INDUSTRY PROCESSES FOR SPACE DEBRIS MITIGATION IN EARLY MISSION DEFINITION FOR LEO SATELLITES: CURRENT STATE AND ROOM FOR IMPROVEMENT

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ABSTRACT

In the early phases of a satellite design project, there are still a lot of uncertainties in dealing with Space Debris Mitigation (SDM) regulations. Requirements on space debris mitigation (in particular the implementation of ISO 24113) are a driver for the spacecraft design. The following requirements specifically pose a challenge to manufacturers of medium and large LEO satellites:

- Requirement for removal from protected region within 25 years
- Requirement on maximum ground casualty risk
- Requirement for passivation of on-board energy

In the past, these issues did often not receive sufficient attention (or were even not considered) in the early definition phase leading in some cases to significant system modifications and resulting development costs later in the project.

This paper aims to summarise the current processes in place to deal with space debris mitigation requirement compliance for LEO satellites and highlight the areas with potential for improvement. The overarching goal is to allow an early needs assessment for the mission by filling identified gaps in knowledge, tools and standardisation. A specific aspect discussed in the paper is how to integrate early SDM planning in concurrent engineering processes. In particular, a very early evaluation of casualty risk will be beneficial as it is a driving factor for the design of the propulsion system.

1 INTRODUCTION

Space debris is a problem that the space community has been aware of at least since Donald Kessler's work in the 1970s [1]. However, only the last decade has seen big strides in standardisation and framework agreements to ensure ensure future space missions do not add to the problem. Now it has become common practice to apply space debris mitigation requirements to any new mission [2,3].

For large system integrators (LSIs) this change has brought with it some challenges. While the requirements themselves are relatively clear, how to achieve them and how to verify compliance to them is everything but clear.

Two years ago ESA responded to this uncertainty and issued a handbook for space debris mitigation compliance verification [4] which could answer some of the questions arisen from the requirements but also created some new problems and areas needing clarification.

From industry perspective there these can be described as:

- Lack of common standards
- Knowledge gaps
- Technology development gaps
- Unclear/unnecessary requirements

Lack of standards result in each industrial player developing their own set of standard procedures to ensure compliance of future space missions where these answers are not, or not sufficiently, given by the ESA handbook. The areas most urgently needing further definition are addressed in this paper.

Lack of knowledge gaps leads to too conservative – or conversely not conservative enough – approaches used in the modelling of certain risks and the planning of necessary manoeuvres. It also means that some techniques that could reduce the cost of compliance are not considered, as too little is known about them, e.g. semi-controlled re-entry. This paper addresses some of the most important knowledge gaps.

Technology gaps likewise mean that some techniques for space debris mitigation cannot be applied due to their low TRL. In the development of a spacecraft the number of components that require some technology qualification are minimised to reduce risks and cost. Thus, spacecraft designers often choose well tried methods and technologies over more promising new developments. These gaps are currently being addressed by ESA in the frame of the CleanSpace program. This paper aims to add an overview of the most significant technology gaps, i.e. the technologies that are estimated to make the biggest impact on the design processes when they are closed.

Finally, some requirements are in themselves problematic. In particular, the passivation requirement is seen as difficult. It is discussed in section 4 of this paper.

All findings are summarised in the conclusions.

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SDM PROCESSES

1.1 Current Process

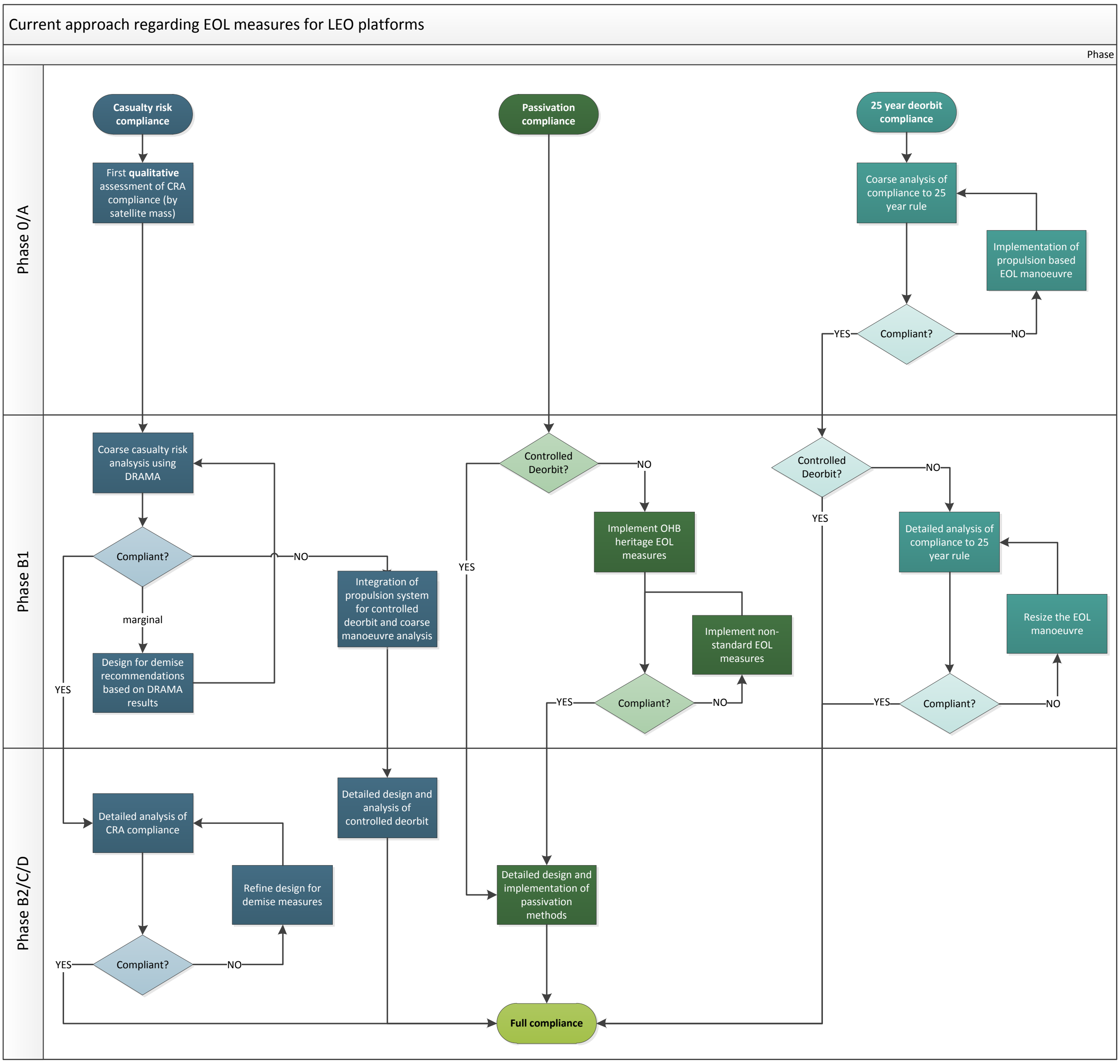

Figure 1: Current SDM process

The above figure shows the current approach to assessing and ensuring SDM compliance for LEO platforms at OHB. It can be seen that the three main areas of SDM requirements are assessed separately.

The diagram has been split into the different design phases of a mission. Currently, only the 25 years in orbit are quantitatively assessed in **Phase 0/A**. Passivation is not touched in this phase. While the casualty risk is considered in Phase 0/A, it is usually only judged qualitatively based on the total satellite mass and key components to estimate if a controlled re-entry may be necessary.

In **Phase B1** most of the SDM compliance design work is performed. For the casualty risk compliance this involves an object oriented casualty risk analysis (using DRAMA or similar). Upon these analysis results the re-entry strategy is chosen. For compliance or marginal compliance a passive re-entry approach is chosen and some design for demise measures identified. This is currently mainly focussed on the resizing of structural elements to increase demisability. In case of clear non-compliance to the casualty risk requirement, a controlled re-entry system is now designed and the manoeuvre analysed coarsely. Passivation is only necessary in the case of an uncontrolled re-entry.

In Phase B1 initially OHB standard measures for the passivation are applied. This is then discussed with the customer and if found insufficient, non-standard measures are assessed.

For the 25 year in orbit, a more detailed analysis is performed.

In **Phase B2/C/D** any design measures and analyses for SDM compliance are refined. It is not expected that the fundamental methods of SDM compliance (controlled vs uncontrolled re-entry, method of deorbit, etc.) need to be changed in this phase.

1.2 Future Process

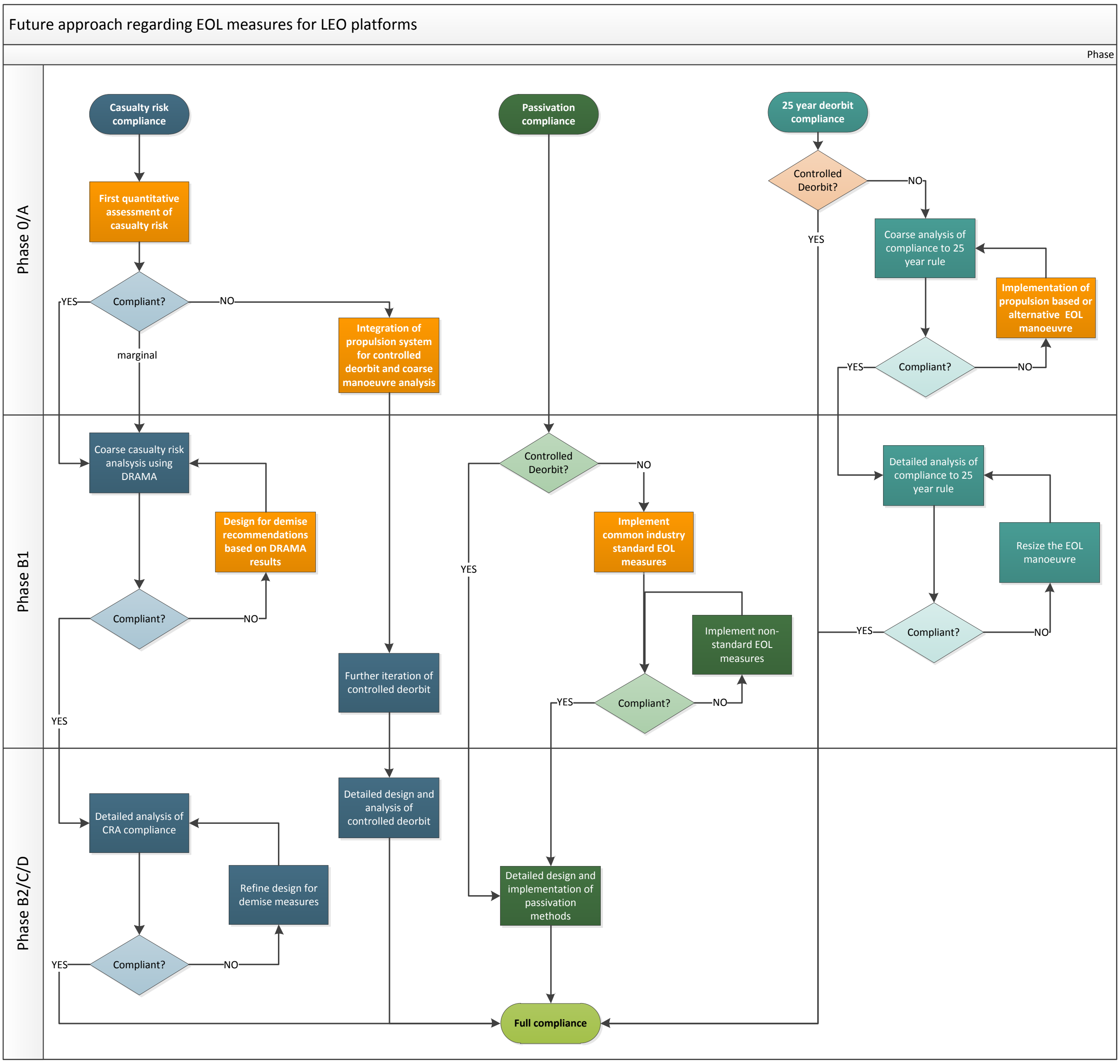

Figure 2: Desired future SDM process

The above figure shows an improved future process for the assessment and assurance of SDM compliance of LEO platforms at OHB. This new process can be enabled by technology development, research and standardisation activities suggested in this paper. The boxes highlighted in orange are new compared to the state-of-the art above.

For the assessment of **casualty risk**, a better understanding of survivability of satellite components and better standards for the assessment of casualty risk would enable a quantitative analysis in Phase 0/A. This would significantly improve the early design process as a decision on controlled/uncontrolled deorbit can be performed far earlier in the mission design timeline.

Novel **controlled deorbit** technologies and strategies can be considered if the satellite is not compliant to the casualty risk requirement. These methods can be implemented in the satellite design in Phase 0/A already avoiding a redesign in Phase B.

For an uncontrolled deorbit, new standard **design-for-demise** technologies can be implemented to increase the demisability of the spacecraft and decrease risk on ground.

In the **passivation** design procedure industry-wide standards for passivation implemented at component and subsystem level help to ensure system compliance. Non-standard measures will only be necessary in the case of non-standard components.

As the decision on controlled vs uncontrolled deorbit is taken already in Phase 0/A, the **25 years in orbit** compliance needs only be assessed if an uncontrolled deorbit is chosen. In this case a new range of novel methods for lifetime reduction can be considered to be included in the spacecraft design to ensure compliance.

The next chapters discuss the proposed activities, developments and areas of research to improve the satellite design processes

2 SATELLITE REMOVAL

In this section the knowledge, standardisation and technology gaps to improve the satellite design process to ensure compliance to the 25 year requirement are discussed.

2.1 Passive Orbital Decay

Passive orbit removal makes use of the orbit perturbations in particular aerodynamic drag to deorbit within 25 years after the end of operations and without requiring further actions. This method is the easiest to implement and also usually the cheapest method of orbit removal. It can only be used under the following conditions:

- The spacecraft is compliant to the on-ground casualty risk requirement
- The spacecraft is compliant to the passivation requirement
- The spacecraft meets the 25 year requirement

The first is a difficult to confirm condition in Phase 0/A as a reliable casualty risk analysis can only be performed when a detailed spacecraft design with component selection is available (typically in Phase B). However, a decision on the method of deorbiting is desired as early as possible due to the large impact on the spacecraft design if an active deorbiting system is required. See section 3.1 for a further discussion on the re-entry casualty risk assessment.

A compliance to passivation requirements can usually be ensured. However, there are still uncertainties on the methods and level of passivation as discussed in section 4 of this paper.

The 25 year requirement is a difficult to verify requirement too. This is because the atmospheric density is highly variable with solar activity and seasonal changes. Possible delays and extensions of the mission timeline can impact the time to deorbit massively. These can occur throughout the mission life – even after launch – but are particularly common in early design phases. One option would be to always use a worst case assumption (minimum solar energy in the beginning of the decay phase) but this can be too conservative. The semi-analytical tool STELA (CNES) [5] uses an averaged solar flux to make epoch independent estimates. This tool is accepted for ESA missions. [4]

If the 25 year requirement is not met there is an option to use on-board thrusters to lower the orbit perigee in order to reach compliance. A further option are deployable structures to increase the area-to-mass-ratio of the spacecraft and speed up decay. Although such devices have already been demonstrated in space [RDs] they are not yet considered standard practice for satellite designers. However, the right steps have been made in the last years to push this technology. At the same time, the range of missions that could benefit from the technology is limited to small satellite masses in low orbits. On medium and large satellites the system impacts become too high for a competitive solution. It is therefore of higher interest for manufacturers of small satellite.

2.2 Active Deorbit Manoeuvre

Under certain conditions an active deorbit manoeuvre is necessary – in particular if the casualty risk requirement cannot be met. If this is the case, this manoeuvre then often drives the satellite propulsion system design. The deorbit manoeuvre is typically performed in two steps.

In the first step the perigee is lowered over one to several orbits until the perigee altitude is as low as possible while the satellite can still be fully controlled and a rapid loss of apogee altitude due to drag does not occur within a time frame of weeks.

The final step is then a single deorbit thrust arc centred around apogee to lower the perigee from the safe altitude to below 50 km or further, depending on re-entry analyses. This final manoeuvre is often the driver for the minimum thrust of the propulsion system. Additionally the full manoeuvre adds a significant contribution to the delta-v budget in the order of 100 to 300 m/s.

Further requirements on the spacecraft accommodation can arise from this manoeuvre. For example it is advantageous to have the main thrusters pointing in anti-velocity direction when the spacecraft is in a near aero-stable attitude, so that the satellite does not have to perform attitude manoeuvres between the thrust arcs at apogee and the high drag regimes at perigee.

Different industry players will have developed their own approaches to the design and validation of active deorbit manoeuvres. These will certainly be similar in most aspects which can be described as common sense. However, there may well be significant differences in some of the details. It would therefore be welcome to define an industry standard approach to controlled deorbiting with guidelines on operations and re-entry perigee selection.

2.3 Semi-controlled Re-entry

Due to the space debris mitigation requirements the casualty risk for any re-entry event must remain below a given threshold whose value depends on the legislation considered. The traditional approach to this question was rather straightforward: If it was determined that an uncontrolled re-entry – being the cheaper solution – violates the casualty risk requirement, a controlled re-entry was necessary and implemented. In order to avoid complex and costly controlled re-entry strategies design-for-demise measures (see section 3.2) might have been investigated for some cases.

The approach of a semi-controlled re-entry in essence blurs the borders between controlled and uncontrolled re-entry solutions using elements of both strategies to find a compromise between effort and performance [6]. The resulting trade space is schematically visualised in Figure 3. The difference between the three types of re-entry is the ratio of number and size of fragments touching ground (defining the casualty area) to the size of the area over which they are spread, known as the impact area. The colour gradient indicates that there are no fix borders and that concepts might overlap in certain areas.

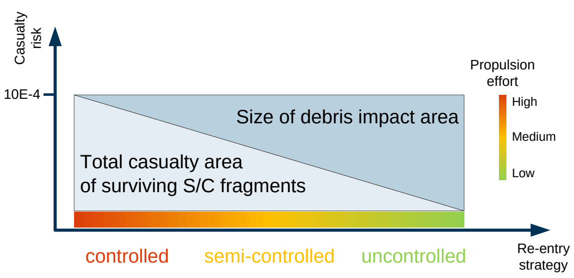

Figure 3: Schematic distinction between re-entry strategies

The concept of semi-controlled re-entry links the deorbit manoeuvre strategy to the demisability of the spacecraft. One cannot be chosen without the knowledge of the other. This makes a decision for either solution more complex due to the iterative nature of this design loop. However, this added effort to choose a semi-controlled strategy can pay out: A much cheaper solution could be achieved if a mission led to a change in launcher with a controlled re-entry and design-for-demise measures were not enough to allow an uncontrolled re-entry.

Currently too little is known about this method to be a standard tool in the satellite design process. The premise shows great promise, however, and it is hoped that these knowledge gaps can be filled within the near future.

2.4 Design for Removal

A wide variety of active debris removal studies currently on-going or have been completed in the recent past. A prominent example is ESA’s e.deorbit mission designed to deorbit ENVISAT. This target as well as many other ADR targets are by definition uncooperative. The e.deorbit study has shown that this fact is the largest driver for the chaser satellite design. Both GNC and capture mechanism are majorly driven by the target characteristics.

The concept of Design-for-removal (D4R) can be summarized as:

Increasing the reliability of (ADR) missions through the implementation of supporting technological means on potential target spacecraft.

These supporting technologies can facilitate different aspects of the ADR mission such as:

- The characterisation of the target state (i.e. position, attitude and corresponding rates)
- The approach and rendez-vous
- The capturing by several different kinds of capture mechanism (robotic, flexible, contactless)
- The stabilisation and de-orbit manoeuvres.
- More far-reaching approaches, e.g. by using some resources of the target spacecraft (fuel, attitude control, power, etc.) by remote control from the servicing spacecraft and transfer to it.

Of course, D4R concepts will need to be implemented on any satellite design. Ideally the space community can agree on common D4R standards allowing an ADR mission to efficiently remove multiple targets not necessarily belonging to the same operator. The D4R technologies should be selected taking into account results of ADR studies such as e.deorbit to understand which of them provide most benefits. At the same time they have to be simple, cheap and without large impacts on the host spacecraft.

3 UNCONTROLLED RE-ENTRY

3.1 Re-entry modelling

There are a large number of different tools available for re-entry modelling. These range from simple, easy to use tools such as ESA's DRAMA [7] to complex simulations such as HTG's SCARAB [8]. As the model of the spacecraft matures the tools used to assess its demisability become more advanced. The problem arises from the fact that a principle decision on passive versus active re-entry should be taken as early as possible in the satellite design due to the large design implications of this decision (see section 2.2).

It is suggested to work on the assembly of a **demisability database**. Such a database would contain demisability information (number of surviving fragments, surviving mass, impact area etc.) for different key platform components such as reaction wheels, magnetorquers, tanks, etc. of different sizes computed with a high fidelity tool, e.g. SCARAB. During the very early stages of the design process the resulting casualty areas can be added up like an additional design budget. For non-standard components like satellite structure and payload, a DRAMA analysis can be performed and also added to the budget. This would allow an early assessment with reasonably high fidelity. It is strongly advised that such a database be created and made available for public use.

An additional complication arises from the typical competitive situation during Phase 0/A/B1 phases. A desire to keep the mission cost low and to remain competitive does not motivate the satellite designers to use a very conservative approach to re-entry modelling. In combination with the modelling freedom of the early design this leads to the situation that detailed simulations in later phases cannot confirm the first results. The consequences include mission cost overruns and significant schedule delays because of the design-driving nature of this requirement. One possible solution would be to introduce more detailed standards for the demisability assessment or to subcontract the re-entry assessment to an uninvolved company.

3.2 Design for Demise

As briefly introduced above, design-for-demise (D4D) measures are design changes aiming at reducing the casualty area of satellite components in case of an uncontrolled re-entry. They can be implemented on multiple functional levels of the spacecraft:

- Mission level
- System level
- Subsystem level
- Component level

A distinction can be made between direct and indirect D4D technologies.

- Direct technologies modify an otherwise non-demisable component in order to make it demise.
- Indirect technologies modify a certain component in order to make another one demise or more likely to demise.

The suitability and chances for success of a given D4D technique strongly depend on the specific mission and spacecraft design. A standard recipe in the sense "How to reduce the casualty area of a satellite by X %" cannot be given. It is therefore important for a satellite manufacturer to build up expertise in the field of atmospheric re-entry and get access to latest simulation and test campaign results.

With the introduction of the casualty risk requirement a new system budget has evolved in the design of spacecraft – the casualty area budget. In order to be able to have a level of confidence as high as possible already in early development phases it is useful to include casualty area information in component datasheets. This goes beyond the characterisation of materials, but includes results of component-level demise analysis. One way of providing this information is for example by defining the minimum break-up altitude needed for a component to demise. Having such information available at system level would reduce modelling errors in early phases that in the worst case can lead to complete system design changes later on when it is discovered that a controlled re-entry is actually required for a particular mission.

Many of the indirect D4D technologies aim at an earlier release of difficult-to-demise components in order to increase the convective heat flux and the total heat received. For those techniques, studies that develop such components need to assess which release altitudes can be achieved. In a second order analysis a given release altitude could be characterised with an associated probability of successful release. This information in combination with the individual component demisability when released at different altitudes can provide a more precise casualty area budget. This is particularly important as the re-entry itself is a highly random process whose outcome is chaotic and fix values are easily misleading.

Denoting the casualty area for a given component *i* when released at altitude *h* as $A_{C,i}(h)$ and the probability of release for that component at altitude h as $P_{Rel}(h)$, the total casualty area for the satellite can be expressed as:

$$A_{C,Sat} = \sum_i \frac{\int_{h_1}^{h_2} A_{C,i}(h) P_{rel}(h) dh}{h_2 - h_1} \quad (1)$$

The goal for future D4D studies on component level should be to determine $A_{C,i}(h)$ as precisely as reasonable and for system level studies including indirect technologies to determine $P_{Rel}(h)$.

4 SATELLITE PASSIVATION

4.1 Propulsion Subsystem

4.1.1 Historic Survey

Before elaborating on the requirements and methods for propulsion system passivation it is interesting to examine historic break-up events in Figure 4 [9,10]. It becomes evident that the vast majority of propulsion caused break-ups are attributed to launcher upper stage failures. Satellite propulsion systems are the originator of only one known case, which is related to a solid motor. Hereof it may be deduced, that spending a high effort in satellite propulsion passivation will not improve the SDM problem significantly. However, a historic survey does not necessarily offer solid grounds for deducing future events.

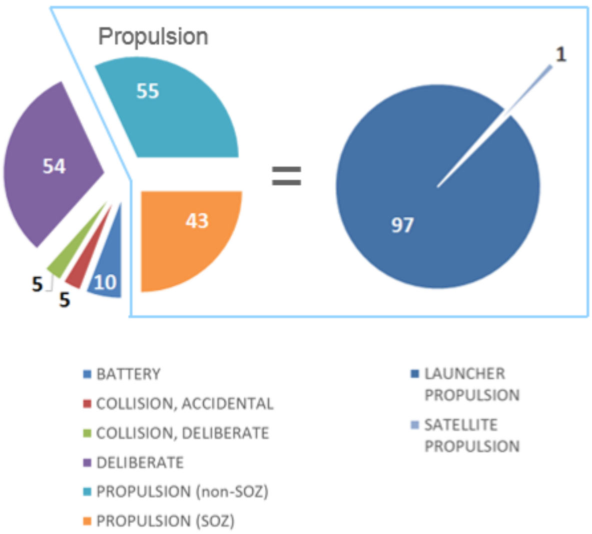

Figure 4: Survey of on-orbit fragmentation with confirmed causes

4.1.2 Key Requirements

The ruling standard is an ISO standard [2] being reflected completely or in parts by most national regulations. Its important requirements are '… shall permanently deplete or make safe all remaining on-board sources of stored energy…' and 'The probability of successful disposal of a spacecraft …shall be at least 0.9…'. The term 'disposal' includes the actions to be performed in the frame of the disposal, thus includes the propulsion passivation.

The important fact is that compliance to the first requirement can be achieved by two possible options. Either a depletion of all stored energy shall be performed or the safe state of the remaining energies on-board has to be proven. In both ways the successful disposal is required with a probability of 0.9. Demonstration of this probability is by analysis.

4.1.3 Methodology of Satellite Propulsion Passivation

Full depletion of the satellite propulsion system is not possible and a strong technical and cost driver. Thus, residuals of the depleted energy will remain resulting into the need to argue about the safe state of that residual. Consequently, it has to be argued in any case which amount or form of energy can be considered safe. Due to economic reasons it is anyhow the goal of a satellite operator to minimize the stored residuals to the maximum extent. Herewith, also the SDM goals might be already fulfilled. An important question to study critical conditions is how destructive different forms of energy are in terms of fragmentation and not so much the pure amount of energy left on-board.

The proposed methodology is in essence a space SDM compliance check. It applies a hierarchy to the relationship between both passivation approaches "make safe" and "deplete".

As discussed above, a "make safe" strategy is required to verify a safe behavior of any residual energy. A stable state (safe state) would be characterized by threshold design parameters applicable to the propulsion system. The logic behind the check is described in Figure 5. It shows the two approaches as boxes.

"Deplete" cannot verify safety. Its purpose is to mitigate risk factors. The outgoing path of this box therefore points back to the "make safe" box. The methodical path to fulfill the compliance check can include up to three sequential decision blocks:

- Fragmentation Probability
- Safety Verification
- Technology development

The first decision block is intended as a mission specific fragmentation risk review. The mission and satellite design are assessed for all applicable fragmentation causes. A root cause list is then evaluated based on the end of life strategy. Analysis for evaluation uses software tools to check margins.

For causes where the risk is above acceptable limits, or no model is available, threshold parameters are selected in a next step. They represent the border to a critical condition in the system that can trigger causes for a fragmentation. As such they act as design constraints to check the system against the remaining causes for fragmentation.

The next step splits the path to two possible blocks. It must be demonstrated that the energy in the system behaves safely by matching the safety thresholds against the technical limitations in the propulsion system. In this step, additional studies for the gas and propellant can also be performed to establish thresholds or confirm their applicability.

When confirmed that the hardware meets the conditions for safe storage, the passivation operations are confirmed and the path opens to successful passing of the compliance check in the next decision block. If not, additional operations are selected and a loop is closed.

The safety verification is triggered when verification of the safe reduction or of safe behavior of the residual energy cannot be demonstrated, i.e. the thresholds cannot be met. In this case, the passivation is improved by adding additional hardware, e.g. venting valves.

The closed loop runs through the "Deplete"-box to check the availability of identified hardware or request new developments and studies. The loop returns to the "Make Safe" box to confirm again the thresholds with the improved subsystem [9].

The above outlined methodology tries to solve the problem of SDM in a pragmatic and economic way. It avoids methods whose benefit is not significant for a reduction of collision risk. As outlined, deplete all energy may not improve the SDM situation at all. So, the make safe approach is always the preferred choice when designing a SDM compliant spacecraft.

We should keep in mind; "To make a difference with our actions against the threat of orbital debris, we must find the right priorities" [11]. "The greatest risk … is the onset of collisions between large objects" [12].

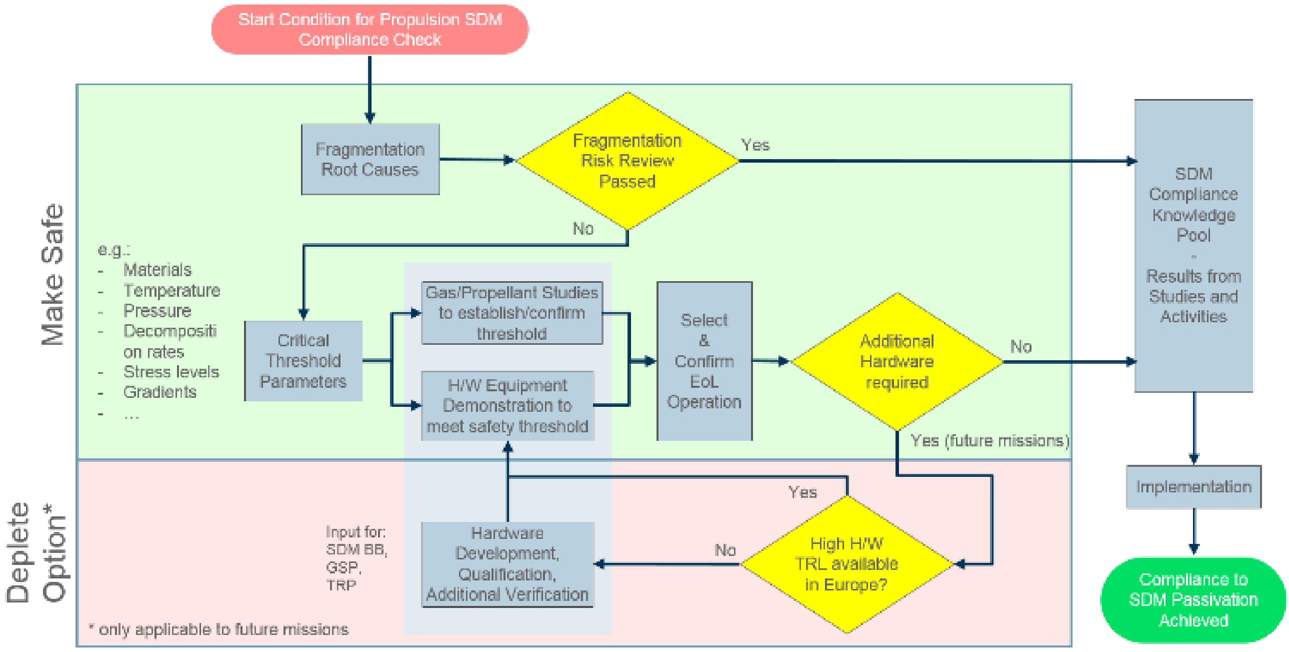

Figure 5: Space Debris Mitigation (SDM) propulsion compliance methodology

4.2 Electrical Subsystem

Passivation of the electrical subsystem concerns the batteries as source of stored electrical energy and the solar array as source of energy imported into the system. Passivation of the two types of components is today studied and implemented separately. Future technological developments aim at modifying the design of the Power Control and Distribution Unit (PCDU) in a way to include dedicated passivation circuits. This development cannot be achieved in the short term. Before this technology is available there are therefore certain standards to be agreed upon between agencies, operators and satellite manufacturers.

In the past there have been satellite break-ups caused by battery explosions. These can mostly be traced back to the use of old NiCd battery technology. Nonetheless, modern Li-ion technology is not safe from the risk of explosions. The question to be answered by testing is under which conditions a battery can be considered safe. Completely depleting electrical energy stored in a battery will likely result in an overdesign imposing more disadvantages to the system. The conditions

The passivation of the solar array can be achieved by disconnecting it from the power bus. The question to be answered by testing is whether this disconnection is safe throughout the time between passivation and re-entry. Safe means that no external influence (e.g. radiation) can cause a re-connection of the solar array. Such tests can be more or less complicated and expensive depending on the type of technology used for disconnection.

For both cases, batteries and solar arrays, tests will need to define environment and component conditions that make those components safe. It is then task of the satellite and mission designers to ensure that these conditions can be met continuously after satellite passivation.

5 SPACE DEBRIS MITIGATION IN CONCURRENT ENGINEERING

The introduction of SDM regulation into the frame of ECSS requirements has direct consequences on the design of satellites. As shown above these consequences need to be considered already in the earliest design phases. These early phases are often elaborated in concurrent engineering facilities. At OHB the CEFO (Concurrent Engineering Facility at OHB) is used from phase 0 throughout phase B1.

It is characteristic of concurrent engineering to iterate multi-disciplinary technical questions quickly. This way of working imposes constraints on analysis tools used in such facilities. They have to provide the useful answers quickly, with simple inputs and with a known limited error. ESA's DRAMA tool is a very good example for such a tool enabling a versed user to quickly assess compliance with the most important SDM requirements.

Yet, concurrent engineering is also always closely linked to automated data exchange and model based engineering approaches. Design information should be inter-exchangeable between different tools without much human intervention to eliminate a source of unnecessary error. In its current version DRAMA's main user interface requires manual inputs. Even simple concepts such as text input files are not supported.

In addition to the tool environment concurrent engineering relies heavily on the presence of technical experts. Many of the space debris requirements lead to multi-scale problems that are not easy to solve by simple answers. Therefore, team leaders and session organisers have to include space debris experts as part of the team. This way mission specific solutions can be found that create optimised results for a given mission. This is in particular important for designs that indicate to be on the borderline between two possible solutions (e.g. controlled or uncontrolled re-entry).

6 CONCLUSION

Current processes at OHB aim to reach space debris mitigation compliance at as early a development stage as possible. But this effort is hampered by certain gaps in standardisation, knowledge and technology.

The "25 years rule" is currently already considered at an early stage. The passive time until re-entry is determined using orbit simulations. If necessary, a perigee lowering or a direct re-entry manoeuvre is included. However, without the knowledge of a possible need for controlled re-entry, the wrong strategy for de-orbiting may be chosen. The most significant gap identified are:

- Standardised guidelines for operations and manoeuvre design for a controlled re-entry
- further evaluation of semi-controlled re-entry

The ground casualty risk is currently computed when sufficient detail at hardware level has been reached, typically at phase B1. This is clearly very late to drastically change the propulsion system if a need for controlled de-orbit is identified. On one hand, it is therefore desirable to perform the casualty risk analysis as early as possible. On the other hand, the level of detail required for simulations with spacecraft-oriented tools is only achieved at a point where design changes are very costly. Suggestions are made to move to an earlier meaningful first assessment of casualty risk by establishing casualty area as an additional budget. The most significant gaps identified are:

- Demisability database of standard platform components
- Technology development of demisable spacecraft components and system-level design-for-demise techniques

The passivation requirement leaves room for interpretation and is applied differently from project to project, often resulting in an identified need for delta verification. There is a clear need to define a common methodology to control and track the fragmentation risk. Currently, there is the tendency to passivate and deplete to the maximum extend, despite an unproven benefit for the fragmentation risk. It is suggested that commonly agreed realistic safety thresholds need to be established and be reflected in space industry guidelines and standards. These thresholds are especially important, since they strongly affect the passivation strategy and subsystem design. To summarise, the most significant gaps are:

- Update of the requirements to specify more clearly what is covered by the passivation requirement and to add realistic safety thresholds
- Standardised guidelines for spacecraft passivation

In conclusion, we are currently in the middle of a great change in spacecraft design driven by space debris mitigation compliance. The first mandatory requirements have been set forth but as of today every player is left to deal with them according to their own best judgement. To move further towards full compliance, common standards need to be established and certain knowledge and technology gaps closed. This way European industry can remain competitive while providing sustainable utilisation of space.

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