IMPACTS OF THE SPACE DEBRIS MITIGATION RULES ON THE SPACECRAFT DESIGN IN AIRBUS DEFENCE AND SPACE

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ABSTRACT

This paper addresses Airbus Defence and Space approach to Space Debris Mitigation (SDM) requirements with a global system perspective from requirements to design and operations. The first part provides a review of the main Space Debris Mitigation rules (ESA policy, French Space Operations Act) applicable to Airbus programs and their impact on the spacecraft design. The second part reviews the various studies and developments performed by Airbus Defence and Space to support the implementation of these Debris Mitigation requirements in the design of the future LEO and GEO satellites. All main topics are addressed: passivation needs and principles (fluidic and electric), design for demise techniques, re-orbitation and deorbitation strategies, re-entry simulations issues.

After designing satellites for 25 years, Daniel Briot is since 2015 the transnational coordinator for Space Debris mitigation topics in Airbus Defence and Space Earth Observation directorate.

1 SDM TOPICS IN AIRBUS DEFENCE AND SPACE

Airbus Defence and Space is actively involved in Space Debris Mitigation (SDM) issues since several years. In the 2000’s the first discussions occurred with the French ministry and CNES to elaborate the now existing French Space Operations Act (FSOA), called in French “Loi des Opérations Spatiales” (LOS), applicable to all French space operators. Since that several Airbus internal activities were carried out to prepare the answers to these new SDM requirements. In 2014 a first study was done with CNES to analyse the main SDM impacts on S/C designs. Since 2014 Airbus actively participates to the numerous studies managed by ESA through the Clean Space initiative. Some of the results of these studies are summarized in the next chapters.

Due to the increasing number of subjects, and the wide field of applications (LEO, GEO) a transnational SDM working group has been created in Airbus Defence and Space, with several objectives:

- Centralize and disseminate information (requirements, study results) in the 4 Airbus countries (France, Germany, United Kingdom, Spain)
- Provide expertise to the projects, to help identifying the most adequate answers to the SDM needs
- Provide harmonized Airbus position in the formal discussions with approval authorities (French LOS office, ESA safety office) and in the ECSS/ISO working groups

2 REVIEW OF THE MAIN SDM RULES

Space debris mitigation has been discussed at international level since the early 90’s and has led to the issuing of policies and laws at international and national level. Globally these laws impose safe satellite operation in orbit (no creation of debris, collision avoidance) and safe removal from the useful orbit domain (LEO and GEO) at the end of the mission (with “safe” re-entry).

Precise rules imposed by CNES and ESA are now applicable to Airbus satellites in development, with major impacts on the S/C design. The objective of this chapter is to summarize the main issues of these SDM requirements, to identify their potential impacts on the satellite.

2.1 French Space Operations Act (FSOA)

French space law (FSOA) has been issued at Ministry level in 2008, imposing safety rules for all space operations (launchers, satellites) under French operator responsibility. An independent LOS Office has been created in CNES to check the compliance to the law; to help industry the LOS office has then elaborated in a practical application rules (law is sometimes imprecise) through the “Guide des bonnes pratiques”.

Law entered into force in 2010, with a 2 steps approach in order to provide time to the industry to adapt their products to the new SDM requirements.

- all new SDM requirements will be fully applicable for launches after 1st January 2021
- in the meantime, French operators shall for the SDM topics, adopt a “best effort approach” (to be justified and discussed with the LOS office).

The French FSOA is demanding and on some topics currently more constraining than ESA/ECSS and ISO rules.

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

2.2 ESA policy

ESA issued a first space debris mitigation policy in 2008. This policy has been updated in 2014 (ESA/ADMIN/IPOL(2014)2), and is now applicable to all ESA space programs.

ESA policy calls ECSS-U-AS-10C specification and completes it (casualty risk < 10^{-4}): the ECSS itself is largely based itself on the ISO24113 standard.

All ESA projects, with SRR (System Requirements Review) held after 28th of March 2014, are required to fulfill new ESA IPOL (2014) policy on space debris.

A new "Independent Safety Office" has been recently created to guaranty that ESA projects will follow the new rules.

This Safety office has also issued a practical handbook of guidelines to cope with the new SDM requirement.

3 SUMMARY OF MAJOR ISSUES FOR LEO SATELLITES

The most impacting requirements are summarized in the following table (by order of potential impact). They are detailed in the next chapters.

Main issues	Impact
LEO Casualty risk < 10-4 (human severe injury or death)	Imposes the choice between : • uncontrolled re-entry • controlled re-entry (costly, and +8 to 10% additional S/C mass)
LEO **Reentry within 25 years** or reorbitation after the end of the operational phase	Impact on the propellant budget ⇨ additional spacecraft mass
LEO/GEO **Passivation** at the end of the operational phase	Need = no remaining energy reserve on board during disposal phase, to avoid generation of new debris through internal self-explosion or collision with existing debris • Electric passivation ⇨ no energy in battery • Fluidic passivation ⇨ no pressure in tank
LEO/GEO Probability of success of the disposal phase	New requirement in the French LOS update (0.85) • 0,80/0.85 achievable with classical redunded design (with standard reliability calculation rules, known to be pessimistic)

Note for GEO satellites: re-entry issue is less constraining than for LEO satellites, because re-entry occurs only in case of launcher failure. Main design impacts are: re-orbitation to get out the GEO area, electric and fluidic passivation.

4 RE-ENTRY AND RE-ORBITATION SOLUTIONS

The most constraining new SDM requirement concerns the re-entry of LEO spacecraft.

The requirement objective is to free rapidly and safely the LEO protected region (altitude below 2000km). The S/C shall get out of the LEO useful altitude range in less than 25 years, either by falling down, and either by climbing up to the stable disposal orbit (circular 2000km altitude). Choice depends on the mission nominal altitude. As an example, the typical values from a 700km circular orbit and S/C shape like SPOT-6 or Pleiades are the following:

- Uncontrolled re-entry in < 25 years : done by perigee decrease as low as 550km ⇨ required ΔV about 50 m/sec
- Altitude increase up to 2000km disposal orbit ⇨ huge ΔV required = about 600 m/sec from 700km. Solution feasible only for high altitude missions (above 1350 km altitude)
- Controlled re-entry: specific large manoeuvres to fall down in the SPOUA (South Pacific Ocean Unhabited Area»). This is done in 2 steps: decreasing of perigee altitude to about 240 km in several short manoeuvres (ΔV 130m/s), then strong single final burst (ΔV 70m/s) to fall in the SPOUA. This requires a very high thrust level (typically > 80N) and a total of about 200m/s : these are very demanding needs on propulsion design, marginally feasible for classical 800-1000kg smallsats, feasible on large satellites

5 CASUALTY RISK AND DEBRIS ISSUES

5.1 Definitions and requirement

The human casualty risk (risk of severe injury or death) is defined as follows:

Casualty risk= Casualty Area x Mean population density

The casualty area (CA) is the total dangerous area impacted by debris itself; the CA is calculated by the following formula which considers the size of the debris but also the size of a human body (normalized to a circle of 0.36m²)

$$\text{Casualty area} = \sum (0.6+\sqrt{A_i})^2$$

where Ai is the physical area of each debris with kinetic energy above 15J.

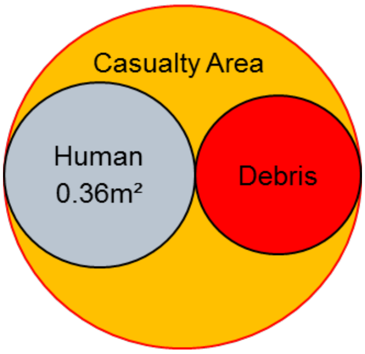

Figure 1: Casualty area (CA) definition

The 15J energy limit corresponds roughly to a debris mass between 30g-50g only (typical impact velocity is 100-120km/h depending on the debris ballistic shape).

Even such a small piece > 15J has a casualty area of at least 0.36m² whatever its size (1/15th of the satellite allocation).

Currently ESA and CNES proposed methods have slight differences, in the way to calculate the debris physical area on ground (average area of the 3 sides vs maximum area side for a box for example) and in the population density values for after 2030 (about 7% difference in 2050).

At the end the 10^{-4} limit for the casualty risk for re-entry in year 2050 (polar orbit) corresponds to a maximum casualty area of 6.5 m² (FSOA) or 7.3m² (ESA). Both values are very small, and are reached:

- with about only 15 small debris
- a few debris of 0.5m²
- one single large debris of 4m²

5.2 Debris evaluation

Debris evaluation is done through the use of re-entry simulation tools that calculate ablation of the satellite components during re-entry and provide remaining debris characteristics (mass after ablation, impact velocity).

Most frequently used tools by industry are DEBRISK (CNES), DRAMA (ESA) and DAS (NASA). All these tools are reference tools provided to the industry by Agencies to do first level assessment. These tools are called object-oriented tools, because the satellite is modelled as elementary elements (objects) that are all separated at the same time at a chosen fragmentation altitude (reference is 78km).

In Airbus the most frequently used tools are DEBRISK and DRAMA. DAS is used occasionally.

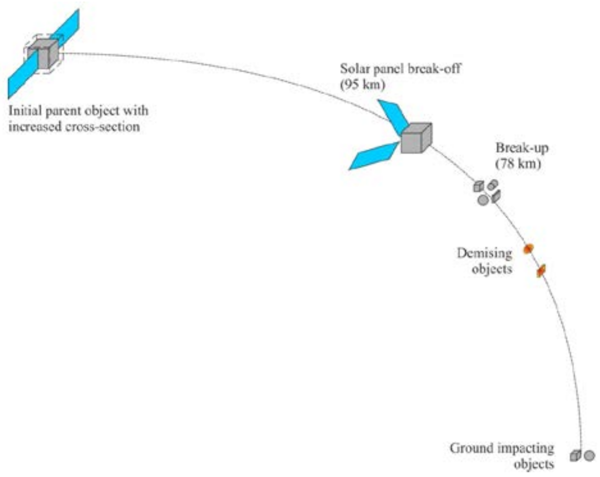

Figure 2: DRAMA/SESAM break-up process

Pieces of structure, main electronic units, pieces of payload (mirrors, antennas…) are all modelled independently, by one of the following available shape (box, sphere, closed cylinder, disk...). Tools calculate heat fluxes during re-entry of each object which depend on its ballistic coefficient (mass and shape ratio), and evaluates the progressive ablation of the object (that depend on the melting point temperature of the object material).

More complex and powerful tools exist also, but are not directly available to manufacturers:

- the SCARAB tool, proprietary of HTG company. This tool allows a complete 3D modelling of the whole spacecraft. This tool requires a complex (and relatively costly) modelling and is then not done at the beginning of the design. This tool is mainly used for ESA projects, to complete or confirm the first level DRAMA results.
- The PAMPERO tool, used by CNES for 3D modelling of complex objects. This tool is still under development and is used to validate DEBRISK evolutions.
- CFD (Computational Fluid Dynamics) tools that do the real Fluid dynamics calculations. However these tools are extremely complex, and are used only for local and short calculations for correlating simpler tools.

5.3 Simulation results: classical debris with current satellite design

Classical critical items (remaining debris) are usually built in materials with melting temperature over typically 1200-1500°C (the exact limit depends on the shape/density of the item, that impact the item velocity during re-entry and then the aerothermal fluxes).

Critical materials are then:

- Metals like Titanium, Invar, Stainless steel, Tungsten
- Optical glasses (like Zerodur) and Ceramics used in the optical payloads

Typical debris found in simulations are the following:

- Titanium tanks (whatever their size)
- large Titanium or Invar parts (e.g. brackets): on the contrary small titanium pieces like bolts do not re-enter (or are below the 15J limit)
- large Stainless steel parts (like balance masses)
- large actuators in steel alloy (flywheel of reaction wheels)
- large magnetorquers
- large pieces of optical glasses
- pieces in Ceramics

6 DESIGN FOR DEMISE (D4D) APPROACH

"Design for Demise" (D4D) is a specific design approach aiming at increasing the destruction of critical units during re-entry, either by modifying the unit itself (change of shape, change of material), either by increasing the heat flux on these critical units (modifications at satellite level).

6.1 D4D at unit level

The first solution to reduce the number of debris is to avoid the use of high temperature materials, like Titanium, Invar, and stainless steel.

Several studies have been done recently in the frame of the ESA CleanSat Building Blocks study. The most promising solutions identified today are the following:

<u>Tank (low pressure)</u>

Aluminium tank shell instead of Titanium: the tank demisability is guaranteed in that case. The main drawback (usually acceptable) is a mass penalty of a few kgs.

<u>Tanks (high pressure)</u>

COPV (Carbon Overwrapped Pressure Vessels) tanks for pressures up to 200bars, with aluminium shell instead of titanium shell: the main drawback is that despite the aluminium use, the demisability is not complete. The aluminium shell will melt but the Carbon fibres will not demise. Aluminium shall largely disappear, and the carbon fibres shell will probably collapse. Even if above the 15J limit, the final "soft" debris will be much less dangerous that the equivalent tank with steel shell.

<u>Reaction wheel (RW)</u>

Use of aluminium instead of stainless steel for the RW flywheel: demisability of the RW is largely improved. The main drawback is the larger volume required to have the same inertia with aluminium instead or steel. For the same RW volume, there is several % inertia loss (probably acceptable in several cases).

<u>Magnetorquers</u> (MTQ)

Some interesting modifications (material, shape) are proposed to have full demisable MTQ, even the large ones.

<u>Balance masses</u>

Instead of having a monolithic block of steel, solutions with several thin sheets glued or fixed together can be used.

<u>Additive Layer manufacturing (ALM)</u>

Another solution to improve the demisability of some structure supports is the use of ALM: this technology allows the manufacturing of complex shapes with less raw material. This is an interesting way to limit the use of critical materials.

6.2 D4D at satellite level

A system solution is to increase the heat flux on critical units, either by modifying their implementation in the platform (to less protected locations), or by voluntary exposing the using during the re-entry phase. This has been studied in detail in the "System Design for Demise" study carried out by Airbus for ESA in the 2 past years.

<u>Accommodation of critical units</u>

The idea is simply to implement critical items that demise not completely (RW, MTQ) close to the heat flux: for example implementing RW deep inside the platform under several units and the tank, shall be avoided. Implementing such units directly outside the platform is also conceivable, despite higher radiation levels and more complex thermal control.

<u>Platform opening or early breakup</u>

A more complex, but probably more efficient D4D technique is to voluntary increase the heat flux on critical units by opening the platform panels or by breaking the structure in several parts: this can be done actively at the end of life (just before passivation), or passively through devices actuated by temperature increase during the re-entry, like Shape Memory Alloys (SMA) devices.

Both solutions are promising but require the development of adapted devices, and require strong satellite redesign: structure, but also harness routing and thermal blankets design (to ease structure opening).

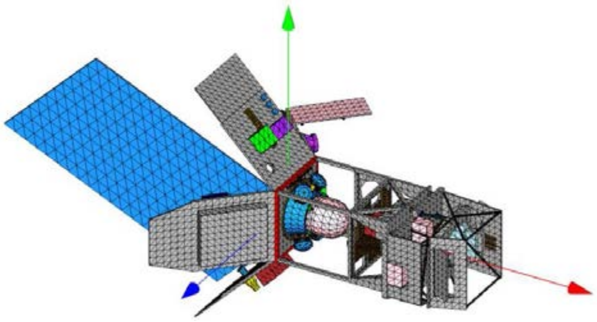

Figure 3: Illustration of side panels opening (SCARAB model)

Use of D4D techniques: when?

D4D techniques are useful for satellite with uncontrolled re-entry.

Currently, because optical payloads create a large level of debris, the focus has to be put on payload demisability improvement. Modifying platform elements for optical missions is not sufficient. Today, for large optical satellite (1 ton range) the only short term solution is the satellite controlled re-entry.

For satellites with non-optical payloads, improving the demisability of platform units is very useful.

The cost of complex D4D techniques shall be compared to the cost of the controlled re-entry. For some missions, if the launcher limit is not a problem, the controlled re-entry will be preferred because all the S/C design will be designed without compromising the performance through the use of less stable materials.

7 SPACECRAFT PASSIVATION

7.1 Introduction

The requirement is to leave the satellite with no "dangerous" remaining energy reserve on board (electric, pressure, mechanical energy (rotating parts)) during the disposal phase (< 25 years for LEO, > 100 years for GEO). Current design cannot achieve that goal completely: specific passivation devices have to be developed and embarked.

However the exact requirement formulation is "to deplete or make safe". The "make safe" option opens the door to a nearly complete passivation.

7.2 Criteria for selecting a passivation device

The complete passivation, electric or fluidic, necessitates additional new passivation devices. But these devices can, in case of failure, kill the mission. Consequently the main criteria for the design of passivation devices are:

1st: safety

- actuation through 2 separate orders (arm, fire) from the spacecraft
- single failure tolerant (no single failure shall activate the device)

2nd: reliability

- Probability of successful activation after 10 to 20 years in orbit shall be in the range of 0.95 or more (to cope with the S/C global disposal success probability of 0.85)

7.3 Fluidic passivation

The requirement is to have no dangerous energy in tanks, i.e. no pressure, for propellant and pressurant, during the disposal phase. Airbus has carried out a detailed Propulsion passivation study in 2015-2016 for ESA. The main outcomes are the following:

Complete fluidic passivation (with passivation device)

This can be achieved through the use of additional specific passivation device that will put tanks/piping to vacuum at the end-of-life.

Several solutions are under development:

- Pyrovalve (PV) with extended lifetime: classical PVs are usually used beginning of life. Their current lifetime is then limited to a few years and is not compatible with the passivation that occurs after 10 years (LEO) or 20 years (GEO) in orbit. Different PV lifetime tests are currently on-going.
- CNES micro-perforator: this pyro device, developed initially for pressurant lines, is currently under lifetime test (no criticality foreseen). Use of this device on propellant lines is not yet qualified.
- Shape memory alloy valves: this non-pyro device has no major lifetime concerns. An SMA element will expend under temperature increase and break locally the piping. One main advantage of such solution is the slow process (a few minutes) involved during device actuation. In case of failure or unwanted actuation, an independent look at the local temperature increase can identify the error and the S/C software can then automatically trigger the power line shut off. This is an additional security compared to instantaneous pyro devices.

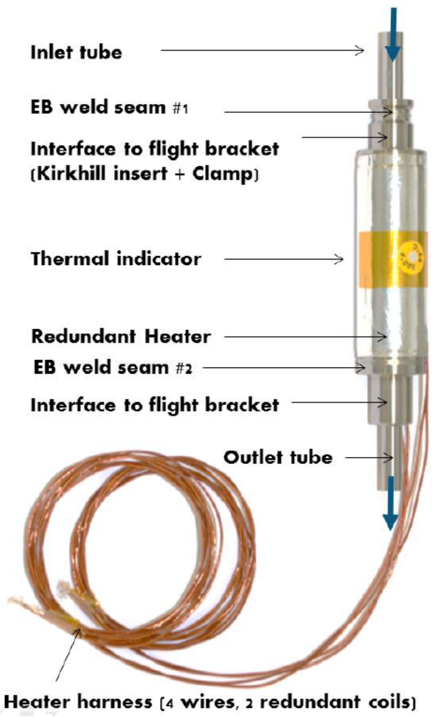

Figure 4: Airbus Safran Launchers SMA valve

Acceptability of the partial passivation through thrusters

With current designs (without dedicated passivation device), the only solution is the use of the thrusters. Depending on the propulsion system design, the achieved passivation is more or less complete.

<u>Tanks without membrane</u>

For tanks without membrane (like PM22 of AS250), propellant and pressurant can be emptied through the use of the thrusters. After numerous thrusts it is possible to achieve a final pressure far below the classical limit of 5.5 bars recommended by thruster suppliers. Even at low pressure, with incomplete combustion, propellant and gas are expulsed despite the use of the thrusters outside their qualification range. The final pressure is less than 1 bar.

During this passivation, thrusts shall have short durations because thrusters eject a mix of hydrazine and Helium creating thrust variations and then satellite instability (AOCS control concern). This may lead to long operations (due to huge number of small thrusts).

The final remaining pressure is very low, and the residuals very limited

- about 1% of the propellant capacity for LEO tanks
- about 0.5% for large GEO tanks

However this small amount of propellant could evaporate and dissociate during the disposal phase, due to the possible high temperature of the tank during the disposal phase (thermal blankets will degrade). Dissociation of propellants (into lighter molecules) depends on the propellant type: decomposition ratio is between 1 and 2.

For a LEO S/C, with the tank at 100°C, the pressure inside the tank can reach 25 bars. This is under the burst pressure (so no self-explosion), but the tank could explode under hyper velocity impact with debris. The situation is not completely safe (however the collision probability is small).

For a GEO S/C, with the tank at 100°C, the pressure inside the tank can reach only a few bars (<5 bars): this is clearly a very safe situation.

<u>Tanks with membrane</u>

The propellant emptying is done through numerous thrusts, up to the 5.5 bars limit.

Pressurant emptying is partially achieved through membrane, due to membrane porosity.

7.4 Electric passivation

The requirement is to have no remaining energy in the battery, whatever the satellite attitude during disposal phase. For Airbus, the preferred solution is to cut the line between the Solar Array (SA) and the battery.

This was not possible with existing designs like AS250 avionics (with a direct line between SA, PCDU and battery).

PCDU upgrades (with internal SA switch) are under implementation for all current AstroBus products line: AstroBus Small, AstroBus Medium and AstroBus Large (e.g. AS400 PCDU used on MetOp-SG).

8 CONCLUSIONS

Debris mitigation is an important issue to be considered in the early phases of the design (e.g. phase A) of a spacecraft, due to high potential impacts. Most critical issues are for LEO S/C, in particular for the casualty risk requirement, leading in some cases to the need of the demanding controlled re-entry. The summary of the main impacts of these SDM requirements on the LEO S/C design are recalled in the following figure 5.

Airbus Defence and Space has fully integrated all the new SDM requirements in its satellite designs. Several major modifications have already been implemented (like electric passivation); some are still under analyses and shall be discussed soon with approval authorities (ESA, CNES).

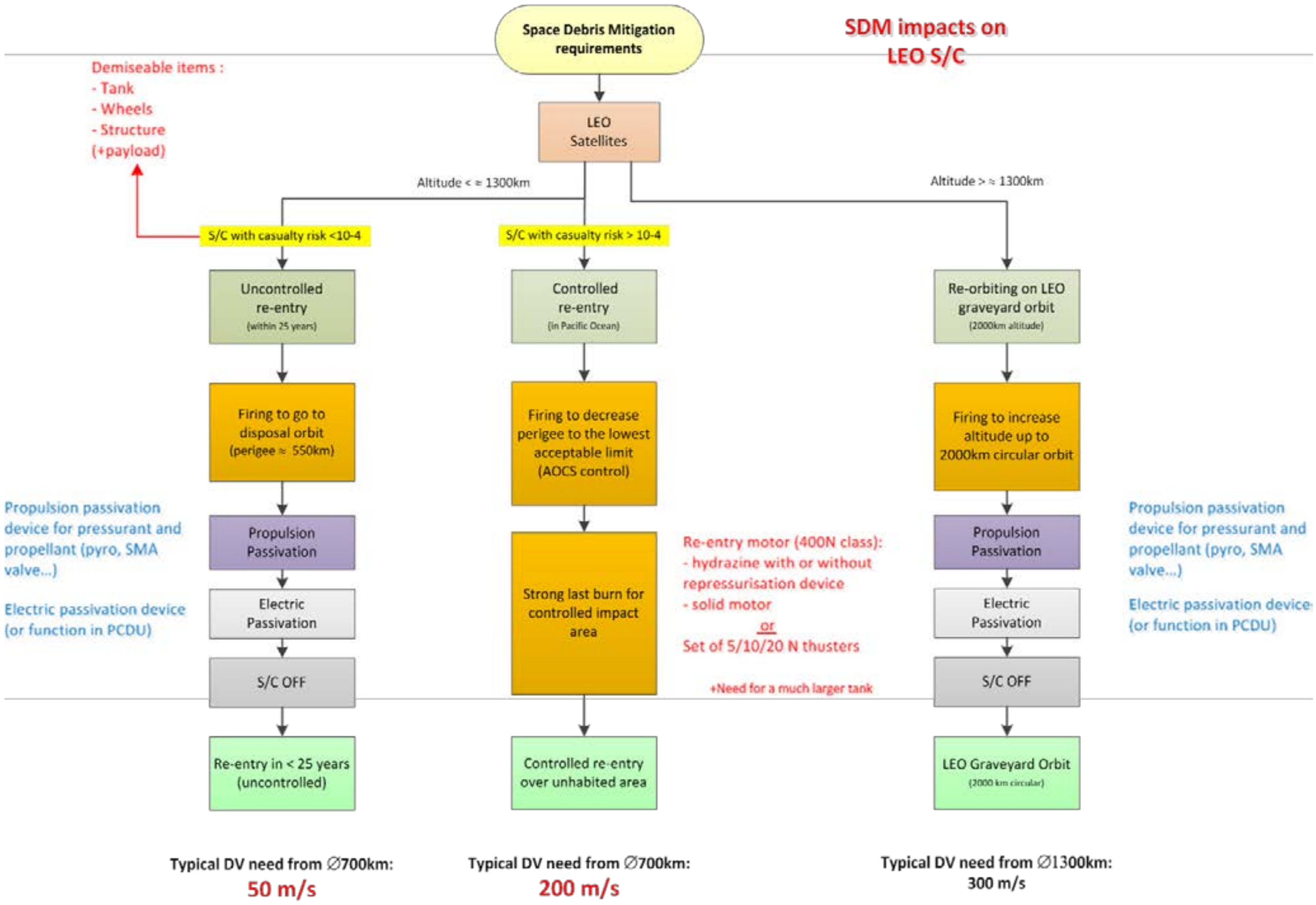

Figure 5: summary of main SDM requirements impacts on LEO S/C design

9 ABBREVIATIONS AND ACRONYMS

ALM	Additive Layer manufacturing
CA	Casualty Area
COPV	Composite Overwrapped Pressure Vessel
D4D	Design for Demise
FSOA	French Space Operations Act
LOS	Loi des Opérations Spatiales
PV	Pyro Valve
MTQ	Magnetorquer
SDM	Space Debris Mitigation
SMA	Shape Memory Alloy

10 REFERENCE DOCUMENTATION

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- Space debris mitigation policy for Agency projects, edited by ESA director JJ.Dordain (ESA/ADMIN/IPOL(2014)2, 28th of March 2014)
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