The ESA Clean Space Office has been systematically developing technologies and supporting research about design for demise since the first Space Debris Mitigation (SDM) guidelines were discussed, which makes it one of the most reliable and competent institutions on the topic. This effort in terms of design verification resulted in the publication of DIVE (see [14]), a document that summarises the guidelines for analysis and testing the demise of man-made space objects during re-entry. However, a structured and complete summary of existing design for demise techniques is still missing. For this purpose, a Design for Demise Guidelines Handbook is currently under development. The content of this paper has been elaborated in the framework and with the same scope of the Handbook. The aim of this paper is to provide a broad overview about the state-of-the-art design for demise technologies, linking them to the D4D techniques that they employ. Some of them are system level technologies, that impact the whole spacecraft (*e.g.* demisable joints, exothermic reactions), while others are equipment level technologies (*e.g.* demisable tanks, demisable reaction wheels, demisable magnetorquers). Lesson learnt from studies of the past will be pointed out, as well as proposed technologies that should be further investigated in the future. A final section will be dedicated to the ongoing or foreseen studies that aim at better understanding the demisability and fragmentation processes (*e.g.* solar array driving mechanism, electronics).

2. TOP LEVEL OVERVIEW

In this section, a brief introduction to the evaluation of the on-ground casualty risk will be given. Then, D4D terminology will be introduced and a first definition of the D4D techniques will be given.

2.1. On-ground casualty risk

The on-ground casualty risk is evaluated by multiplying the casualty area A by the mean population density of the predicted impact point:

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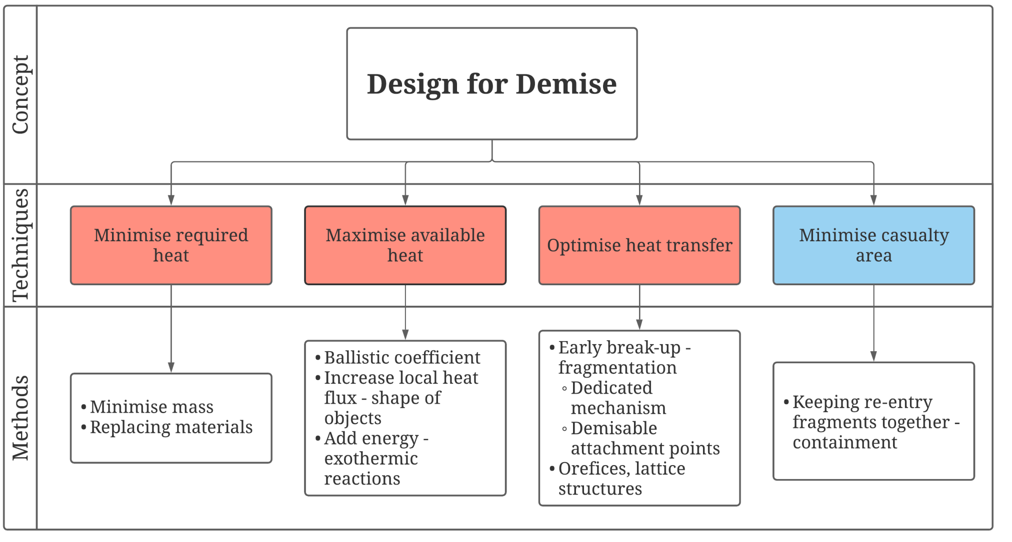

Figure 1. D4D terminology and categories.

$$r = A \times \rho \quad (1)$$

Therefore, to reduce the casualty risk, it is necessary to either reduce the overall casualty area, or to reduce the average population density of the target area, by choosing an uninhabited zone or by reducing the re-entry time. D4D addresses the first term of this equation, aiming at lowering the overall casualty area.

The casualty area is defined as the total area impacted by a fragment that can overlap with the average human:

$$A = \sum_i (\sqrt{0.36} + \sqrt{A_i})^2 \quad (2)$$

A_i is the area of each piece fragment with energy greater than 15 J originating from a single satellite, while 0.36 m^2 is the average surface covered by a human body. 15 J is the energy per object that is considered to be threatening for a human. This is why objects with less energy are not taken into account. The casualty area of each fragment is estimated using software tools that simulate the re-entry, such as SARA within the DRAMA suit (see [16] and [20])

Therefore, to reduce the overall casualty area, either the individual area of each fragment or the overall number of fragments shall be reduced.

2.2. Design for Demise techniques and methods

Various techniques to apply Design for Demise have been hypothesised in the past years. The most used categorisation is based on how these techniques intend to improve demisability and can be visualised in Fig. 1. The techniques in red aim at lowering the individual casualty area of each fragment, while the ones in blue aim at reducing the number of fragments.

A brief explanation of each technique is given in the following:

- **Minimising the heat required for the ablation** process corresponds to reducing the mass of the spacecraft or of the component, but it can also be achieved by replacing the materials that constitute them. For example, a lower melting temperature or a lower emissivity could anticipate the beginning of the ablation process.
- **Maximising the available heat** can be obtained by changing the shape of the spacecraft, which can affect the ballistic coefficient of the system and therefore the heat flux rate during the re-entry. Another alternative is to add energy by planning and causing exothermic reactions during the re-entry.
- The **optimisation of heat transfer** is mostly related to the fact that internal pieces of equipment are shielded from the heat flux by external structures. Achieving an early break-up or including some strategical orifices or lattice structures would expose them to the flux earlier or and would therefore enhance their demise. Changing the configuration of internal components can also optimise their exposure to the external heat flux, and in turn increase their demise.
- The fourth method has a different approach with respect to the others; instead of enhancing the demise, it aims at minimising the overall casualty area by reducing the amount of fragments released during the re-entry. This can be achieved with the so-called **containment techniques**, that ensure that surviving debris are kept together and land as one piece.

These techniques are strictly inter-related, which means that often the usage of one of them implies the exploitation of another one. Indeed, more than one technique can be applied within a single technology.

Each technique makes use of some methods (see Fig. 1), which can be applied to multiple technologies. In the following sections, each identified technique and method will be further explained and linked to all the demisable technologies that have been developed or researched employing it.

In the field of demisability, technologies are often divided into two categories: system level and equipment level.

Applying a D4D technique at system level means to act on the spacecraft as a whole or to multiple subsystems at a time, possibly increasing the demisability of the overall system and in particular the total casualty area. Some of the system level techniques that will be further explained in this section were already introduced in the past by [8], but since then have been further investigated.

D4D has also been successfully applied to one piece of equipment at a time. In this case, the demisability critical elements that were identified by previous studies, such as [5], [11] and [28], were further investigated and enhanced by using a manifold of different techniques. By including one or more of the following demisable alternatives, a Large Systems Integrator (LSI) will be able to reduce the overall casualty risk of a mission and be compliant with the threshold indicated by the re-entry requirements. Clearly, the benefit is that they will be able to perform uncontrolled re-entry, avoiding additional complexity related with the controlled re-entry strategy.

3. MINIMISE REQUIRED HEAT

The first method to enhance the demise of a spacecraft or of its components, is to minimise the heat required for it to melt, ablate and break up into pieces. This can be achieved in two main ways. Of course, with a lower object mass, less total heat will be required for demise. Another way to achieve this is changing the materials that constitute the object, for example to ensure a lower melting temperature and lower emissivity.

3.1. Minimise the mass

Minimising the mass reduces the amount of material that it is needed to burn during the re-entry. Usually, minimising the mass is usually part of the design of a satellite because it reduces the cost of a mission. In this subsection, an example of equipment with potential for mass reduction is described.

Reaction wheels Reaction wheels (RW) are used in space for three-axis attitude control. The RW usage is based on an electric motor attached to a flywheel, which, when its rotation speed is changed, causes the spacecraft to counter-rotate proportionately through conservation of angular momentum. Momentum depends on rotational inertia and rotation speed. Therefore, the mass of a RW could be reduced, if the speed would be increased, without changing the key performance parameters of the wheel. However, increasing the speed of a RW, which usually operates up to 6000 rpm, could impact the lifetime of the wheel. Therefore, it would require life tests, which are known to be quite long and therefore expensive.

3.2. Replacing materials

To tackle the challenge of hardly demisable materials, first some studies were conducted to identify the most critical materials. The driving parameters were of course high melting temperatures and and high specific heat of fusion (or specific enthalpy of fusion) required for the demise. The critical materials identified by [5], [11] and [28] were stainless steel, beryllium, titanium, tungsten, super invar and silicon carbide. These materials are mostly present in tanks, which are traditionally made of titanium, and in reaction wheels and magnetorquers, which include steel components. For all these components, alternative materials have been proposed in literature and sometimes practically tested in the framework of D4D studies. Due to their requirements on thermal stability, optical payloads often include ceramics, which are another category of highly non-demisable materials. However, at the moment, no demisable alternatives have been found to substitute ceramics and therefore other D4D solutions will have to be applied.

Tanks Tanks are the only kind of debris that have been confirmed to occasionally reach surface. They were identified as a critical element because they are usually made either of Titanium, which has a very high melting temperature and specific enthalpy of fusion, or of a metallic liner covered with a composite overwrap which is hardly demisable.

First of all, it is important to divide the tanks into two main categories, depending on the propulsion system that they support: high pressure tanks, used for electric propulsion and usually made of a Composite Overwrapped Pressure Vessel (COPV), and liquid propellant tanks, traditionally metallic and used for mono and bipropellant propulsion systems.

The demisability of the COPV tanks was investigated in the past by [1]. The main challenge of this study was related to the fact that the thermal characteristics of the composite layer are not yet well known, and this makes it difficult to model it. In particular, the composite overwrap does not have a specific melting point after which it can be considered to be gone. On the contrary, usually the carbon fibers would gradually peel off. Therefore, the main conclusion was that, even if the Aluminium liner

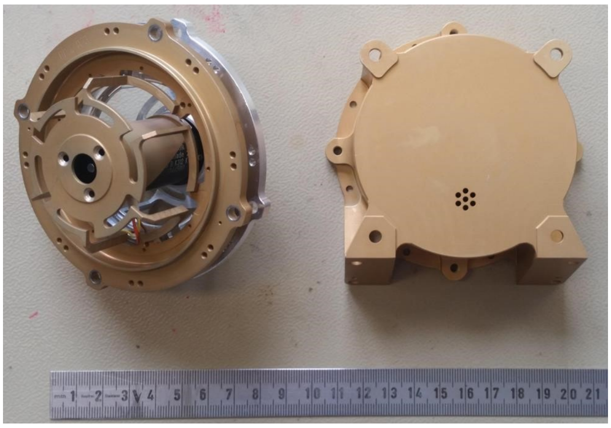

Figure 2. Reaction wheel housing [8].

would melt inside the COPV, it is not clear how it could escape the composite overwrap. Moreover, it is challenging, if not impossible, to extrapolate the results related to one type of composite to apply them to a different one. Currently, there are ongoing studies, for example by Peak Technology, that focus on enhancing the demise by using different manufacturing processes for the COPV tanks. Another study that is ongoing is carried out by Haydale Composite Solutions, which is investigating the materials and processes required to obtain a fully non-metallic gas tank. It is expected that non-metallic tanks could offer advantages in terms of reduced mass, lower manufacturing costs and lower lead times. The main challenge related to the development of this technology would be the ability to meet the permeability requirements without employing a metallic liner.

Regarding liquid propellant tanks, the usual solution proposed to enhance their demisability is a change in the material. In particular, [3] and [24] proposed to substitute the commonly used Titanium alloy (TiAl6V4), which has a high melting temperature and heat capacity, with Aluminium alloys, such as Al-Cu, Al-Mg and Al-Li. The main advantage of the first one was its maturity. The Al-Mg alloy would be compatible with green propellant but its manufacturability was not demonstrated yet. Al-Li had good structural properties and it would have allowed for thinner tanks, but its manufacturability was also not yet well known. [2], which was focusing on green propellants, proposed a thermoplastic liner with a carbon composite overwrap, that would however present the same issues pointed out for COPV tanks, and potentially leak problems because of the lack of a metallic liner. In the past, only the tank shell was modelled and analysed, while now a more comprehensive assessment is performed, including interfaces and Propellant Management Devices (PMD), that should be demisable as well. Currently, various volume ranges have been identified and distinguished. Large tanks, with a volume range between 170 and 220 L are currently being investigated by MT Aerospace, while demisable alternatives for small ones, with a volume range between 40 and 52 L, are being researched by the Polish Institute of Aviation.

Figure 3. Magnetorquer [8].

Reaction wheels Analysis showed that medium and heavy RWs can survive re-entry. Moreover, satellites typically employ four RWs at a time, which means that a demisable alternative could greatly benefit their overall casualty risk. On top of this, RWs include various components, and the most internal ones are shielded by the external ones during the re-entry. In particular, the earlier the housing would demise, the earlier the internal components would be exposed to the heat flux and the more they would demise. Fig. 2 shows the housing of a RW. Among the proposed solutions in the context of [7], the most promising were to change the materials of the most critical sub-components, such as the flywheel or parts of the ball bearing unit. However, RWs are complex mechanisms, which means that some changes in their design can take a long time to be qualified, especially if a life test is required. This will probably be investigated in the future.

Lastly, changing the material of the flywheel without changing the size of the RW leads to an extensive increase of speed and torque need, which in turn requires a re-designed external drive electronics, with a great power increase.

Magnetorquers Magnetorquers (MTQ) were identified as critical elements because they are made of various sub-components that are hosted one inside the other. As a consequence, the most internal elements, such as the core, are exposed to the flux even later. Moreover, they are often mounted directly on the spacecraft panels, and therefore are shielded by them until their mounting feet break. This means that they are fully exposed to the heat flux only late during the re-entry. An example of MTQ is showed in Fig. 3.

[23] investigated possible solutions to enhance the demisability of MTQs, and the most promising ones aimed at exposing the core as early as possible during the flight, since the core material itself could not be changed as it is strictly linked to the functionality of the MTQ. Therefore, the material of the mounting feet was changed to support an earlier separation and the housing material was changed to guarantee an earlier exposure of the core. An inductive coil as small as possible could also enhance the demisability. Another option that was investigated was to split the core in juxtaposed cylinders.

4. MAXIMISE AVAILABLE HEAT

Another option to enhance the demisability of a spacecraft during the re-entry phase is to provide additional energy to it. Of course, it is important to channel such energy into the melting and demisability processes, avoiding its dispersion in unwanted ways.

4.1. Ballistic coefficient

The ballistic coefficient B is defined as:

$$B = \frac{m}{C_D A} \tag{3}$$

where m is the mass of the spacecraft, C_D its drag coefficient and A its cross-sectional area.

A variation in the ballistic coefficient can impact the trajectory profile (*i.e.* velocity and flight path angle). In particular, an higher ballistic coefficient makes the trajectory steeper, while a lower one makes it more gradual. However, when trying to tweak the parameters that define the ballistic coefficient, two quantities should be taken into account: the peak heat flux, which is important to achieve the melting point, and the total heat required to achieve full demise. For example, decreasing the cross-sectional area will increase the ballistic coefficient and, in turn, the heat peak flux. However, this would correspond to a faster re-entry, which potentially may not reach the total heat required to fully demise the spacecraft. At the same time, decreasing the cross-sectional area also reduces the heat losses. To conclude, changing the ballistic parameter impacts on various other parameters and maximising the demise becomes in this case a complex optimisation challenge. For this reason, this method has not been implemented yet.

4.2. Increase local heat flux

The heat flux around a spacecraft is not uniform. Indeed, local heat flux is known to be higher at corners and edges. Therefore, a method that has been identified to enhance spacecraft demise is to change shapes locally, to trigger in such points an earlier start of the demisability process. The effect that certain shapes have on the local heat flux has been observed both in simulations and tests, but further studies are needed before this concept can be applied.

4.3. Exothermic reactions

Exothermic reactions can be triggered to increase the available energy during the re-entry. For example, they could be used to achieve interface separation or severing of harnesses and pipes. Exothermic reactions have been investigated to enhance demisability of certain critical components, such as reaction wheels, but their effects at system level still need to be assessed.

Reaction wheels The usage of exothermic reactions to enhance the demise of RW was tested within [12] and [10]. The RWs were merely chosen to test the concept of exothermic reactions, but the conclusions could be extrapolated to other technologies. In particular, these tests demonstrated the thermite ignition in the relevant environment, Plasma Wind Tunnel (PWT), and the release of a significant amount of energy. However, the impact on the demise of the test samples was quite limited. In particular, they had issues related to a sub-optimal thermite composition, leading to unreliable ignition and even partial ignition, but also with an insufficient quantity of thermite for the selected test sample. Moreover, an overly complicated test sample, although close to an actual flight application, introduced additional unknowns in the test. Lastly, the formation of slag was identified and its influence on the test result was hard to assess. In conclusion, these tests identified the need for further studies and concepts that would allow to properly channel the energy released to support the melting process, because otherwise most of it would be lost. The selection of the amount and placement of thermite to support demisability during re-entry is a difficult optimisation problem that could not be tackled in the context of the past studies and that needs to be addressed in the future.

5. OPTIMISE HEAT TRANSFER

It is well known that during the re-entry phase, the usage of the heat that could serve the purpose of triggering the fragmentation and demise of spacecraft is not often optimised. As a matter of fact, when designing a space mission, there are various other constraints that have to be taken into account to select a certain spacecraft architecture and configuration. In particular, previous missions that did not employ any D4D technology would often expose the most internal pieces of equipment to the heat flux when it was too late for them to be demised before reaching the ground. By achieving an earlier exposure, for example through the triggering of an earlier break-up of the external structure or of an early separation between different elements, the casualty area of each fragment could be greatly reduced.

5.1. Early break-up technologies

The earlier internal elements are exposed to the heat flux, the more they will demise. Therefore, various ways to achieve a so-called early break-up have been envisaged and investigated. Currently the break-up is observed to happen at an altitude of approximately 78 km. [25] investigated various option to increase the break-up altitude, such as composite inserts, Shape Memory Alloys (SMA) cylinder and bonded cleats. Some of these concepts are based on weakening the joints that hold together the various spacecraft panels, so that they will fail earlier on during the re-entry phase. SMA are materials that expand when heated up, and therefore could be triggered to apply a rupturing force on the joints that need to be broken during re-entry. Of course, all these concepts still have to guarantee the performances required for the launch and operational lifetime of the spacecraft. Composite inserts showed no gains in demise. Bonded cleats would provide a low cost solution, but showed small demisability gains. Demisable inserts in two parts and SMA cylinders were selected as the most promising technologies. The former is a simple replacement of the current insert technology. They do not store any energy themselves, but due to their enhanced melting process provide the chance for the forces present during the re-entry to separate the panels. They also have a low system impact and complexity. SMA cylinders expand when heated and therefore introduce a force to assist in the panel release. This concept has a high TRL, but also a high system impact. The increase of mass and cost was estimated to be proportional to number of joints.

However, it is important to notice that at current break-up altitudes the Multi-Layer Insulation (MLI) is usually significantly destroyed due to the mechanical forces, or to the interaction with atomic oxygen in the atmosphere during the mission lifetime and orbital decay phase. Therefore, it is acceptable to not consider its effect in current break-up simulations. However, when envisaging a break-up at higher altitudes, where the mechanical stresses on the spacecraft and the oxygen quantity in the atmosphere are lower, it must be taken into account that the MLI could still be in place. Its presence could prevent the heating of demisable joints or SMA actuators and thus the early break-up. For this reason, OHB is carrying out further tests to assess the impact of the MLI on the demisability process.

[9] investigated the behaviour of various kind of joints under re-entry conditions. The film adhesive used to connect sandwich panel facesheets to the honeycomb core are likely to peel relatively early, resulting in loss of structural stiffness. Therefore, panel failure is not a gradual melt, but a relatively fast process. The failure of Carbon Fiber Reinforced Polymer (CFRP) panels is expected to be delayed relative to aluminium equivalents, due to the high heat resistance and low in-depth conductivity of CFRP. Instead,Instead, the epoxy potted sandwich panel inserts have a slower failure of the joints, because the heat needs to soak in the epoxy potting material, which has very high failing temperatures. However, the inserts release from CFRP facesheets much more easily than from those constructed of aluminium. This is due to bending failures around the hole which may be induced by thermal stresses. An analysis of titanium bolts through aluminium brackets was also conducted. This kind of joints did not fail under the thermal stresses that were tested. However, the aluminium insert threads and the aluminium brackets both deform significantly by 3500° C. This induces loosening of the bolts, which could result in substantial loads being applied in a dynamic environment. TAS-I has investigated more in detail the concept of a demisable washer, built in a material that would reach its melting point earlier than traditional alternatives and earlier than

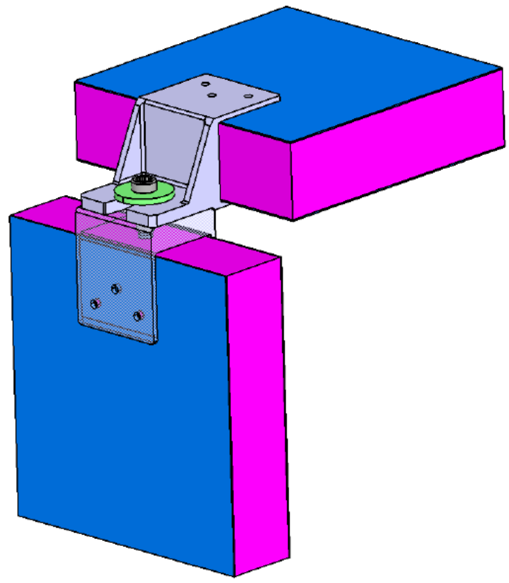

Figure 4. Demisable joint [18].

the other joint assembly items. Near its melting temperature, the washer structural performances are very low, thus it can be either broken by the structural loads, or disintegrated by ablation. Once the washer has demised, the cleats can have a mutual shift, due to the proper hole in one of them, eventually leading to the joint dismantlement. The demisable joint is shown in Fig. 4.

The SMA dismantle mechanism were also investigated by [4] and [6]. The concept that were proposed are:

- The SMA washers used to get frangible screws complied with all the requirements (high temperature requirement for passive capability, heaters, and thermal sensors for active capability). They were also very easy to manage, very versatile and they had the lowest development risk.
- SMA inserts to release the screws from inside panel inserts were the most innovative and efficient compromise for panel release. Certain temperatures in the dedicated inserts could achieve screws release. This solution could fit the usual panel inserts and eventually be removable and replaceable. However, it needed to be demonstrated with tests and was linked to development risks.
- SMA cutting cords constituted a concept that had the capability to break structural parts, but required further investigation. Moreover, it was the least mass efficient solution of the ones available.
- SMA Sleeve could be used to dismantle struts, bars, booms for external appendages or Payload modules. It was proved that this concept could work for most applications. It was recognised that the sizing of the

elements shall be design to low-level stress inside SMA.

The first two concepts were identified as the most promising. The materials that could have been used for the various SMA concepts were categorised depending on their activation temperature: low temperature (Ti-Ni), high temperature (AlCu-X), very high temperature (TiNi-X). AlCu-X resulted to be the most suitable for the various temperature ranges required by different applications.

Reaction wheels In the context of [7] it was also assessed that the dismantlement or separation of the various components could enhance the demisability, but it is hard to perform. In particular, the separation of RW electronics increases the demisability. The dismantlement of the flywheel or of the core slightly improves demisability, but its feasibility is still to be confirmed, while the dismantlement of the internal core parts improves the demisability, but it is complex and hard to implement.

Balance masses In early studies, heavy balance masses were found to be prone to survive re-entry. A solution that was proposed by [19] was to develop layered balance masses. This concept would have been combined with a passive release system of the layers. According to their simulations, the balance masses would always completely demise if this was put into practice.

However, it must be remembered that balance masses are different for every mission and can normally be easily adapted. Therefore, for the time being, it was deemed to not be convenient to investigate further this demisability solution, since it would have not been generic and applicable to all cases.

5.2. Orefices, lattice structures

This kind of structure or holes could be included in the outer panels of a spacecraft to allow for the heat to reach the internal elements faster during the re-entry phase. Clearly, this should not compromise the structural properties of the spacecraft itself, which shall be able to successfully withstand various loads throughout its operational lifetime. This method has been proposed, but has never been further investigated.

6. MINIMISE CASUALTY AREA

Currently, the only method identified to minimise the casualty area without enhancing demise is containment. Indeed, this technique aims at reducing the number of fragments that will land, therefore reducing the overall casualty area, rather than reducing the individual casualty area of each one of them. However, reducing the total casualty area by keeping fragments together might result in an increment of the impact kinetic energy, possibly making it higher than the safety threshold (15J), therefore making re-entering debris dangerous. Thus, it will be important to further investigate potential benefits and implications of these techniques.

6.1. Containment

Unlike other techniques, containment does not seek to encourage components to demise, but instead to reduce the total casualty area due to undemised components. For some satellites, the casualty requirement can be met if all the undemisable debris lands as one item rather than several separate ones. Although implementation would not be easy, as rearranging the components to keep the critical ones together would affect the mass properties and thermal engineering, doing so could significantly reduce the total casualty area. As it was already anticipated, containment is usually applied to components for which more demisable alternatives have not been found yet, such as optical payload. Those include high melting temperature materials that cannot be changed due to its functional and performance requirements. Containment of fragments can be achieved in various ways. Some of them have been identified by [13] in the past and will be summarised in the following.

Containment box To avoid the separation of parts during the re-entry, an undemisable container could be used to keep the fragments together. This is a reliable method, that becomes especially useful when the undemisable components that have to be contained are normally close to each other, or already enclosed in a solid structure. Of course, the material of the containing housing needs to be undemisable as well, to retain its mechanical and structural properties even when exposed to the high fluxes of the re-entry phase. In the framework of previous studies, suitable materials that were identified were silicon carbide (SiC), carbon fibre-reinforced silicon carbide (C/SiC), carbon-carbon (C/C), and ablators such as Phenolic-Impregnated Carbon Ablator (PICA). A careful trade-off should be carried out to assess if the disadvantages of such materials with respect to their traditional counterparts, such as increased mass for the same structural property, are counterbalanced by their advantages. It must be remembered that such a containment method does not allow its internal pieces to be exposed to the heat flux, therefore guaranteeing with almost certainty that the whole box will reach the ground with an unchanged mass with respect to the operational phase of the spacecraft. Therefore the only parameters affecting the impact kinetic energy of the fragment are the release altitude and state vector.

Containment net Conversely, a containment method that takes advantage of the re-entry heat flux to reduce its overall mass is the usage of a net. However, nets

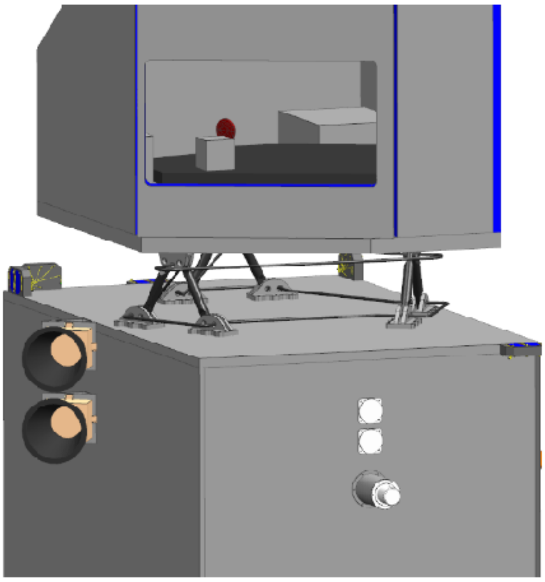

Figure 5. Containment tether [27].

present other design challenges. First, the mesh needs to be designed to ensure that no fragment will be allowed to escape it. Moreover, the net will need to sustain not only the high heat fluxes and stresses deriving from the re-entry descent, but also the mechanical stresses due to the movement of the fragments that it is containing. Testing the efficiency of a containment net in current re-entry simulators is not possible because of its shape and flexible behaviour. In general, assessing the demise of objects contained in a net will be quite challenging with current technologies.

Containment tether Another containment concept that presents certain similarities to the containment net is the containment tether. Indeed, the material of the tether could be similar to the one of the net. The advantage of using a tether is the same of using a net: in both cases the equipment that is contained is exposed to the flux, which means that the mass and area of the fragment reaching the ground will be minimised. The tether also has to survive the high heat flux and mechanical stresses of the re-entry, but presents an additional challenge. Indeed, the junction points of the tether to the various pieces of equipment shall be proved to be undemisable as well, otherwise the tether would fail its containment purpose. An visualisation of containment tether is showed in Fig. 5.

Undemisable joints These joints would aim at keeping together different pieces of equipment through a rigid link. The concept is similar to the one of the tether, but in this case no relative movement of the objects would be allowed during the re-entry.

Currently, some of the aforementioned techniques are being investigated by Thales Alenia Space and OHB.

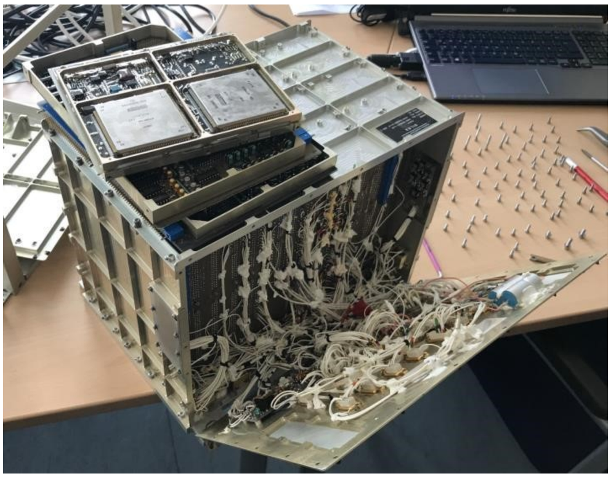

Figure 6. Electronics box with rear housing open showing backplane [8].

Optical payload Payload, and in particular optical instruments, have many design constraints that need to be fulfilled and that are hard to be transcended while applying D4D. Notably, some materials, such as ceramics, cannot be substituted at all which are needed because of their thermal stability, and the glasses and mirrors that are used for the lenses. A secondary challenge that has been identified when trying to apply D4D techniques to optical instruments within [26] is that the most undemisable component, such as ceramics and glass, are not well characterised. Indeed, the ceramic breakage is hard to predict, while glass can have a viscous behaviour that is difficult to model. Currently, the most promising method identified to minimise the casualty area without enhancing the demise is containment. This technique aims at reducing the number of fragments that will land, therefore reducing the overall casualty area, rather than reducing the individual casualty area of each one of them.

Other options that were taken into account but that were deemed to be less promising were design for fragmentation, *i.e.* divide lenses into multiple smaller components that shall easily separate during re-entry, and the usage of pyrotechnic devices, such as pyrobolts.

7. ONGOING RESEARCH

Since D4D is an evolving and fairly recent field, not all the technologies that have been identified as critical in the past have been already investigated. In particular, D4D technologies have not already been applied to all of them, because further investigations were needed to better understand their demise and fragmentation processes.

Driving mechanisms Large mechanisms are often made out of steel and titanium because of load and stiffness requirements, and are therefore hard to demise. In

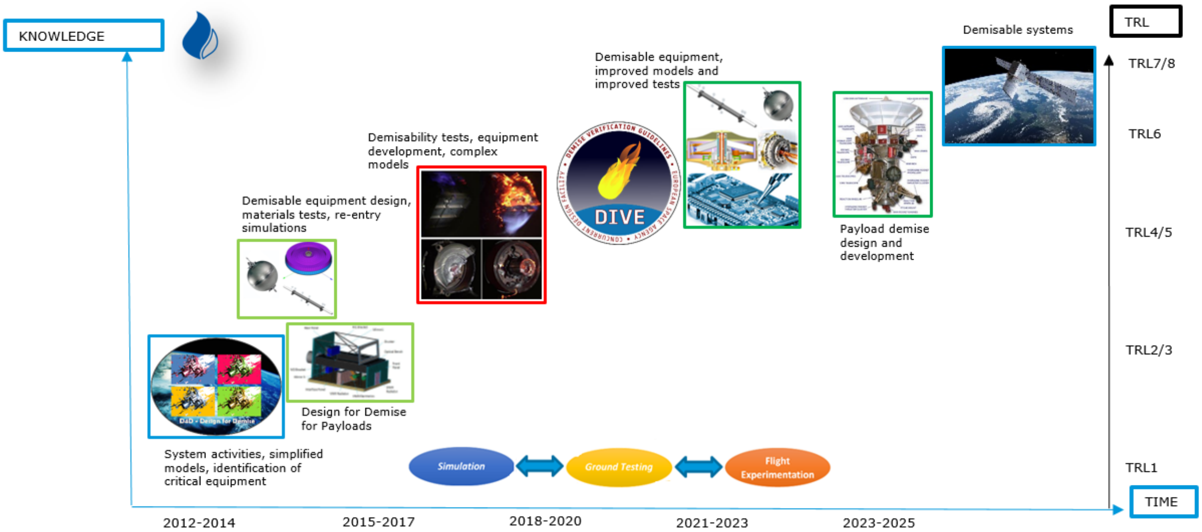

Figure 7. D4D knowledge and technologies evolution timeline.

the past, driving mechanisms and in particular Solar Arrays Driving Mechanism (SADM), were identified as critical because they contained such critical materials.

Two main kinds of SADM can be distinguished: the ones that allow for continuous rotation and the ones that do not allow it. Both can rotate for 360°, but one can keep on rotating whereas the other needs to rotate back during eclipse. The difference is that continuous rotation requires a slipring, while the other option uses a twist capsule or cable wrap. The SADM allowing for continuous rotation may be harder to demise, due to the slipring materials and due to their higher complexity and mass. However, the missions that include the continuous rotation SADM are usually heavy and could therefore not be able to perform uncontrolled re-entry even if a demisable SADM alternative was available. Lastly, many Radar Earth observation missions exploit a dawn-dusk orbit and do not even require a SADM. In any case, a more demisable SADM may be useful or needed for a restricted number of applications.

The SADM has one external face, but the rest is inside the spacecraft and often attached at the end. Despite having a great amount of harness holding it, it could potentially be ripped out when the solar array detaches from the spacecraft.

Considering that different kind of SADM exists, it is still hard to draw conclusions that are applicable to all of them. Studies of the past, such as [21], reported that a SADM would demise only if released above the usual chosen threshold altitude of 78 km. Another demisability assessment of SADM is currently being carried out by KDA.

Platform optics and electronic equipment With state-of-the-art knowledge, equipment such as Star Trackers, Remote Interface Unit (RIU), Power Control and Distribution Unit (PCDU) and batteries are elements of great uncertainty and for which the demise models need to be matured and validated. It has been identified a need for a better characterisation of the fragmentation and demise process of critical equipment, through tests and simulations. If necessary, further studies could be conducted to propose design changes to improve the demise of these equipment and to develop models to evaluate and verify their impact. An electronic box can be visualised in Fig. 6.

In particular, batteries were already analysed in the past. The assessment of the battery demise initially suggested that they were a critical item, but a refined analysis inclusive of fragmentation to cells resulted in complete demise. [8] suggests that the key aspect of the demisability is the failure of the Glass Fiber Reinforced Polymer (GFRP) material which contains the cell packs in the batteries. Where this is predicted to fail, there is no obvious physical reason why the fragmentation to cells should not occur. To guarantee this, the break-up process should be studied in more detail.

The same holds for star trackers, which traditionally have been always modelled as Aluminium boxes. Clearly, this is not representative of the parts of the star tracker which are known to possibly be critical: the lenses and any Titanium insert.

8. CONCLUSIONS

Design for Demise is a topic that is becoming increasingly important because it allows to decrease the casualty risk and eventually perform uncontrolled re-entry, with a great potential for cost savings. In particular, since the population density is expected to increase in the next years, a lower total casualty area threshold will be allowed to be compliant with the on-ground casualty risk requirement. Therefore, design changes of the spacecraft hardware resulting in a safer re-entry will become crucial in the future.

For these reasons, ESA has been supporting various research and development activities that are aiming at improving the current understanding of the demise and fragmentation phenomena, the accuracy of the re-entry predictions models and therefore investigating, applying and verifying design for demise techniques and technologies. In particular, techniques at system and equipment level have been applied and the resulting state-of-the-art technologies have been described in this paper.

In the past, system activities were first carried out to better understand the criticalities linked to the re-entry phase. Then, demisability concepts have been proposed. Some of them are currently being tested on-ground and further investigated. This has resulted in the publication of [14], the Demise Verification Guidelines. In the future, improved models and testing methods will be available and will allow to develop even more demisable established technologies, leading to an increase in their use. It has been recognised that D4D still needs further developments, in terms of guidelines, established verification methodology and technology development and usage. For this reason, ESA has been working on a D4D Guidelines Handbook, that will be published in the short future. An envisaged timeline for the Design for Demise knowledge and technologies evolution is represented in Fig. 7.

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