AN OVERVIEW OF ESA'S DESIGN FOR DEMISE INITIATIVE

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ABSTRACT

With the increasing presence of orbital debris, Design for Demise (D4D) has become essential to safe and sustainable space operations. D4D aims to minimize the risk of human casualty on Earth by ensuring that satellite components fully disintegrate during re-entry, preventing debris from reaching the ground. As part of the European Space Agency's (ESA) Zero Debris approach, this paper presents the results obtained in D4D research across materials (e.g., fused silica, Zerodur, CFRP, and FFRP), and critical components for the casualty risk including electronics, bipods and thrusters. Moreover, this paper provides an overview of lessons learned from these studies, contributing to develop a robust understanding of demise behaviour in diverse areas of spacecraft design. In parallel, ESA is working with industry to develop Zero Debris Platforms fully compliant with Space Debris Mitigation standards by 2030. By integrating D4D findings into platform-level designs, ESA is establishing a new benchmark in D4D and advancing solutions for a safer orbital environment.

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

1 INTRODUCTION

With the rapid increase in space activity, the risk posed by re-entering space debris has become a growing concern. The mitigation of space debris is a challenge for any space mission, particularly in Low Earth Orbit (LEO), where satellite re-entries must comply with international safety regulations. The European Space Agency (ESA) has introduced the Zero Debris approach, aiming to tackle debris generation and improve spacecraft demisability to meet sustainability goals by 2030. If a satellite's on-ground Casualty Risk (CR) exceeds 1 in 10,000, controlled re-entry is necessary, significantly impacting design complexity and mission costs. To avoid such constraints, Design for Demise (D4D) strategies have been developed to ensure that spacecraft and their components fragment and burn up during atmospheric re-entry, minimizing ground risks.

ESA's Clean Space initiative has been at the forefront of D4D research, investigating technologies that enhance demisability. Various approaches can enhance demisability, such as replacing non-demisable materials by low-melting-point ones, optimising structural designs increasing local heat flux through geometric modifications, or developing technologies prompting an early fragmentation. To support these efforts, ESA has been conducting extensive research on material properties and component-specific behaviour during re-entry, focusing on critical elements such as electronics, structural components, thrusters, and batteries.

A key challenge in D4D research is accurately predicting the demise of materials and spacecraft components, as existing models often include significant uncertainties. The research presented in this paper builds upon recent activities conducted within ESA and the European Space Industry on the re-entry behaviour of various materials, including Fused Silica, Zerodur, and composite structures like Carbon Fibre-Reinforced Polymer (CFRP) and Flax Fibre-Reinforced Polymer (FFRP). Additionally, it presents the findings of the thermal and structural evolution of critical components from the demise perspective, such as bipods, thrusters, and large electronic elements. By consolidating these findings, this paper contributes to the ongoing effort to develop demisable space systems and thus to the ESA's Zero Debris goals. Therefore, the objectives of this research are:

- **Advance the understanding of material demise** by analysing thermal, mechanical, and fragmentation behaviours.
- **Develop improved models** that integrate experimental data to reduce uncertainties in demise predictions.
- **Investigate component-specific demisability** for electronics, thrusters, and structural elements.
- **Support the ESA Zero Debris Platforms activity** by using these findings to develop new platform-level designs, aiming for fully demisable satellite platforms by 2030.

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2 MATERIALS DEMISABILITY RESEARCH

The selection of materials is critical for the demisability of spacecraft components during atmospheric re-entry. One of the D4D strategies is minimising the heat required for ablation by replacing materials with alternatives that exhibit lower melting temperatures, lower emissivity, or reduced specific heat of fusion. These properties can accelerate the beginning of material degradation, promoting earlier fragmentation and reducing the likelihood of intact debris reaching ground.

Hardly demisable materials include Titanium, Stainless Steel, Tungsten, Molybdenum, and composite materials.These materials are commonly found in structural components, as well as propellant tanks (COPVs and often titanium-based), reaction wheels, thrusters or bipods. Additionally, materials used in optical payloads, such as glasses, remain highly challenging due to their requirement for thermal stability. Several D4D studies have explored alternative materials aiming to maintain mechanical performance while enhancing demisability.

This section presents recent research on material demisability, focusing on metals, glasses, and composites. The findings from these studies have contributed to refining re-entry models and updating the ESTIMATE material database, improving the accuracy of spacecraft demise predictions.

2.1 Metals and Alloys

The study of metallic alloys is fundamental to improving spacecraft demisability, as many structural and functional components utilize high-melting-point metals that resist ablation during atmospheric re-entry. In cases where dedicated re-entry tests are unavailable, material properties from specialist databases, such as NIST-JANAF, are used as a reference. However, as these databases often lack complete information for the ablation process, approximations must be applied.

For metallic materials, key properties influencing demisability include melting temperature, emissivity, and oxidation behaviour. Emissivity values, particularly total hemispherical emissivity, are typically available for virgin surfaces but may not be well-characterized for oxidized or ablated surfaces. In the absence of specific test data, a baseline emissivity of 0.8 is assumed, following consistency observed in experimental testing Moreover, oxidation heat release and surface catalycity should remain at default values (0 and 1, respectively) unless specifically justified by test results.

This section provides an overview of newly introduced and updated metallic alloys, their properties, and their implications for spacecraft demise modelling.

This section details advancements in newly investigated metals, such as Haynes 25 and Molybdenum, as well as updates on previously researched metals like Inconel 718 and Tungsten.

2.1.1 Haynes 25

Haynes 25 is used as a baseline for cobalt-nickel-chromium alloys. Material properties have been derived from specialist databases and validated through experimental testing [1] and it exhibits high-temperature strength and oxidation resistance, making it a critical candidate for demise studies.

Plasma Wind Tunnel (PWT) tests revealed significant differences in the behaviour of thin (3 mm) and thick (20 mm) samples. Thin samples exhibited melting at the datasheet-defined temperature, whereas thick samples demonstrated delayed demise due to the formation of an insulating oxide layer. This oxide layer acted as a thermal barrier, protecting the internal material from ablation and prolonging structural integrity. Based on these findings, it is recommended to consider the demise behaviour of thick samples for components exceeding 3 mm in thickness. Particularly, the tests produced three unexpected results:

1. The sample was expected to fail at 970 kW/m². However, despite exceeding its melting temperature by 200°C, the material remained intact due to the formation of a rigid oxide layer (see Fig. 1). This layer was sufficiently strong to contain the molten core, delaying structural collapse and indicating higher resistance to demise than initially expected.
2. No clear melting was observed at the edges, despite this being the region subjected to the highest heat flux.
3. Contrary to expectations, material ejection originated from the central region rather than the edges, suggesting localized internal melting rather than uniform surface degradation.

These findings highlight the complex oxidation and thermal behaviour of Haynes 25 during atmospheric re-entry. The results emphasize the need for further investigations into oxide layer formation and its impact on spacecraft demise.

Figure 1. Haynes demise behaviour in PWT test.

2.1.2 Inconel 718

Inconel 718 is a class example for nickel-chromium alloys and serves as a baseline for other materials in this category. While properties of similar alloys can be inferred from Inconel 718, individual validation remains necessary. The results from the SCORED activity showed that a key factor influencing the demisability of Inconel 718 is the formation of a protective oxide layer (see Fig.2), which delays melting and alters thermal response. To better align with experimental results from [1], the resulting material model artificially increases its latent heat of fusion, intending to account for this delayed demise. However, the observed demise was still slower than predicted the one predicted by these models. Further refinement of the model is required to accurately capture the influence of the oxide layer and improve the capabilities for spacecraft demise analysis.

Figure 2. Inconel 718 demise behaviour in PWT test.

The PWT tests demonstrated that while Inconel 718 exhibits oxide-layer inhibition similar to Haynes 25, its demise behaviour differs significantly. The oxide layer delayed melting but was breached more easily compared to Haynes 25, with the melting point remaining close to the nominal value. Unlike Haynes 25, where the molten material was contained by a rigid oxide layer, Inconel 718 displayed a partial release of molten metal, yet the oxide layer remained mostly intact.

It remains unexplained that the bolts in the test sample failed despite the main structure remained intact. This behaviour suggests that additional factors, such as localized stress concentrations or variations in oxidation dynamics, may influence the demise process.

2.1.3 Molybdenum

Molybdenum has been investigated as a potential material for bolts and design for containment concepts due to its high-temperature stability and mechanical strength. As a pure metal, its properties have been derived from experimental testing documented in [4].Due to its exceptionally high melting point and resistance to oxidation, it requires careful consideration in spacecraft design from the demisability perspective.

PWT tests were conducted on M8 and M4 molybdenum screws with comparative analysis with M8 and M4 titanium screws, all mounted on a titanium plate. The results showed that both titanium bolts melted at approximately the same time, whereas both molybdenum bolts exhibited significantly delayed melting (see Fig.3). This outcome confirms molybdenum's high resistance to ablation, reinforcing its classification as a non-demisable material. Therefore, the use of molybdenum in spacecraft components should be carefully assessed, particularly for non-demisable hardware. In applications where complete demise is required, alternative materials with lower melting points should be considered to enhance spacecraft demisability.

Figure 3. Molybdenum and Titanium screws demise behaviour in PWT test.

2.1.4 Tungsten

Tungsten is a high-melting-point metal commonly used in thrusters and reaction wheel flywheels, making its demisability a challenge. Therefore, its inclusion in spacecraft design requires alternative D4D approaches, such as fragmentation-promoting structures.

PWT tests [4] were conducted to evaluate Tungsten's thermal response, demise behaviour and potential for containment, focusing on oxidation-driven material loss. A Tungsten Cube was tested until the rear thermocouple reached 1000°C, at which point outgassing was observed, indicating tungsten oxide formation (see Fig. 4). Another test with longer-duration exposure confirmed the heating profiles consistent and revealed 1 mm of surface recession, attributed to vaporized tungsten oxide. Results indicate that while tungsten undergoes oxidation-driven material loss, its overall structural integrity remains largely unaffected.

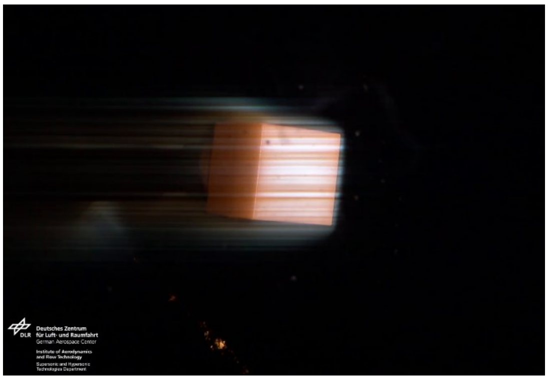


Figure 4. Tungsten cube demise behaviour in PWT test.

2.2 Glasses

Glass materials present significantly different demise behaviours compared to metals and alloys, largely due to their unique thermal, mechanical, and chemical properties. Unlike metals, where demise is driven by melting and oxidation, glasses undergo degradation primarily through surface viscosity changes, thermal fracturing, and molecular recombination effects. These mechanisms require alternative modelling approaches, as standard ablation models do not adequately capture the behaviour of glass materials during atmospheric re-entry.

One of the main challenges in modelling the demisability of glass structures is their low catalytic efficiency, which directly impacts the heat flux received at the surface. Unlike metallic surfaces that are typically assumed to be fully catalytic, glass materials present a low catalycity effect, which reduces the actual heat input.

Another critical factor is the failure mechanism of glass materials, which instead of undergoing melting in a well-defined manner, experience gradual viscosity reduction at high temperatures which leads to structural weakening and eventual collapse. Given these unique characteristics, dedicated PWT experiments have been conducted to refine demise models for glass materials. This section presents the latest research findings on the demise behaviour of Fused Silica and Zerodur.

2.2.1 Fused Silica

Fused Silica is used as a baseline material model for glassy structures. It is widely used in optical payloads, windows, and structural glass components due to its high thermal stability and resistance to chemical degradation. Its properties are fitted to experimental data [3], demonstrating minimal mass loss during re-entry, and the demise of Fused Silica is driven by surface viscosity.

Figure 5. Fused Silica 10 mm diameter rod demise behaviour in PWT test.

PWT tests were performed to evaluate both shape evolution and material degradation of Fused Silica. Three cylindrical samples of 3 mm, 6 mm, and 10 mm diameter were tested under high heat flux conditions to observe the onset of viscosity-driven failure. The 3 mm rod had rapid deformation, with significant shape changes occurring early in the test. The 6 mm rod presented minor deformation, suggesting a threshold effect due to sample size and heat penetration. The 10 mm rod remained structurally intact, with no observable softening before the sample holder failed (see Fig. 5), indicating larger structures retain mechanical integrity for longer time.

Moreover, a Fused Silica optical window was subjected to controlled heating conditions to obtain steady-state surface energy balance data. This test allowed for direct measurement of catalycity and emissivity. The results confirmed that Fused Silica exhibits low catalycity, significantly reducing the effective heat flux input compared to fully catalytic materials. This is to be accounted for in the material model for demise simulations to avoid overpredicting the demisability of Fused Silica.

2.2.2 Zerodur

Zerodur is a glass-ceramic material produced by Schott, widely used in precision optical applications, telescope mirrors, and space instrumentation due to its near-zero thermal expansion and high thermal stability. However, these same properties significantly influence its demisability during atmospheric re-entry, making it different from fully glassy materials such as Fused Silica.

PWT tests were conducted to increase the understanding of Zerodur's demise, focusing on mass loss, surface degradation and structural failure. As with other glass materials, demise occured primarily through shear failure of the hot surface layer once viscosity was sufficiently reduced. However, unlike traditional glass, Zerodur showed delayed degradation, with surface softening at higher temperatures than expected. This extended stability is attributed to its glass-ceramic composition, which resists thermal fracturing and maintains mechanical integrity longer than fully glassy materials.

Moreover, the heat flux input was significantly lower than standard models predicted, as Zerodur's surface does not efficiently catalyse atmospheric species. Therefore, it was concluded that previous demise models, which assumed full catalycity, overestimated material loss. The current ESTIMATE model accounts for Zerodur's non-catalytic nature and high surface viscosity to accurately represent its demise behaviour [3].

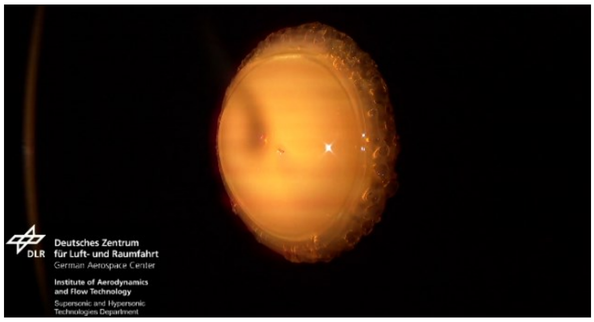


Figure 6. Zerodur demise behaviour in PWT test.

2.3 Composites

Composite materials, particularly Carbon Fibre Reinforced Polymers (CFRPs), are extensively used in spacecraft structures, from primary load-bearing elements to Composite Overwrapped Pressure Vessels (COPVs). Their demisability is influenced by several factors, including resin pyrolysis (decomposition of the polymer matrix at high temperatures) and fibre delamination and oxidation (which affects the structural integrity and demise kinetics). This section presents advancements in the demisability assessment of CFRPs, focusing on a baseline CFRP material (HTS45/VTC401) and the novel cut-carbon fibre technology (cut-CF), and Flax Fibre Reinforced Polymer (FFRP).

2.3.1 Carbon Fibre Reinforced Polymer baseline HTS45/VTC-401 and cut-CF

CFRP materials are widely used in spacecraft structures, particularly in load-bearing components and pressure vessels, due to their high strength-to-weight ratio and thermal resistance. However, their demisability remains a concern, as the combination of resin pyrolysis and fibre oxidation defines their breakup during atmospheric re-entry. To better understand their demise behaviour, PWT and Static Re-entry Chamber (SRC) tests have been conducted on the CFRP baseline HTS45/VTC-401 and alternative more demisable options such as cut CFRP [5].

The tests revealed that previous CFRP models were inaccurate, with DRAMA's built-in model predicting material loss at room temperature due to incorrect pyrolysis reaction parameters. The new experimental data led to a recalibration of five key parameters, refining pyrolysis kinetics and oxidation behaviour to more accurately represent the demise process.

- Resin Weight Fraction: Previously misrepresented as a composite ratio, this parameter significantly affects the pyrolysis process.
- Pyrolysis Reaction Rate: Adjusted to correct the erroneous low-temperature onset of CFRP demise.
- Epoxy Activation Energy: Updated to better represent energy required for resin decomposition.
- Char Oxidation Reaction Rate: Previously set to zero in DRAMA, this was corrected to account for fibre oxidation during re-entry.
- Char Heat of Formation: Updated to reflect the actual energy change during char oxidation.

Comparative studies using SARA demonstrated that the updated model results in a higher predicted surviving mass than the previous DRAMA model, making it more conservative for CR assessment. A Monte Carlo parametric sweep was conducted, confirming the dependency of the final mass on initial geometry and mass, with the new CFRP parameters proving more reliable across different scenarios. As an outcome of these findings, a revised CFRP demise model has been implemented in DRAMA, incorporating updated reaction terms and material properties.

Additional tests on a discontinuous carbon fibre (cut-CF) composite showed improved demisability compared to traditional continuous CFRP. The cut-CF presented enhanced fragmentation and fibre bundle spallation, leading to earlier material breakup. The matrix composition was also found to significantly impact the ablation rate, with the M55J/EX-1515 system displaying lower resistance to high heat flux compared to HTS45/VTC-401.

2.3.2 FFRP

FFRP has recently gained interest for aerospace applications, including spacecraft structural panels. Investigations by [5] demonstrated the feasibility of using FFRP in space structures, with a case study based on the Copernicus Sentinel-1 satellite's lateral panel. Compared to CFRP, FFRP exhibits significantly higher demisability (see Fig. 7), with an ablation rate three to eight times greater and a demise onset temperature much lower than aluminium. However, challenges remain, including increased processing complexity due to humidity sensitivity, lower fiber compaction, and the need for autoclave curing to achieve high mechanical properties. Additionally, FFRP has reduced stiffness and strength compared to carbon-reinforced composites.

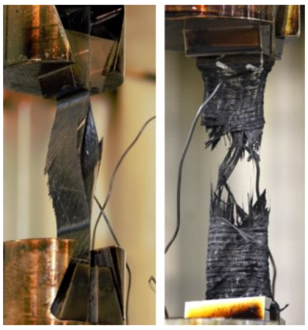


Figure 7. CFRP and FFRP demise behaviour in SRC test respectively.

Therefore, tests have been performed to evaluate FFRP's thermal behaviour during atmospheric re-entry. It was observed that the carbonizing flax fiber/matrix system undergoes a unique demise process, transforming into a three-dimensional fibrous structure. The introduction of a reactive metallic filler (AlMg) was explored to enhance FFRP's thermal properties, with a filler proportion of 1% by weight relative to the epoxy mass. This resulted in a 10% increase in through-thickness thermal conductivity without mechanical property degradation. Under medium heat flux conditions, AlMg-filled FFRP exhibited a 4% improvement in ablation rate and a 17% higher proportion of demised plies compared to virgin FFRP. Optical recordings confirmed faster ply disintegration and increased front surface temperature, indicating an accelerated demise process.

FFRP samples displayed a characteristic dynamic carbonization process with continuous ply breakdown, in contrast to the slower fiber-by-fiber spallation observed in CFRP. Under maximum heat flux conditions, this process was further intensified. FFRP maintained consistently lower front surface temperatures than CFRP, while the AlMg-filled variant exhibited an earlier failure onset (-11 s) and a slight temperature increase (+22 °C). These findings confirm FFRP's superior demisability compared to conventional composites and highlight the potential for further optimization through filler integration and structural tailoring.

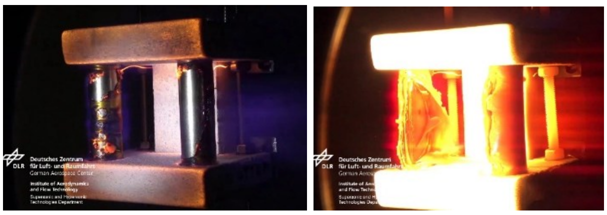
2.4 Equipment Specific Materials

Certain satellite components, such as batteries and electronics, contain materials that are inherently difficult to demise during atmospheric re-entry. These materials often consist of high-melting-point metals or thermally resistant composites. To address this challenge, material models have been developed based on experimental studies [2]. The approach used for modelling these components is the use of metal proxies, simplified material representations that mimic the thermal and mechanical response of complex assemblies. Metal proxies allow for practical implementation in re-entry simulation tools by capturing the bulk thermal properties and demise characteristics observed in PWT. This section specifically focuses on the metal proxies derived from recent test campaigns of ABSL battery cells and GFRP components used in electronics and battery structures.

2.4.1 Battery cells

ABSL battery cells are widely used in space applications due to their reliability and energy density. However, their demisability is affected by the presence of a steel casing. Since testing opportunities for full-scale batteries are limited, developing an accurate material model is needed to predict their behaviour in re-entry simulations.

To investigate the demise characteristics of ABSL cells, individual cells were tested under various heating conditions. Static tests were conducted on two cells (P20 and I28) at increasing heat flux levels (see Fig. 8 and 9). The results were consistent with previous SECRET test campaigns, showing no significant difference in demise behaviour between the two cell types.



Figures 8 and 9. Individual ABSL cells demise behaviour in PWT.

Based on these findings, a material model, Bat-Cell-ABSL, was developed to capture the demise behaviour of large ABSL cells. This model is based on Steel A316, with adjusted latent heat of fusion and thermal conductivity to better match experimental results. Since cell demise is primarily dictated by the steel casing, a Steel Proxy Material was implemented in DRAMA, incorporating reduced latent heat to improve predictive accuracy [2]. This model successfully represents ABSL cells, and the demise behaviour of SAFT cells is expected to be similar, though remains unverified.

2.4.2 Glass Fibre Reinforced Polymer

GFRP is widely used in battery modules and electronics due to its mechanical properties and electrical insulation capabilities. In particular, GFRP components in electronic assemblies and battery modules require further investigation to refine material models. To address this, PWT have been conducted to characterize GFRP demise behaviour and develop an equivalent metal proxy model to improve re-entry simulations.

The GFRP from electronics cards was first tested in a stagnation configuration with a steel backing plate, preventing warping and enabling a controlled assessment of demise onset. Initial heating caused softening and warping, but no significant mass loss. At moderate heat fluxes, surface melting was observed, though with high viscosity preventing material loss. At higher flux levels, the viscosity decreased sufficiently for material flow, leading to mass loss above ~1200°C.

Additional dynamic tests evaluated fragmentation behaviour, particularly in battery modules. Fragmentation was found to be driven by GFRP failure, with rotational motion accelerating the process. However, fragmentation was not instantaneous, and in cases where no substantial mass was present, the material deformed rather than disintegrated into small, demisable fragments. This suggests that GFRP layers should be explicitly included in predictive models. Indeed, the GFRP sheet was tested separately also in stagnation configuration, and it was observed an immediate delamination and warping, followed by the material bending around the sample holder (see Fig. 10 and 11). At higher heat flux, even melt was observed, partly driven by the much smaller length scale of the material bent around the sample holder.

Figures 10 and 11. GFRP sheet of battery module demise behaviour in PWT.

Based on these findings, the thermal material demise model for GFRP was refined. The revised model indicates a slightly lower demisability than the previous SECRET proxy model but remains sufficient for use in DRAMA CR assessments. Comparisons with glass materials in SAMj confirm that GFRP behaves similarly to Zerodur and is less demisable than borosilicate glass.

Extrapolation to orbital conditions suggests that GFRP will reach the ground from nearly all release altitudes, consistent with findings from both SECRET and PADRE studies. The material behaviour is complex. The tests demonstrate that the material becomes soft at relatively low temperatures, and can be bent and twisted by relatively low mechanical forces. Where there is a substantial mass on the material, it is possible that this may induce a tearing of the material, as observed with the breaking of the sample from the sample holder. Consequently further characterization are considered necessary.

3 COMPONENTS DEMISE RESEARCH

In recent years, ESA and the European space industry have invested significant effort in developing spacecraft components that are more likely to demise during re-entry. Critical components, such as reaction wheels, tanks, magnetorquers, structural elements, and more, have been identified as high-risk due to their potential to survive re-entry. Efforts to improve their demisability have focused on material changes, structural modifications, and advanced engineering techniques.

Research on reaction wheels has studied using alternative materials and exothermic reactions to promote demise. Propellant tanks typically made of titanium or COPVs, are replacing this material by aluminum alloys and other demisable CFRPs. Magnetorquers, with their layered sub-components, have been studied to promote earlier break-up by altering mounting feet and housing materials. Structural panels and joints, which determine break-up altitude, are being modified with demisable inserts and shape memory alloys.

Building on this foundation, current research is addressing remaining knowledge gaps. The following sections present the latest advancements in these areas, including efforts to understand the demise behaviour of electronics, batteries, thrusters and star trackers. Bipods and supporting structures are also being investigated for materials that promote faster thermal degradation as well as new designs for demisable structural panels and joints.

3.1 Demisable structural panels and joints

Optimising spacecraft structural materials for demise requires a trade-off between structural integrity and controlled disintegration upon re-entry. The ideal demisable material should exhibit a low melting temperature, specific heat, heat of fusion, char yield, and surface emissivity while maintaining high thermal conductivity and catalytic activity. Among commonly utilized facesheet materials, FFRP has demonstrated superior demisability in comparison to aluminium and CFRP (preferred for its structural performance).

To improve early demise of structural panels without significantly compromising mechanical performance, the following material modifications were investigated:

- **Hybrid Reinforcement:** Incorporation of carbon and flax fibres in facesheets to balance structural strength with enhanced demise behaviour.
- **Thermally Conductive Fillers:** Integration of aluminium-magnesium (AlMg) micropowder within the matrix to enhance thermal conductivity and mitigate convective blockage effects.
- **Cut-CF Prepregs:** Use of pre-cut CFRP prepregs to promote controlled ply-by-ply (pbp) separation and facilitate fragmentation upon re-entry.

The material configurations studied for the matrix were epoxy (thermoset) and epoxy/PVB blend with AlMg micropowder, and for the facesheets (see Fig. 12):

- CF: Tenax HTS-45 (50 gsm)
- FF: AmpliTex® 5040 (300 gsm), 5043 (200 gsm)
- CF-FF Hybrid: AmpliTex® 5027 (160 gsm)
- Cut-CF Prepreg: AS4-8551

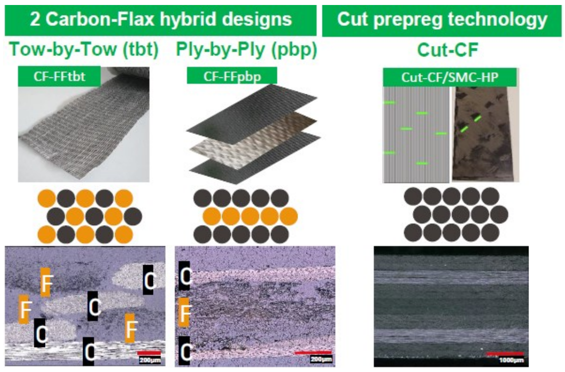


Figure 12. New structural panel designs from [ref alex].

The panels were subjected to various testing methods to assess their demisability under re-entry conditions, from which the following results were observed:

- **SRC Tests:** The CF-FFpbp hybrid exhibited earlier fracture at lower temperatures than CFRP, promoting more effective demise.
- **PWT Tests:** Flax hybridization increased ablation rates by 1.5× to 3×, confirming its superior demise characteristics.
- **Cut-CF vs Continuous-CF:** Pre-cut CF prepregs promoted early ply separation, while continuous CF

prepregs experienced failure at the top pin.

- **AlMg Integration:** The addition of AlMg micropowder improved thermal conductivity and advanced the onset of demise by approximately 15 °C, enabling earlier fragmentation.

Not only structural panels but also panel fasteners were investigated for their structural integrity and demisability. Common fastener materials include stainless steel, Ti6Al4V, and Al7075. So as to research new designs and materials that would enhance demisability, composite fasteners were explored, specifically CF/PEEK with continuous CF fibres and with short CF fibres. Different tests were conducted, where the following results were obtained:

- **Tensile & Shear Tests:** Short CF fibre fasteners performed comparably to continuous CF fasteners in mechanical strength.
- **Torque Clamp Force & Fatigue Tests:** Short CF bolts demonstrated sufficient structural integrity for spacecraft applications.
- **SRC Tests:** Short CF bolts exhibited earlier separation at lower temperatures compared to SS and continuous CF bolts confirming higher demisability.
- **Failure Mode Analysis:** Brittle fracture was observed in CF/PEEK fasteners, facilitating more effective re-entry breakup.

Moreover, the structural panel was subjected to diverse testing in a sandwich panel configuration with a bolted joint insert system. The obtained results were:

- **4-Point Bending Tests:** The CF-FFpbp hybrid exhibited stiffness-to-mass ratios comparable to aluminium and CFRP panels.
- **Dynamic Mechanical Analysis:** CF-FFpbp panels showed enhanced damping properties, particularly at higher vibration modes.
- **Humidity Exposure Tests:** CF-FFpbp absorbed twice as much water as aluminium and CFRP, resulting in a 60% reduction in stress resistance.
- **Oxidation Study:** SEM analysis revealed a 2.5× to 3× increase in oxide layer thickness on aluminium facesheets following prolonged humidity exposure.

In conclusion, the findings from this research indicate that both the demisable structural panels and composite fasteners offer viable alternatives to traditional materials. Specifically, short CF/PEEK fasteners present a balanced trade-off between mechanical performance and re-entry demisability, and the CF-FFpbp hybrid, particularly with AlMg integration, demonstrated enhanced ablation rates, improved thermal conductivity, and predictable ply separation, making both promising candidates for future demisable spacecraft structures.

3.2 Electronic Components

The assessment of electronic components demisability presents unique challenges due to material properties, structural configurations, and thermal response during atmospheric re-entry. Electronic components consist of a combination of metallic and composite materials, each exhibiting distinct thermal and mechanical behaviours. Main considerations for demisability include selecting the housing material, the response of electronic boards, and the failure mechanisms of internal components.

PWT testing was conducted on several electronic components. Specifically, for EnMAP Electronics Card it was observed that the board softened and deformed, undergoing oscillatory motion in the plasma flow. Localized delamination occurred at the edges, where heat exposure is highest (see Fig. 13). And failure happened along the pivot line, but significant material demise was not observed.

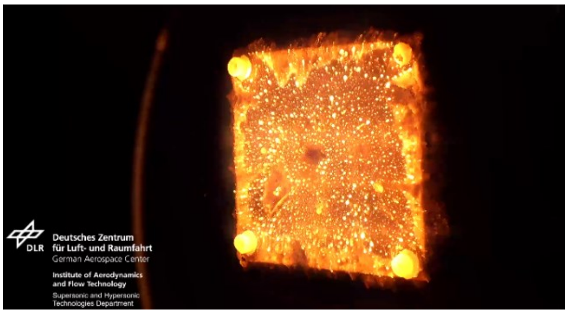


Figure 13. EnMAP Electronics Card demise behaviour in PWT.

In the case of PD Electronics Card, the componentry remained attached to the board despite oscillations. Delamination occurred at the leading edge, exposing more of the card to heating and full demise was observed at 1200°C, as the material softened sufficiently to flow from the card. For BCM Electronics Module, the cabling detached early, leaving the module intact until aluminium began to melt and warp. Tearing and cracking occurred at the module edges as material weakened. The aluminium housing failed catastrophically, leaving the electronics cards nearly intact, and the rear card remained cooler due to thermal shielding from the front card, delaying its demise (see Fig. 14). Finally, in the PCDU Electronics Card the aluminium frame shielded part of the card, but demise was observed at the rear section. Upon housing removal, the card bended and oscillated, failing near its mounting point.

Figure 14. BCM Electronics Module demise behaviour in PWT.

In this activity not only the demise behaviour of electronic components was studied, but due to the observed low inherent demisability of GFRP-based PCBs, several approaches were assessed as options to improve re-entry breakup behaviour:

- Replacing GFRP by aluminium would significantly improve demise. However, GFRP-based PCBs are industry standard, making this change impractical.
- Introducing pre-designed failure points in the fiberglass cloth arrangement would contribute to promote earlier fragmentation. Still, this is difficult to implement due to functional and environmental constraints.
- Reducing PCB size could improve demise behaviour, but this might not feasible due to functional limitations in electronics design.
- Exploring higher-force material tear mechanisms to accelerate failure could be an option, but static facility tests would be necessary for further investigation.

In summary, this research provided findings such that aluminium housings shield the electronic components initially but then fail catastrophically exposing internal electronics, GFRP-based PCBs exhibit poor demise behaviour with oscillatory bending as the primary failure mode, componentry (particularly transformers) can survive re-entry posing a potential CR and that higher heating (~1200 °C) is required to fully demise electronic cards. Research into controlled failure mechanisms e.g. pre-induced tear points, is recommended to enhance the demise potential of electronic assemblies.

3.3 Batteries

Batteries are a critical component in spacecraft design, often encased in protective housings and containing energy-dense materials that may influence their thermal and structural behaviour during atmospheric re-entry. Their demisability is of particular interest due to the potential ground risk posed by intact battery cells, especially larger shaft cells, which exhibit lower demisability compared to smaller cells. Experimental and modelling efforts have focused on understanding the role of GFRP fragmentation (already introduced in section 2.4.2), cell exposure, and rotational effects on battery demise. Therefore, a series of static and dynamic PWT tests were conducted on representative battery modules to assess their demisability. The modules, provided by ABSL, were designed to remain representative of larger batteries while fitting within the PWT.

In the static tests, it was observed that corner cells heated more quickly due to their prolonged exposure to plasma flow (see Fig. 15). As GFRP deteriorated, corner cells detached first, followed by the outermost rows of the battery. Moreover, some tests showed significant cell demise, while others indicated that many cells remained largely intact even after separation.

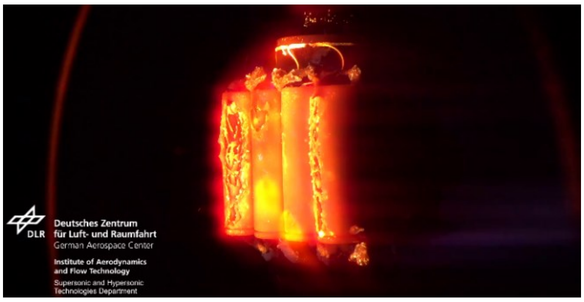


Figure 15. Battery Module demise behaviour in static PWT test.

For the dynamic tests, they were conducted at two rotation rates: 0.3 Hz and 2 Hz. At 0.3 Hz fragmentation occurred due to GFRP sheet recession, but no significant cell demise was observed, while at 2 Hz fragmentation was accelerated due to higher centrifugal forces, leading to faster cell detachment and increased heating exposure. Moreover, in low-flux conditions, the battery components remained largely intact, with only minor GFRP damage. However, at higher flux levels, the first row of cells began to demise, suggesting that cell heating exceeded predictions based on module length scale (see Fig. 16). Outgassing and material recession intensified, further accelerating structural failure.

Figure 16. Battery Module demise behaviour in dynamic PWT test and high-flux conditions.

Given the observed fragmentation behaviour, potential methods for improving the demise of spacecraft batteries include:

- Investigating Larger Cells: Larger shaft cells pose a higher risk due to their lower demisability compared to small cells. Further testing is needed to develop mitigation strategies for these higher-risk batteries.
- Enhancing GFRP Fragmentation: Since battery breakup is primarily driven by GFRP failure, exploring methods to increase its recession rate could lead to earlier exposure and demise of cells. Modifying GFRP composition or using pre-designed failure points may improve fragmentation behaviour.

In conclusion, the main findings from this research are that small-cell batteries are expected to fully demise from most relevant release altitudes while larger cells exhibit lower demisability. GFRP recession is the primary driver of battery fragmentation, defining the exposure and subsequent demise of cells, and rotation increases breakup speed, particularly at higher spin rates.

3.4 Star Trackers

Star trackers have sensitive optic and electronic elements for precise attitude determination for spacecrafts. Due to their compact design and highly robust materials, their demisability varies depending on size and structural composition. Small star trackers have a probability of demise, while for larger ones, at least one part is expected to survive re-entry and pose a ground risk. Critical elements to assess star tracker demisability are:

- Focal Plane Array Housing and Optical Barrel: Both typically made of titanium.
- PCBs: Potential ground risk depending on heat exposure and fragmentation behaviour.
- Lenses: Often made of borosilicate glass, which exhibits a distinct viscosity profile and can deform and escape rather than shatter.

The demisability of star trackers depends on their fragmentation behaviour, material properties, and exposure to heat flux. Tests were performed on both large (Base: 80mm², Barrel: 38mm Ø) and small (Base: 40mm², Barrel: 19mm Ø) star tracker mock-ups, in static and dynamic PWT conditions. A rotation of 0.1 Hz was used in the large mock-up dynamic test, leading to a generally even heat distribution through the test, though shock impingement on the barrel created localized hot spots. No complete demise was observed, but the bolts holding the base to the barrel slid out probably due to failure of the helicoils. For the dynamic test of the small mock-up, the rotation rate was increased to 2 Hz, which increased centrifugal effects but did not lead to full demise. The bolts failed at the first heat flux condition like in the large mock-up test.

For the static tests of the large mock-up, the initial heating also showed shock wave impingement on the cylinder, creating localized hot spots. The base's small length scale resulted in high localized heating, and steady state was reached, with no immediate demise. Moreover, at higher flux conditions, melting was observed in hot spots, but the main structure remained intact. It is to be noted that in one test, the lenses inside the barrel deformed and slowly escaped, indicating viscous flow rather than fragmentation. This suggests that borosilicate glass lenses pose a smaller casualty risk than previously assumed. Furthermore, when increasing to high flux conditions, melt propagation started at the barrel's tip and shock impingement locations, leading to partial demise. The front section of the cylinder was demised, while the rear section remained intact even at elevated heat flux (see Fig. 17).

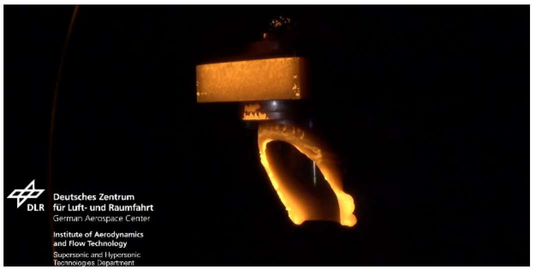


Figure 17. Star tracker demise behaviour in static PWT test and high-flux conditions.

Finally, for the static tests of the small mock-up, the heating profile was similar to the large model, with shock impingement on the base causing localized hot spots. Steady state was reached across four heat flux conditions with no full demise. At 580 kW, melting initiated at the base and propagated to the cylinder, but only the front section was lost, likely due to the shock shape.

From these tests, it can be concluded that:

- Star tracker demisability is size-dependent – smaller units may fully demise, while larger ones pose a risk of surviving re-entry.
- Critical components (Titanium barrel, focal plane housing) are highly resistant to demise, requiring improved modelling and possible design changes.
- Helicoil behaviour remains uncertain and represents a knowledge gap in assessing fragmentation.
- Glass behaviour should be further tested. Preliminary results suggest borosilicate glass lenses are less hazardous than previously thought.
- Shock-wave heating effects drive local melting but do not guarantee complete demise of titanium parts.
- A refined material model should be developed to incorporate viscosity-driven melting for glass and Titanium dynamic fragmentation mechanisms.

Moreover, some demisability improvement strategies were assessed:

- To investigate alternative materials for Titanium components, considering that changes may impact performance and require careful trade-offs.
- To promote early break-up would be an alternative but requires further research to determine if it really improves demise probability. If beneficial, demisable inserts or helicoils could be designed to promote part separation.
- Size reduction was considered not feasible for applications requiring high accuracy, limiting this option as a demisability strategy.

3.5 Thrusters

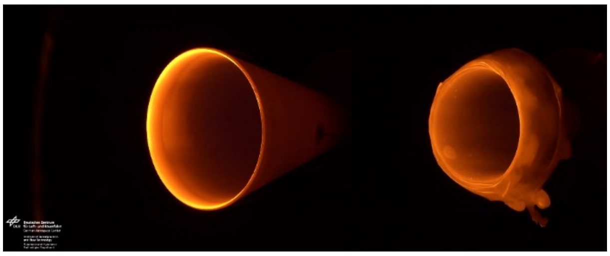
Thrusters contain multiple subcomponents, hence the difficulty of modelling these components in demise simulations. Based on the hereby presented research [1], a minimum of two modelled components is necessary to accurately capture their demisability, since the lower thruster half is significantly more prone to demise compared to the upper section. This has be concluded based on several PWT tests. A total of five Ariane Group 1N thrusters were subjected to testing:

- One thruster was separated into four distinct parts.
- One thruster was split into two halves.
- Three intact thrusters intact for full-system testing.

Additional tests were conducted on thruster piping (Titanium pipes from Ariane Group) and nozzle mock-ups (Various sizes and material compositions, including Haynes 25 and Inconel previously introduced in sections 2.1.1 and 2.1.2 respectively).

The main results from these tests are:

- Pipes do not pose a CR due to the low mass and small size despite being made of titanium. And the thruster heatshield demises rapidly due to its low mass once melt temperature is reached.
- The thruster large inlet part demise was delayed due to internal potting material outgassing, considering it to have low demisability. While the thruster small inlet part is resistant to demise, since only some surface melting was observed.
- For a small nozzle (20 mm) of Inconel 718, melting was observed along the rim and the strong oxide layer formed affected the material recession. And the large nozzle (50 mm) of this same material showed a similar behaviour, indicating scalability. However, for a large nozzle of Haynes 25, the oxide layer significantly delayed bending and demise, having higher resistance to motion (see Fig. 18 and 19).



Figures 18 and 19. 50 mm diameter nozzle of Haynes 25 demise behaviour in PWT test.

- The thruster lower half showed relatively simple demise, specially under high heat flux which led to rapid material loss. Otherwise, the thruster upper half showed slow demise due to its thick material and potting outgassing.
- The whole thruster was tested at 0 °, 30 ° and 60 ° angle of attack conditions. In the first case the lower half demised quickly and the upper slowly with significant outgassing effects as expected. For the second case, demise progressed from front to rear, with the lower half demised quickly and the upper slowly. In the last case, the behaviour was similar to the first one, with the lower half demising rapidly and the upper half demise delayed.

Figures 20 and 21. Whole thruster at 0 ° and 30 ° respectively demise behaviour in PWT test.

3.6 Bipods

Bipods are critical for demisability as they are typically made of high-melting-point materials like titanium and have complex geometries with small structural features that influence their fragmentation and heating behaviour during re-entry. To better understand its demise, a baseline titanium bipod, designed to hold an 8 kg mirror, was tested in PWT. It was observed that the bipod demise is driven by melting, with cutouts failing first and contributing significantly to early fragmentation. This baseline bipod was more demisable than standard models predict, due to incorrect heating length scales, typically approximating bipods as simple boxes.

Moreover, alternative bipods designs with additive manufacturing were produced and tested to evaluate them as more demisable options. Such designs and their results were:

- **Hollow Bipod:** Reduced mass led to a faster demise.

- **Holes Bipod:** The increase in heating due to holes resulted in the leg demising at a similar time to the cutouts (see Fig. 20), showing an increase in demisability, changing the fragmentation process, and being the most effective alternative design.
- **Reduced Holes Bipod:** Showed improvement over the baseline but less than the full-flow hole design.

Figure 20. Holes bipod demise behaviour in PWT test.

4 FUTURE MODELLING AND PREDICTION IMPROVEMENTS

The upcoming release of DRAMA 4.1 will introduce advancements in material modelling, particularly for glasses, through the implementation of the Simplified Heat Balance Integral (SBI) model. This new approach will offer a more accurate yet computationally efficient method for predicting the demise of glass and composite materials during re-entry, including new material entries in ESTIMATE for Fused Silica, Zerodur, Soda Lime, Borosilicate, GFRP, CFRP LY556, CFRP EX1515 and CFRP L20.

Unlike the previous Heat Balance Integral model, which was complex and prone to instability in Monte Carlo simulations, the SBI model achieves robustness while maintaining computational efficiency similar to bulk heating models. It enables the representation of temperature gradients within a material without requiring a full 1D simulation, making it ideal for high-variability re-entry scenarios.

For glass components, demise occurs primarily due to surface shear once the material's viscosity becomes sufficiently low. The SBI model integrates the Vogel-Fulcher-Tammann equation to track viscosity changes and determine the temperature at which material removal begins. By incorporating a simplified quadratic temperature profile, the model accurately predicts the depth of the critical temperature zone and calculates mass loss rates based on experimental data.

These enhancements will significantly improve spacecraft demise predictions, particularly for glass components such as optics and structural elements, ensuring better-informed design-for-demise strategies and risk assessments in future missions. The model accounts for the viscosity-temperature relationship of the glass material and removes mass from the hot surface at a rate which is proportional to the viscosity.

5 ONGOING RESEARCH

Beyond the research presented in this paper, ESA continues to develop new demisable technologies to address remaining gaps in D4D.

Upcoming research focuses on studying how to reduce the ground casualty risk by redesigning spacecraft component shapes to increase the experienced heating in re-entry, inspired by the promising results of the holes bipods PWT tests discussed in Section 3.6. Additional efforts include designing and testing an optical bench of CFRP to demise during re-entry, and manufacturing and testing breadboard models of two typical Earth Observation payload supporting brackets or bipods designed to demise during re-entry.

Another activity aims to develop a demisable Krypton tank. This explores a strip tape matrix concept for the composite overwrap of a COPV, with 1 L breadboards being designed and tested to confirm feasibility while maintaining compatibility with Krypton propellant at minimum 310 bar.

Another activity aims to develop enhance demise ability of Magnetorquers (MTQ) with external layer constituted by CFRP.

Another activity aims to develop a demisable version of big Solar Array Drive Mechanism (SADM).

Furthermore, ESA is investigating demisable structural joints for LEO telecom platforms. Current work focuses on understanding the failure mechanisms of different joint designs, identifying key factors influencing their demise, and testing new demisable concepts to refine and validate their effectiveness.

These ongoing activities represent a significant step forward in expanding D4D capabilities, ensuring that more spacecraft components are designed to disintegrate safely during atmospheric re-entry.

6 ESA'S ZERO DEBRIS PLATFORMS

ESA's Zero Debris strategy seeks to mitigate the risks associated with space debris accumulation, ensuring safe and sustainable space operations for future generations. In line with the Zero Debris Approach, a series of platform-level initiatives have been kicked off, targeting various types of spacecraft and orbits. These initiatives focus on adapting and evolving platform designs to integrate the Zero Debris Policy across large LEO satellites, Satcom, small satellites, and CubeSats. Additionally, future activities may extend these strategies to lunar missions, applying the Zero Debris principles beyond Earth's orbit.

To achieve Zero-Debris Platforms by 2030, technology improvements are essential in a broad range of areas.

These technological efforts include design for demise. By adapting and further developing the D4D findings and technologies presented in this paper into platform-level designs across various satellite types, ESA aims to ensure that platform designs meet the technological needs for demisability, reliability, and space sustainability. Through this approach, ESA is establishing a new benchmark in D4D and advancing critical solutions for a safer orbital environment. Together, these initiatives underscore ESA's commitment to a sustainable space environment through proactive management, policy innovation, and technological progress.

7 CONCLUSIONS

This paper has presented the latest advancements in D4D, focusing on the demisability of spacecraft materials and components to improve re-entry safety. The results from PWT testing campaigns and modelling have provided insights into how different materials and structural elements behave under extreme heating and mechanical loads.

One of the main outcomes of this research is the improved understanding of composite materials and their fragmentation and burn-up characteristics, particularly for CFRP components. The introduction of the SBI model for glass materials will also enhanced demise predictions, allowing for a more accurate assessment of viscosity-driven mass loss. Additionally, the study of structural elements such as bipods and perforated components has demonstrated how specific design modifications can significantly increase re-entry heating and demise efficiency. These findings are critical for improving spacecraft designs to minimize the risk of surviving debris.

Building on these findings, ongoing research is expanding D4D strategies to other spacecraft components, including demisable optical benches, payload support structures, Krypton tanks, and structural joints. In parallel, ESA's Zero Debris Platforms initiative integrates these technologies into next-generation spacecraft designs.

Achieving higher demisability standards requires continued improvements in material modelling, experimental validation, and spacecraft design adaptations. The research presented in this paper provides a solid foundation for future advancements, supporting the transition toward more efficient and predictable demise solutions. Through ongoing testing, modelling, and design innovations, ESA continues to push the boundaries of D4D, to ensure a safer and more responsible spacecraft disposal.

8 ACKNOWLEDGEMENT

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