Study on Demisability of Optical Payloads: Executive Summary Report

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SUMMARY

This document is the executive summary report for the ESA GSP "Study on Demisability of Optical Payloads" (ESA contract 4000117570/16/NL/LvH). Spacecraft and their payloads are required to meet a casualty risk threshold for uncontrolled re-entries. The requirements demand that consideration be paid to the whole spacecraft and payload in order to achieve an optimised mission that is not penalised, where possible, by the cost of performing a controlled entry. The demisability of the spacecraft bus has received significant attention in recent years, the demisability of payloads has received less focus.

This study aims to identify design solutions to improve the demisability of optical payloads, without impacting their performance. With the final goal of producing a set of guidelines and requirements to be used by optical payload designers and manufactures. The work performed was split into four tasks:

1. Review of the space debris mitigation requirements and identification of the critical issues affecting the demisability of optical payloads (i.e. critical materials and associated component size, etc.)
2. Identification of design for demise techniques for reference optical payloads
3. Assessment of design for demise techniques on reference optical payloads, including impact of spacecraft bus
4. Derivation of guidelines and requirements for design of demisable optical payloads, proposed technology road map and test plans

Preliminary investigations found that the demisability of a significant number of optical payload objects is poor within their anticipated mass and size limits. The material was found to have the most significant impact followed by mass.

Four reference optical payloads were selected for investigation, aimed at covering a wide range of demise behaviours. Design for demise techniques were derived and the relevant techniques selected for each payload. The bespoke nature of the payloads meant the most applicable techniques were dependent upon the payload construction. The most effective techniques are essentially joint-based: either the joints need to be strengthened to reduce the number of separate undemisable components from reaching the ground, or weakened to enhance break-up and provide improved demise of the separated components.

A parametric approach was used to assess the impact of the spacecraft bus, it found that the results of a payload demise study might vary depending on the placement of the payload within and the demise of the spacecraft bus. Comparisons were made between component-oriented and payload-oriented simulations. The interaction of components in the payload-oriented approach is important and can yield different conclusions than would be found in a purely component-oriented study.

Due to the bespoke nature of the optical payloads it is difficult to provide precise guidelines which will guarantee acceptable demise behaviour. Instead the guideline provided intend to open the conversation on demisability with the designers, providing a simple insight into the components which may cause a casualty risk.

1 INTRODUCTION

In order to reduce the impact of space debris on future missions, ESA has adopted a set of Space Debris Mitigation (SDM) guidelines [1] [2] which are applicable to all current and future projects. Spacecraft and orbital stages are required to re-enter Earth's atmosphere within 25 years of mission completion, and this re-entry shall not cause a casualty risk greater than 1 in 10000. Small spacecraft are generally able to comply with the casualty risk requirement with an uncontrolled entry, but once the dry mass of the spacecraft is of the order of 500kg, then this requirement can become a constraint. Since the extra fuel mass and complexity required for a controlled entry can substantially affect the mission cost, these SDM requirements have become key design drivers at system level.

The processes involved in the re-entry of individual objects into the Earth's atmosphere are well known. However, there are very large uncertainties in the manner in which objects break-up, in the predictions of the survivability of objects to the ground, and in the related casualty risks. Clearly the most practical way to prevent any on-ground casualty, without resorting to designs which allow for disposal by controlled entry, is to ensure that no objects reach the surface. Achieving this by tailoring the specific design of a spacecraft through the materials used, the aerodynamic shapes of the components, and the design of the joints for optimum breakup is known as design for demise (D4D). Recently, significant effort has been put into understanding the basics of D4D, and identifying the critical items on a spacecraft which can survive re-entry. The focus has generally been on the spacecraft bus, as improved demisability of the bus reduces the requirements on the payload and does not carry the risk of affecting the functionality of the instruments, and thus the mission. However, the casualty risk predicted from surviving payload objects in a number of recent missions suggests that the payload is an important contributor.

This study aims to identify the critical components from optical payloads and come up with design solutions that will help future designers and manufactures make a payload that conforms to the SDM requirements. The work has been split into four task, the output from one feeds directly into the next. These tasks are as follows:

1. Demisability assessment of optical payloads, including review of the SDM guidelines and identification of reference payloads
2. Derivation of design for demise techniques for optical payloads
3. Assessment of design for demise techniques on the reference optical payloads
4. Generation of guidelines and requirement for optical payload designers and manufactures

Each task forms a section within this report. The overall outcome of this study is a set of guidelines and requirements that optical payload designers and manufactures will follow to improve the demisability of their payload.

2 TASK 1: DEMISABILITY ASSESSMENT OF OPTICAL PAYLOADS

The first task was focussed primarily on the characterisation of optical payload components and their materials for atmospheric re-entry and demise simulations, in order to understand the ground casualty risk associated with non-demising elements. The aim of this task was to motivate the current study with a preliminary assessment of the typical materials, components and demisability of optical payloads, and review types of optical payload that may be found in Low Earth Orbit (LEO).

Because of the diverse range and complexity of the component shapes, it is extremely difficult to determine (even with CFD in some cases) accurately the heating rates to the components under hypersonic re-entry. The uncertainties associated with this difficulty, along with uncertainties in the component aerothermal and aerodynamic response means that it is not currently possible to perform a high-fidelity re-entry assessment of a spacecraft and its payload with the current state-of the-art. Instead the determination of debris fields and associated casualty risk should be determined on a statistical basis driven by these uncertainties. SAM was selected as the destructive re-entry tool for the entire study. This tool was selected for two primary reasons: the range of materials modelling capability is wider than in other codes (including a viscous shear model appropriate for glasses, developed for this activity), and both simple analysis and compound modelling [3] can be conducted which allows one code to be used throughout the activity.

It is not anticipated that the Space Debris Mitigation (SDM) requirements will be too restrictive to the manufacture and design of optical payloads, or to the application of D4D techniques. The casualty risk requirement is the most relevant to this study and one of the most challenging requirements to meet if an uncontrolled re-entry is desired.

2.1 Building Block Study

The preliminary assessment of optical payload components took the form of a building block study. The building blocks that make up an optical payload were identified and then tested. The four types of optical payload building block identified are:

- Structure: the optical bench on which the payload is mounted
- Mirror: reflective payloads, low CTE materials
- Fixtures: the rods and tubular elements which are used to affix the components
- Lenses: reflective and refractive payloads, high transmissivity materials

For each of these building blocks a range of objects has been defined, ranging from relatively small items to a reasonable upper limit on the size/mass. The materials considered covers the commonly used and future ones for satellite optical payload systems. The existing material models were also investigated. For the first three categories, light-weighting of the object is also considered by running the same objects with different masses.

At this initial stage of the analysis, generation of an initial estimate of the uncertainties is useful. Three key parameters have been varied parametrically for this analysis. They are: release altitude; the demise of objects is significantly enhanced by early release. For each object 11 release altitudes are considered, from 60km to 90km in 3km steps. Aerothermodynamic heating; there is significant uncertainty in the heat flux to even basic shapes. For each object, three heating rates are considered, at 80%, 100% and 120% of the nominal SAM heating correlation [4]. Emissivity; the emissivity is notoriously difficult to measure, and the surface properties after significant time in space are not well known. Three values are used for SAM materials where the emissivity is reasonably low. With the parametric assessment of the sensitivities, the number of simulations performed in this building block study is in excess of 33000.

The material was found to have the most significant impact (followed by mass). This indicates that material substitution will be a primary D4D technique. The optical payload component demisability is summarised in Table 1. Note that this is generalised, and some variation may be expected based on mass, release conditions, physical models etc. The mass of the object and release altitude in particular allow the categorisations in Table 1 to become less well defined.

Component (Building Block)	**Demisable Materials**	**Partially Demisable Materials**	**Non-demisable Materials**
Structure (Cuboid)	Aluminium	CFRP	Carbon-Carbon, Silicon Carbide, Titanium
Mirror (Cuboids and cylinders)	Aluminium, Teflon	CFRP	Silicon Carbide, ULE, Zerodur, Optical glass
Fixture (Cylinder)		Titanium, Invar	
Lens (Cylinder)	Soda Lime Glass, Zinc Selenide, Zinc Sulphide, Germanium	Borosilicate Glass, Calcium Fluoride	Fused Silica,

Table 1 Summary (generalised) Component Demisability

The requirement for reflective and refractive optical systems to have high specific stiffness and high thermal stability may make the substitution of materials for structures and mirrors a challenging D4D prospect. Lenses appear to be less problematic with a number of choices available that demonstrate full demise. Full demise of fixtures is possible for cylinders with a sufficiently small radius. This allows the possibility of fixtures being assembled with bundles of smaller fixtures to enhance demisability, providing the required stress/strain character of the fixture is retained.

2.2 Payload Examples

In terms of demisability, the payloads are most simply categorised into reflective and refractive instruments, with the major difference being the mirrors. As a preliminary selection based on interesting components with respect to demise, three reflective and one refractive were examined.

The Multi-Spectral Imager is a visible/near infra-red camera that was launched on the Sentinel 2A satellite in 2015. The camera captures data in 13 bands with wavelength coverage from 443nm-2190nm. This instrument is selected as a silicon carbide based reflective instrument. It has a large monolithic silicon carbide optical bench and three silicon carbide mirrors which are bolted to the support structure.

The Pleiades constellation consists of two identical Earth Observation satellites launched in 2011 and 2012. The satellites contain an optical camera giving high spatial resolution images in both a panchromatic mode (470-830nm) and in a series of broad band filters (blue (430-550nm), green (500-620nm), red (590-710nm) and near-infra red (740-940nm)). The main optics for the camera are a Korsch telescope design using reflective optics based on a set of Zerodur mirrors and so provides a useful contrast to the Sentinel-2 instrument.

The Multi-viewing, Multi-channel, Multi-polarization Imager (3MI), for the ESA/Eumetsat-MetOn ,is included as it is an example of a system with refractive fore optics. The science goal of the instrument is to determine key atmospheric aerosol parameters. The instrument is still in the design phase but a preliminary design has been developed based on the successful POLDER instrument [5].

The Sea and Land Surface Temperature Radiometer (SLSTR), for the Sentiel-3 satellite, measures the flux in four main wavelength bands from 0.55 to 12µm.

These selected payloads have been used as the example payloads to be investigated throughout the rest of this study. It is believed that the demise behaviour of the selected payloads will be diverse.

3 TASK 2: DESIGN FOR DEMISE TECHNIQUES FOR OPTICAL PAYLOADS

The main focus of this task is the identification of design for demise techniques to reduce the casualty risk from optical payloads without any reduction in the instrument capability. The work separates neatly into three parts:

- Identification of likely surviving objects
- Identification of design for demise techniques
- Selection of the most promising techniques, ensuring that there is no compromise on performance or violation of Space Debris Mitigation (SDM) guidelines

Within this task, a set of design for demise techniques applicable to optical payloads has been constructed and applied to the payloads selected in Task 1. In order to ensure that the analysis is robust, a statistical approach has been considered with 1000 Monte Carlo run simulations used for all analyses, object-oriented and spacecraft-oriented, considering relevant uncertainties. The uncertainties and their range is provided in Table 2. This is the first campaign of its type to use significant uncertainty analysis, and the first to apply this to a reasonable number of spacecraft oriented simulations.

Parameter	Distribution	Range
Aerothermodynamic Heating	Uniform	±20%
Fragmentation Altitude	Uniform	78km ± 10%
Speed	Uniform	7700m/s to 7850m/s
Flight Path Angle	Uniform	-0.05^0 to -0.5^0
Material Emissivity	Uniform	ε-0.2(1-ε) to ε+0.5(1-ε)
Initial Attitude	Uniform	Attack -180^0 to 180^0 Sideslip -90^0 to 90^0
Joint Fragmentation Criteria	Uniform	Fail temperature ± 100K Fail force ± 200N

Table 2 Uncertainty Parameters

3.1 Identification of Design for Demise Techniques

Within this assessment, it is assumed that an uncontrolled entry is required, that the inclination of the decaying orbit is fixed such that the casualty area is the driving parameter as the risk is dependent upon the orbit inclination, and that no techniques which violate SDM guidelines other than the casualty risk criterion are considered.

From the Task 1 analysis of the building blocks for optical payloads, it is clear that the main drivers for survival are the mass/material of the object and the release altitude. In order to achieve enhanced demise, three main methods are highlighted. These are sufficiently general that they are useful for application to all D4D assessments. The three methods are:

- Enhanced Environment: These techniques aim to improve demisability by modifying the conditions which are experienced by the component, but do not modify the component itself.
- Increased Demise Potential: The demise potential is an intrinsic property of the component, or system and is changed by direct modification of the item itself.
- Reduced Number of Fragments: The casualty risk is reduced by limiting the number of fragments, either by containment of undemisable objects or by ensuring that undemisable objects do not separate and can be considered to land as a single piece.

For each of the payloads, the relevance and appropriateness of each technique will be assessed. It is expected that different techniques will be effective in different cases.

3.1.1 Enhanced Environment Techniques

Techniques which are identified as enhancement of the environment experienced by components are given in Table 3. In general, these techniques work to improve the initial conditions experienced by the component, and therefore require analysis of the component release from the payload or spacecraft. This restricts the usefulness of the analysis which can be performed at the component level for these techniques.

Technique	Methodology	Notes	Test Level
Payload Housing	Earlier flow exposure		Payload
Payload Location on Spacecraft	Earlier flow exposure	High uncertainty in models	Spacecraft
Payload Layout	Place critical items in flow	High uncertainty in models	Payload
Explosive	Breaks large components	Violates SDM requirements	Payload
Corrosive Agent Release	Enhances separation	Risk may not be acceptable	Payload
Payload Jettison	Enhances heating early in trajectory	Passive heat-based trigger (Shape Memory Alloy)	Spacecraft
Failing Element Dynamics	Collapse of charred CFRP under compression	As most forces are compressive, can this have an effect on fragmentation? Behaviour is not well known	Payload
Adhesive Joints	Enhance separation		Payload

Table 3 Enhanced Environment Techniques

3.1.2 Demise Potential

Techniques which are identified as enhancement of the demise potential of components are given in Table 4. Since these techniques directly influence the design of the components, these techniques are most appropriately assessed at the component level.

Technique	Methodology	Notes	Test Level
Modularity	Increases demisability		Component
Component Shape	Tighter curvature of long shapes		Component
Reduced Mass	Lightweighting / design improvement / 3D printing		Component
Materials	Replace with more demisable material	Functionality must not be degraded	Component
Critical Item Replacement	Replace with demisable alternative	No performance degradation	Component
Critical Item Removal	Remove surviving items	No performance degradation	Component
Reduce Component Size	Increases heating	No performance degradation	Component

Table 4 Increase Demise Potential Techniques

3.1.3 Reducing Fragment Numbers

Techniques which are identified as reducing fragment numbers are given in Table 5. The key aspect here is to reduce the casualty risk, whilst not necessarily increasing the demisability of any component.

Technique	Methodology	Notes	Test Level
Containment	Keep surviving components together	Requires confidence in survival of container	Component
Use of Fewer Parts	Less surviving components	Parts must not be more massive to compensate	Component
Undemisable Joints	Prevents separation of undemisable components	Ensure critical parts hit ground as single item	Payload

Table 5 Reducing Fragment Number Techniques

This set of techniques is contrary to the concept of design for demise, but is an extremely important technique to consider where high performance undemisable materials are in use. Essentially, the casualty risk is reduced by keeping undemisable parts together such that multiple parts only contribute to the casualty risk as a single object. As well as simply using fewer parts, there are two other approaches.

3.2 Selection of Relevant Techniques

In order to identify the design for demise techniques for each payload the following process was followed:

- Performance of a building block study to identify size, shape and material of potentially surviving objects. This was performed in Task 1, and provides a wider range of objects that will be obtained from specific payloads.
- Consolidation of the critical objects using the four payloads selected in Task 1. This was performed in an object-oriented manner with uncertainties included on release altitude.
- Identification of design for demise techniques. This was an iterative process to ensure that the performance of the payload is not affected. Assessment of cost and TRL were made.
- Preliminary assessment of the design for demise techniques using the appropriate complexity of tool for assessment of the particular technique. These were performed at component level in some cases (e.g. material assessment) and payload level in other cases (e.g. joints/adhesives assessment, layout assessment).

- As a payload model is constructed for each of the selected payloads, all four of these can be used for the enhanced assessment of the techniques in Task 3.

The SAM model of the payload is constructed by defining a set of components linked by joints, this is known as the compound model. To ensure the computational time of the payload-level simulations is acceptable the total number of components has been kept below 20. This is achieved by modelling similar components as single compound components. The compound model mesh for each of the payloads is shown Figure 1.

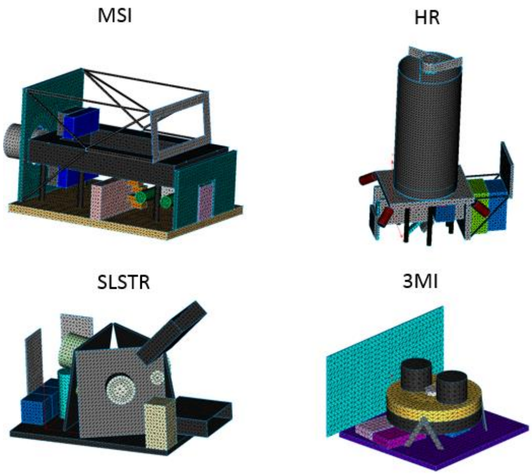

Figure 1 Payload Compound Models

The optical payloads studied demonstrate significantly different demise behaviour dependent upon the payload design, primary structural materials and critical components. For a silicon carbide based payload, such as the Sentinel-2 MSI, the simplest solution is to ensure that the undemisable parts reach the ground connected such that they can be considered a single fragment. This is somewhat contrary to the concept of design for demise, and has the significant risk that joining technologies which can survive the re-entry have never been considered, and quite some testing is required in order to ensure that the joints would survive.

For payloads with CFRP optical bench structures, separation of the parts is highly likely, and the requirement here is to reduce the number of undemisable parts, or to increase the demise of partially demising structures. The first of these requires some redesign of the parts, either to prevent separation or to enhance demise, and the second is most appropriately tackled through enhancing the demisability of joints by ensuring that there is an adhesive failure path which is weak at high temperature. Certain parts can also be redesigned too such that they will not exceed 15J on landing.

Essentially the driving effect for the casualty risk in each of the payload is:

- Sentinel-2 MSI: Prevention of separation of the Silicon Carbide parts
- Pleiades-HR: Redesign of the undemisable parts as they are well separated
- Sentinel-3 SLSTR: Improved joint demisability as the parts are inherently demisable
- Metop-SG 3MI: Containment of telescope lenses

Given the differences between the payloads, it was proposed that all four payloads were to be simulated in Task 3, as oppose to the initial specification of just one, as different techniques have been selected for different payloads (shown in Table 6). This will provide some case studies concerning what can be done to promote demise of optical payloads rather than some generic rules. This is likely to be more useful as it is currently unclear whether a set of generic rules can be satisfactorily applied to all optical payloads.

Payload	**Scenario**	**Techniques**
MSI	1: Reduced Fragment Numbers	Undemisable Joints Adhesive Joints for demisable items
	2: Material Change	CFRP Bench, Mirror, Supports Adhesive Joints for demisable items
HR	1: All Techniques	CFRP Mirrors FPA Mirror Containment Thermal Focussing Unit Redesign
3MI	1: All Techniques	CFRP Main Bipods Carbon-Carbon Telescope Barrels
SLSTR	1: FPA Containment	SiC FPA Housing Fibreglass Baffles Adhesive Joints Smaller Black Body Calibration Units
	2: Demisable FPA	Thinner FPA Housing Fibreglass Baffles Adhesive Joints Smaller Black Body Calibration Units

Table 6 Selected Techniques

The techniques which are most applicable are, as expected, dependent upon the payload construction. The most effective techniques are essentially joint-based; either the joints need to be strengthened to reduce the number of separate undemisable components reaching the ground, or weakened to enhance break-up and provide improved demise of the separated components. These techniques are essentially opposites, and the selection of the most appropriate is payload-dependent. In addition, significant benefit is seen from changes in material, reductions in size and mass and reduction of housing thickness.

It is interesting to note that the joint based approach used in SAM provides spacecraft-oriented solutions which can be clearly understood in relation to the baseline object-oriented solutions, certainly in a statistical sense. This increases the confidence in the solutions obtained, and also demonstrates that the differences generally observed between object-oriented and spacecraft-oriented codes are driven by modelling choices. It is useful to understand that there are cases in which the component level assessment is conservative, and cases where it is not.

This analysis has also highlighted that the understanding of the demise behaviour of CFRP sandwich materials is very poor, as this is a key structural element in a number of the payloads. The standard modelling approach of approximating this by low-conductivity aluminium provides significantly different results from consideration of CFRP facesheets and thus there is a high level of uncertainty in the results for these structures. In order to construct an applicable model, experimental data is required, and this is highlighted as an urgent priority in the analysis of demise of spacecraft structures.

4 TASK 3: ASSESSMENT OF D4D TECHNIQUES ON REFERENCE OPTICAL PAYLOADS

The aims of the work in this section are to:

- Assess the effectiveness of the proposed D4D techniques
- Make comparisons of the ground casualty risk between the payloads of enhanced demisability and the original ones
- Account for the effects of shielding from the spacecraft bus during the re-entry

In keeping with the philosophy of the analysis performed earlier in the study, re-entry simulations were performed using Monte-Carlo based parameter variations (1000 per simulation). This ensures that variations due the significant uncertainties in entry-state, aerodynamics, aerothermal heating, and material response are represented. In total 65,100 payload-oriented simulations were conducted, the MSI scenario 2 run at 80km ran very slowly and so the number of simulations had to be limited to 100.

The simulations and the approach employed attempt to include the influence of the spacecraft bus parametrically; through variation of the payload release height and a simplified spherical shield with fractional exposure of the payload to re-entry flow conditions. These two aspects were assessed independently. The release altitude (a given altitude above which the payload is not exposed to the flow, and thus the heating) was varied from 120km to 80km. Two shielding configuration were considered. The first uses a half-shield, where the baseplate / interface panel is considered connected to the payload and the incident flux from below the payload is neglected (approximately equivalent to the payload sitting on the end of the spacecraft). The second uses the same nominal connection of the payload to the spacecraft, but the range of angles which are considered for heating is reduced to one quadrant (approximately equivalent to the payload being housed recessed within one side of the spacecraft). Both modelling approaches were chosen due to a number of significant advantages including; loss of generality introduced by a specific spacecraft configuration, potential to optimise payload demise through spacecraft D4D, and closeness to the circumstances faced by payload manufactures (i.e. little or no knowledge of the spacecraft details). Payload designers and manufacturers have little or no knowledge of the spacecraft system that the payload will be integrated into – often the spacecraft bus is designed to suit the payload and thus does not exist prior to the payload design.

A general analysis of the impact of the D4D techniques, and the impact of the spacecraft bus proxies has been conducted. For each payload, the predicted casualty areas for all the scenarios, and all the altitude/shield configurations, are plotted on a single figure. In order to capture both the effect of the release altitude, and the effect of the shields, the baseline scenario is plotted in the centre of the figure, with increasing shielding to the left, and reducing altitude to the right. In general, it would be expected that the reduced demisability due to the later object release would result in a minimum casualty risk at the baseline scenario at the centre of the plot, and increasing casualty risk towards each edge.

4.1 Sentinel-2 Mutli-Spectral Imager

The first optical payload studied was the Sentinel-2 Multi-Spectral Imager (MSI), whose casualty risk is primarily driven by components manufactured from undemisable materials (silicon carbide and fused silica). These components make up the fore optics, processing optics and support structures (the critical sub-systems for this payload). Two enhanced demise scenarios were considered, the first aimed to contain the critical components ensuring they landed as one lumped mass whilst the second manufactured them from a more demisable material (CFRP). Adhesive joints were used for the demisable items in both cases.

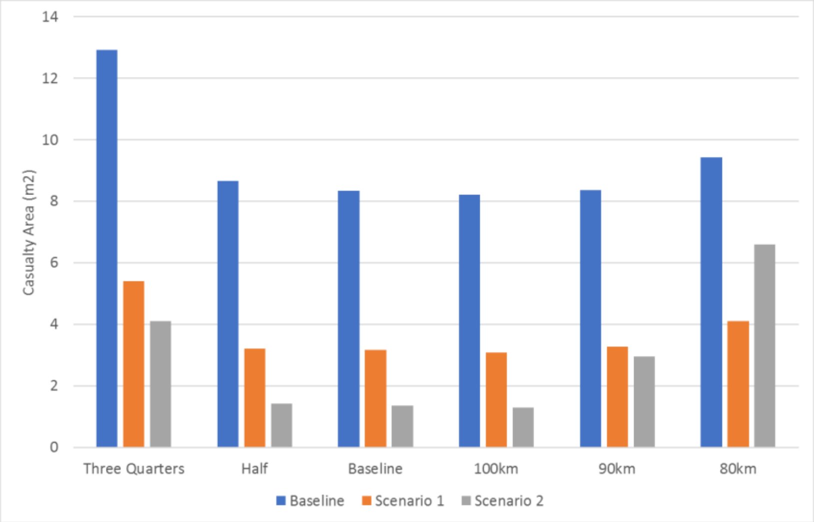

Figure 2 Total Casualty Area for all MSI Scenarios/Conditions

Figure 2 demonstrates that the MSI payload is relatively insensitive to the presence of the payload bus for all three scenarios, unless a more extreme case is considered. Both the selected D4D techniques can be seen to be very effective, and are robust to the existence of the spacecraft bus. Scenario 2 shows worse behaviour than Scenario 1 in only one case, release at 80km, which has been demonstrated as less extreme than the ¾ shield in all other cases. The overall data suggests that the use of demisable materials has a higher potential for demise than the use of undemisable joints or containment. It could be argued that the undemisable joints is a more robust approach, but the results using the ¾ shield provide more confidence than the 80km results as only 100 runs have been considered for the latter case.

From this analysis, it should be expected that the spacecraft bus shielding will result in an increase of the casualty risk relative to the simulation of the payload alone, but that this is most likely to be relatively minor unless the payload is particularly well shielded. This does not have an impact on the selection of the D4D techniques, and their effectiveness is maintained.

4.2 Pleiades High Resolution Optical Instrument

The Pleiades High Resolution Optical Instrument's (HR) casualty risk is again primarily driven by components manufactured from low demisability materials. However, unlike the MSI payload, the critical components are positioned such that it would be infeasible to ensure they landed as a compound object. Instead, three techniques were derived to improve their demisability. These were: to manufacture the mirrors from a more demisable material (CFRP); to contain the focal plane array (FPA) mirror within the FPA housing and to redesign the thermal focussing unit. The material change proved to be the most effective followed by containing the mirror and then the redesigned thermal focussing units.

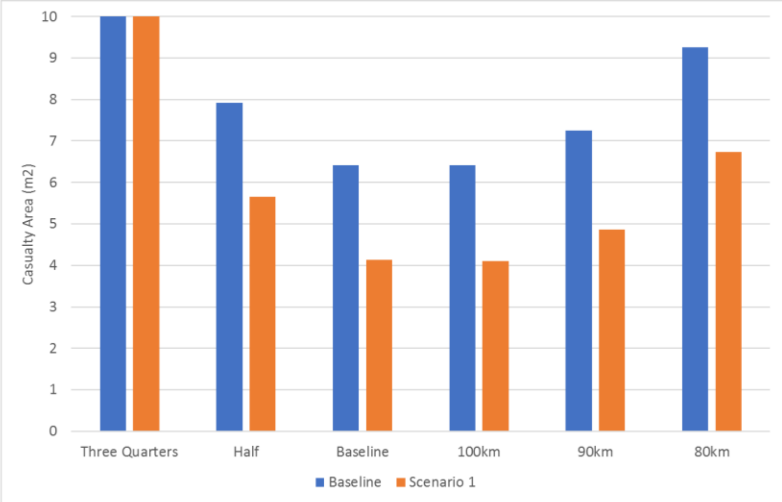

Figure 3 Total Casualty Area for all HR Scenarios/Conditions

As with the MSI analysis, an overall assessment of the potential impact of the payload bus is made. The total casualty area across all the scenarios and initial conditions for the HR payload is shown in Figure 3. For both ¾ shield cases the full height of the bar (baseline: 19.7m^2 and scenario 1: 17.2m^2) has not been shown. These two cases are both extreme results brought about by modelling choices (only relevant when the shielding is particularly extreme) and should not be considered likely. The shape of the curve is very much consistent with the differences being driven by the components which are demisable, but need to be released sufficiently early to demise. The sensitivity to the presence of the payload bus is clearly higher for this payload than has been observed for the MSI payload. This is due to the nature of the components. The D4D techniques applied can be considered successful, and this case provides a useful test case for the potentially large effects of the shielding from the spacecraft bus.

4.3 Sentinel-3 Sea and Land Surface Temperature Radiometer

The Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR) is an optical payload whose casualty risk is primarily driven by components constructed from demisable materials. The majority of the casualty area is from the scan mirrors, the baffles and the focal plane assembly. This was the only payload for which the envisaged D4D techniques, focal plane assembly containment or demise, were ineffective. They were derived mainly from the component-level simulations which can be particularly conservative, especially when the payload is constructed mainly from demisable materials, thus leading to the selection of ineffective techniques. A third, successful, scenario was derived, based off the payload-level analysis. The baffles were manufactured from a more demisable material (aluminium) and smaller black body calibration units were used.

The overall analysis for the SLSTR payload appears quite different from the previous payloads due to the relative ineffectiveness of the containment and fibreglass baffle techniques. In all cases, the majority of the casualty area is from the scan mirrors, the baffles and the focal plane assembly, and only the focal plane assembly is noticeably affected by the spacecraft bus presence. This can be seen in the overall plot of the casualty areas from all the scenarios and conditions shown in Figure 4.

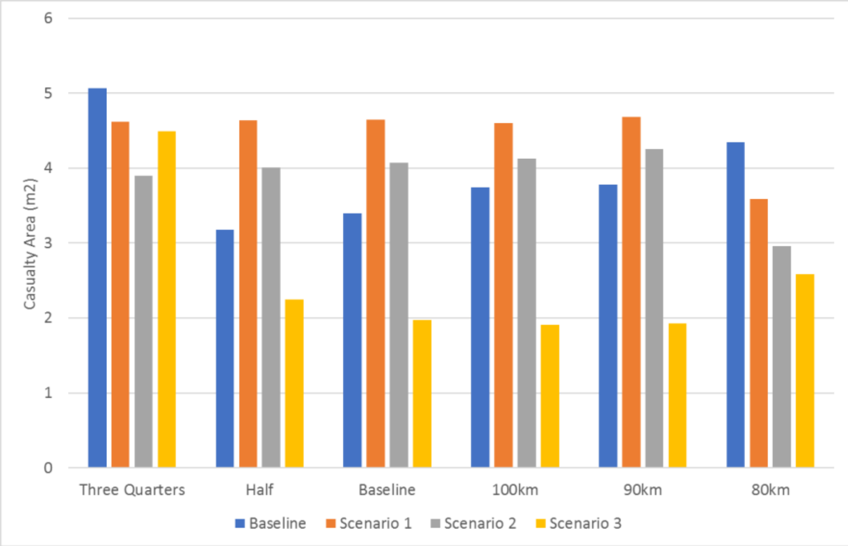

Figure 4 Total Casualty Area for all SLSTR Scenarios/Conditions

The major features on the plot are the effectiveness of scenario 3, and the insensitivity to the shielding. The components for which no techniques are applied are either demisable in almost all cases, or undemisable. The component level analysis suggested that the components could demise, but that there was a significant risk that they might not. This analysis suggests that the spacecraft shielding effects are simply insufficient to drive the solution significantly towards the component level analysis. This is a very useful result as it suggests that the component level analysis can be particularly conservative when the payload is constructed mainly from demisable materials. Even the extreme ¾ shield case does not provide half of the risk suggested by the component level assessment. This is a useful test case for demonstrating the necessity to run spacecraft oriented simulations as a thorough component level analysis proves very conservative for this payload.

4.4 ESA/EuMetSAT-MetOp 3MI Imager

The final optical payload analysed was the ESA/EuMet SAT-MetOp 3MI Imager (3MI) whose casualty risk originates from two sources: the lenses contained within the SWIR and VNIR telescope (fore and processing optics) which made up over half of the risk and the titanium main bipods (support structures). For the demise enhanced scenario, the telescope barrels were manufactured from a non-demisable material (carbon-carbon), in order to contain the lenses, and the main bipods were manufacture from a more demisable material (CFRP).

The robustness of the techniques is shown clearly in Figure 5 when both the shielding simulations and the attitude sensitivity simulations are considered. Even in the ¾ shield case, the reduction in the casualty risk is evident. The most interesting feature of this plot is the counter-intuitive reduction in the casualty area as the release altitude reduces due to the increased probability of the release of the lenses.

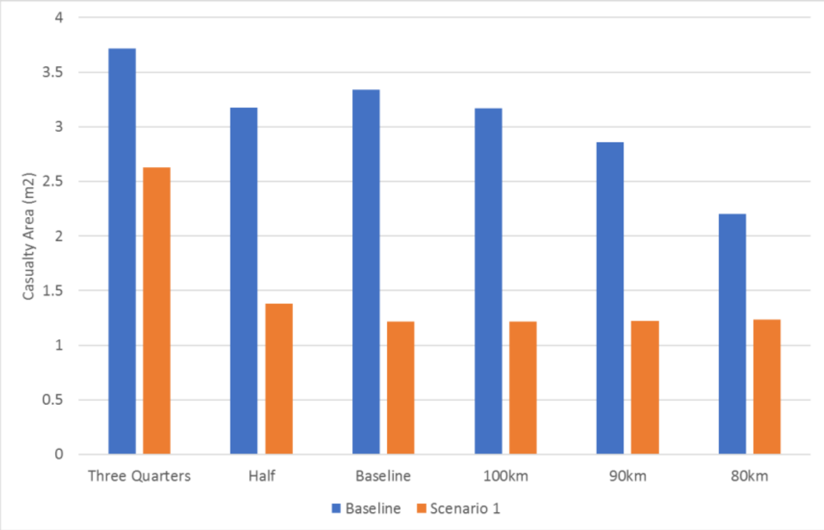

Figure 5 Total Casualty Area for all 3MI Scenarios/Conditions

As this is the most demisable of the payloads, it is interesting that this is the only payload for which a containment technique has proved more effective than an alternative, demisable, approach. Partly, this is due to the nature of the refractive payload as it is not clear how more demisable lenses can be devised, although there is the possibility of designing the lenses such that each lens is sufficiently small that they are below 15J energy criterion on landing. However, it is useful to see that a different class of technique can be effective.

4.5 Remarks on Findings

The results from this work, along with other considerations highlighted by this study, will be used in Task 4 of the study to derive manufacturing guidelines to be applied to the design of future optical payloads. These results will also be exploited in the preparation of test plans to support the development of the demise models and thus increase the viability and confidence in the selected D4D techniques.

Whilst completing this task the payloads' components were categorised into the common sub-systems to assist the development of manufacturing D4D guidelines. The sub-systems responsible for the majority of the casualty risk for each payload were identified. Across all four payloads, the support structures and the processing optics were found to be the most critical (both were critical in three of the cases). These tend to be made up of larger components who are manufactured from less demisable materials. The techniques have had a more positive impact on the support structures; this is because the redesign of the processing optics is likely to affect the performance of the payload. It is expected that the D4D techniques for future payload will mainly focus on these sub-systems however, due to the unique nature of each payload care must be taken as contributions from other sub-systems have also been found to be critical.

Due to the bespoke nature of the payloads, the conclusions of the analysis presented here cannot give a definitive generalisation of the best D4D techniques (in terms of subsystems, materials, containment etc.) as there are different criticalities for different payloads. This was anticipated at the proposal stage, and led to the choice of simulating all four payloads at this point in the study. However, the analytic approach used here is flexible and tractable enough to provide a methodology to design and optimise the payload D4D within the normal system development cycle. This task shows the importance of performing such a study, due to the nonintuitive results that may result from the complexity of the demise pathways. There are also several recommendations that can be derived as a starting point for such analysis, which are specific to the subsystems and/or provide good practises for application of D4D to optical payloads. These will be discussed in more detail as part of Task 4 of this study.

The parametric approach selected to model the impact of the spacecraft bus worked extremely effectively. A range of sensitivities were assessed without the significant effort of generating new geometric configurations. The difference observed between object-oriented and spacecraft-oriented approaches are primarily driven by fragmentation modelling and the heating of components prior to the fragmentation event. In most cases the component level assessment was conservative, which supports an object-oriented approach in the initial design phases of a payload/spacecraft. There are clear exceptions, as with the 3MI payload, but these can be identified within the guidelines to be provided in Task 4. The parametric approach provides both an indication of the robustness of the techniques, and relevant information to pass forward to spacecraft designers to facilitate minimisation of casualty risk from the payload.

5 TASK 4: GUIDELINES AND REQUIREMENTS FOR DESIGN OF DEMISABLE OPTICAL PAYLOADS

The guidelines provided here have been derived from the work conducted throughout this study. They are intended to be a first attempt to open the conversation on demisability with the designers of optical payloads, providing a simple insight into the components which may provide a casualty risk and to provide simple means by which to assess the impact of the payload configuration relative to these critical components. From this, some initial guidelines as to good practice from a demise point-of-view can be elaborated for payloads with differing demise characteristics. The intention is that these guidelines are sufficiently simple, and sufficiently general, that they can be kept in mind and allow choices to be made within the design process which are beneficial to demise, especially where the choice has little effect on performance or cost.

These guidelines are thus separated into two parts:

- Identification of critical elements
- Identification of driving payload demise characteristic, and relevant demisability guidelines

More complex issues such as ballistic coefficient effects have been omitted from this first set of guidelines for simplicity, as it is very difficult to be precise without going into detail which is not considered to be helpful at this initial conversation-starting stage. It is also important to note that all the D4D techniques suggested within the guidelines are fully compliant with Space Debris Mitigation (SDM) guidelines and should provide the payload and spacecraft manufacturers with no problems from the regulators.

5.1 Guidelines on How to Identify Critical Optical Payload Elements

Optical payload elements which may provide a potential casualty risk are identified from the payload material, size and mass. In general, the size and mass are related, so for simplicity only mass is considered here. The critical masses for which components constructed of materials of interest can be considered a potential casualty risk are given in Table 7.

Material	Mass for Potential Risk	Notes
Silicon Carbide	30g	
Titanium	30g	
Invar	1.5kg	
Fused Silica	40g	
Zerodur	1kg	
Carbon-carbon	40g	
Borosilicate glass	1kg	
CFRP	5kg	Large, light items have lower mass threshold Large uncertainties in CFRP behaviour
Aluminium	10kg	

Table 7 Identification of Demisability Risk Components

The majority of the materials listed in Table 7 can be considered undemisable, and thus have a limiting mass for safety of a few tens of grams. This is obtained from the size of component which reaches the ground with an impact energy of less than 15J, which is generally accepted as the impact threshold beyond which a casualty has to be considered. Many of these materials; silicon carbide, titanium, fused silica are in regular use in optical payloads. There are also a number of materials which are slightly demisable; invar, Zerodur, CFRP, which can be used in limited sizes without producing a substantial risk. Aluminium is also included on this list, even though it is considered highly demisable, as it is often used in relatively large masses and these larger components are able to reach the ground.

5.2 Typical Component Risk Guide

As a guide to the ground casualty risks from a set of components, the following table is provided. The components are taken from a range of current and future spacecraft optical payloads. It should be noted that a casualty area of approximately 8m^2 will violate the 1 in 10000 casualty risk criteria, and that a casualty area not exceeding 3-4m^2 is expected to be a requirement from the payload in order to achieve this. In general, most components of concern can be considered to have a casualty area of the order of 0.5m^2 unless the component is relatively large and/or made of a component which does not demise at all. Therefore, a useful rule of thumb is to require no more than six surviving items from the optical payload if an uncontrolled re-entry is to be considered.

Component	Material	Casualty Area
Optical Bench	Silicon Carbide	~2m^2
	CFRP	Small
	Aluminium	Small
Support Structures	Silicon Carbide	0.5-1m^2
Mirrors	Silicon Carbide	0.3-1m^2
	Zerodur	0-1m^2
	CFRP	Small
Beamsplitter Glass	Fused Silica	0.5m^2
Sandwich Panels	CFRP/Aluminium	0-0.3m^2
Electronics		0-0.5m^2
Telescopes	Titanium/Carbon-carbon	0.5-2.5m^2
Lenses	Fused Silica	~0.2m^2

Table 8 Risks from Typical Components

5.3 Critical Design Requirements to Increase the Demisability of Optical Payloads

Once the critical components have been identified, the layout of these components within the optical payload requires assessment. It is important to note that very similar optical payloads can have very different demise characteristics which lead to different potential methods for the reduction of the casualty risk. The driving factor is the number of separate objects which can reach the ground. This can be achieved by reducing the number of components which can survive, or by grouping components together. The assessment of the layout characteristics from a demise viewpoint can be made through answering the questions in Figure 6 and Figure 7.

The first two questions, Figure 6, represent the overall demise characteristics of the payload, which is determined by the nature of the components of concern and the payload structure. Where the answer to both questions is “no”, the techniques are restricted to the special case of the first question in Figure 7, or the individual component construction which is covered in the final two questions.

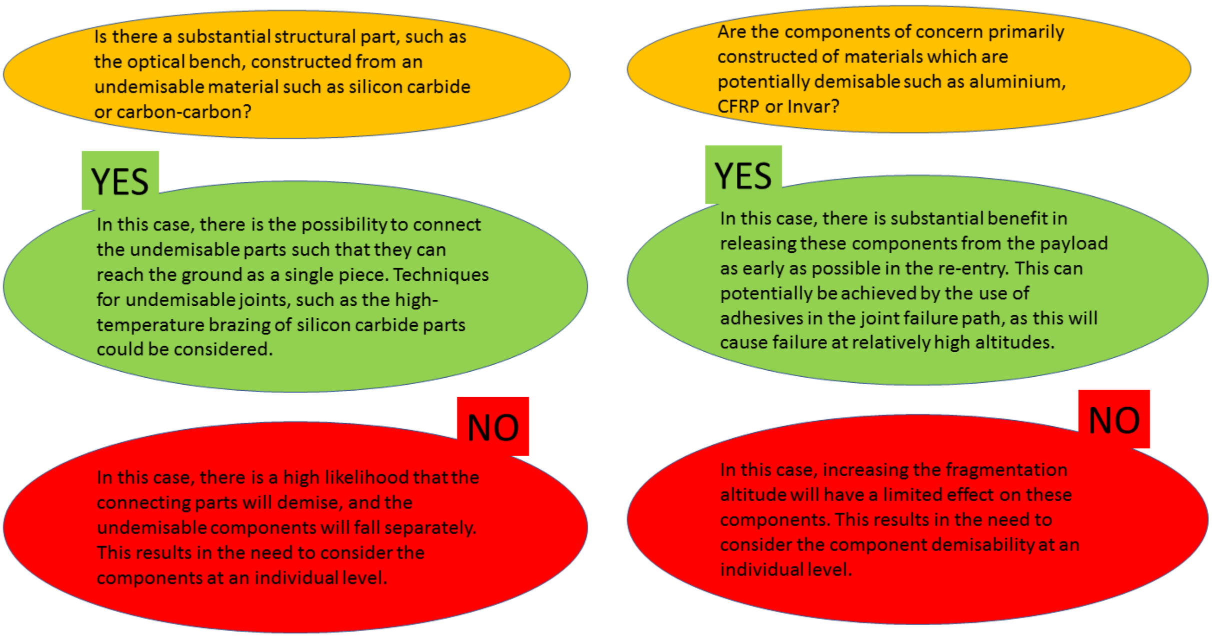

Figure 6 Payload Layout Q&A

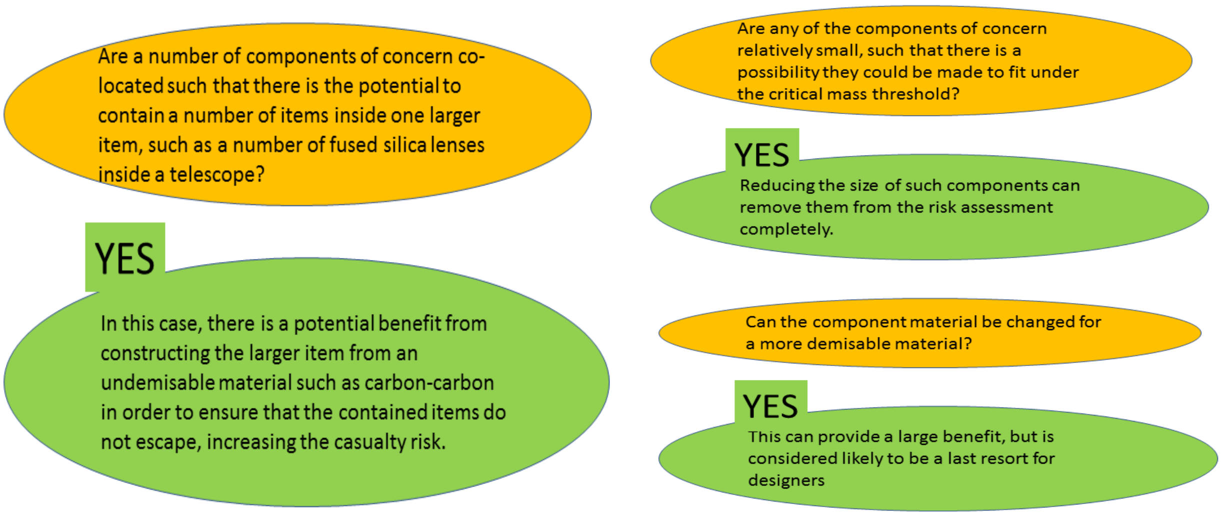

Figure 7 Containment and Component Q&A

A set of design for demise techniques which can be considered in the light of the answers to these questions are given in Table 9. Specific recommendations are made for materials where appropriate.

Technique	Applicable	Recommendations
Undemisable Joints	Undemisable structure	Appropriate for silicon carbide structures
Adhesive Joining Technologies	Components constructed from potentially demisable materials	
Containment	Group of undemisable components are housed together within another component	Do not use titanium for the undemisable housing. It can demise when a shell on a larger object. Carbon-carbon is preferred
Smaller Components	All components of potentially demisable materials	In general, smaller components are more demisable
Reduce Size Below 15J Threshold	Components under ~100g	Likely to be possible for many lenses
Material Change	Components of undemisable material	Only applicable where performance, mass and cost are minimally affected

Table 9 Design for Demise Techniques List

5.4 Overall Approach to Demisability in Design

It is to be expected that all optical payloads will have some components which will be expected to survive re-entry. Therefore, it is good practice to establish a risk budget, which can be done at a basic level in terms of a number of surviving components. As a rule of thumb, for an uncontrolled re-entry, approximately six surviving components can be considered as acceptable. Where a technique such as containment, or undemisable joints is used, the landed components are likely to be larger, and thus a smaller number should be considered depending on the size of the object which is guaranteed to land. It is also recommended to consult with demisability experts on the potentially critical components and layout of the payload early in the design stage in order to assess the likelihood that an uncontrolled re-entry can be considered from a payload perspective.

Recommendations can then be made for the payload which can assist the decision to pursue the possibility of having sufficient demise performance such that this may be achieved.

6 TECHNOLOGY ROADMAP AND TESTPLANS

6.1 Technology Developments for Optical Payloads

The general aims of most satellite development are to make components smaller, lighter and to use more demisable materials. When talking about design for demise, the future technology can be split into two main areas; improving the demisability of the optical bench and support structures, and utilising new techniques and materials to improve the demisability of the optical elements.

A range of materials are currently in use as the optical bench and support structures. The current technological developments are primarily focused on increasing the demisability of said materials. One of the most promising technologies is additive manufacturing, which has the potential to obtain a significant reduction in mass while maintaining the same structural performance. Currently most work on aerospace application is concentrated on metal products however, there is also work on additively manufacturing ceramic components (e.g. Silicon Carbide) [6] [7]. Issues with the production of large monolithic ceramics with the same material properties as traditional methods result in a lower TRL.

Improving the demisability of the optical elements is trickier as it is vital that their performance is unaffected. Aluminium mirrors have space heritage [8] however, they have fallen out of use as they have a relative high coefficient of thermal expansion (CTE) of 23ppm. Recent research has been published where an aluminium-silicon alloy is used that matches the CTE of nickel and could provide thermally matched Ni-Al mirrors [9], a nickel coating gives a better surface finish. Additive manufacture of mirrors is also currently being researched, however it is at a low TRL. Sample mirrors have been made from a range of metals and PEKK polymer [10] [11] however, there are problems with surface figure and so far, the mirrors have been rather small (a few 10s of centimetres).

Carbon Fibre Reinforced Polymer (CFRP) composite mirrors [12] have many desirable properties; low CTE, higher thermal conductivity than glass, high stiffness and low density. There has not been a great use of composite mirrors in current optical payloads mainly due to concerns about surface figure accuracy in production and long term stability. Some environmental testing has been done however, to increase the TRL level further environmental testing is needed along with development of better control of the surface figure after curing. Another way to improve the demisability of the optics is to decrease the size of the optical system. Conventional optics (on and off axis sections of spherical or axisymmetric aspheric surfaces) are limited in this respect. The use of free from optics (non-axisymmetric, higher order polynomial, Zernike polynomial) has the potential to enable more compact designs with the same performance [13]. This technology is currently limited by the ability to measure the optical surface during manufacture. Although, new testing techniques such as phase deflectometry [14] offer the potential to measure more extreme optical forms [15].

The estimated TRL level of the identified technologies is provided in Table 10.

Technology	TRL Level	Estimate cost to develop to indicated TRL level
Additive manufactured metal optical bench	TRL 3-4	0.5-1M€ to TRL 5
Additive manufactured support structures	TRL 7-8	-
Additive manufactured metal mirrors	TRL 3	1-1.5M€ to TRL 5
Additive manufactured silicon carbide structures	TRL 3	20M€ to TRL 7-8
Carbon fibre composite mirrors	TRL 5-6	3M€ to TRL 7
Compact free form optics	TRL 2	1-1.5M€ to TRL 4

Table 10 TRL Level of D4D Technologies

6.2 Test Plans for Material Demise Model Validation and Improvement

The guidelines and recommendations provided have a dependency on the accuracy of the modelling approach employed throughout this study. Therefore, test plans have been laid out to further increase confidence and development in them. These test plans will also support the demonstration of feasibility of the identified design for demise solutions and their future development.

A thorough examination of the modelling approach has identified three main uncertainties, two of which concern the demise behaviour of certain materials and the third is associated with the undemisable joints. The first, and potentially the most critical, uncertainty is the demise model for the aluminium-CFRP sandwich material. This material is regularly used in the construction of optical payloads; large panels and support structures are manufactured from it. The high frequency of its use and the overall large size of the components demonstrate the importance of developing an accurate demise model. The actual demise behaviour of the material is relatively unknown and is likely to include several modes of failure involving ablative and mechanical processes. A lack of experimental data inhibits the construction of a reliable model. Test plans propose to investigate the demise behaviour of this material and produce representative models.

The demise behaviour of optical glasses such as Fused Silica and Zerodur is another area of uncertainty. For the purposes of this study a new model was developed for glass demise. This model is believed to be more representative than a latent-heat melting (metal-like) model, although there is no representative validation data in the open literature. Thus, testing is required to validate and improve the model.

The feasibility of undemisable joints needs to be investigated. This is a D4D technique which prevents the separation of two or more components by permanently connecting them to ensure they land as a single fragment. Potential methodologies for undemisable joints need to be identified and tested. Silicon Carbide, the main target for this technique, is known to be susceptible to shattering by thermal shock. It is highly recommended that prior to the testing of undemisable joints, thermal shock fragmentation of undemisable materials (particularly Silicon Carbide) is investigated. As it is a requirement of the undemisable joint technique that the joined components do not fail.

Detailed test plans were constructed [16].

7 CONCLUSION

Application of design for demise techniques has been shown to be extremely effective at reducing the casualty risk from optical payloads. The real challenge faced by industry will be its integration, whilst ensuring that the techniques have a negligible effect on the payload performance or cost. At present controlled re-entry is preferred for highly critical payloads; D4D will initially only be used for marginal cases (optical payloads with a casualty area between 8-9m^2). A substantial change in the culture is required for D4D techniques to be used for the more critical cases. In order for design for demise to be effectively implemented a new branch of the system engineering process is required, with expert demise engineers to provide guidance. A balanced approach with optical payload manufactures and aerothermal-demise engineers working collaboratively is likely to be the most pragmatic way to include D4D considerations into payloads. A large emphasis must be made on helping designers understand what a payload looks like from a demise point of view, allowing D4D techniques to be discussed early in the design phase.

A similar approach as taken in this study, could be readily integrated into payload system design. The necessity of such an approach is evident from the bespoke nature of the payloads. Early design phases would incorporate identification of critical components (Task 1), intermediate design phases would include the bulk of the work to identify D4D techniques and provide preliminary qualification of uncontrolled re-entry simulation (Task 2), then in the final design phases, detailed qualification simulations would be performed (Task 3). At all stages, this study used an expert in optical systems, to approve choices and steer the study/design to a feasible solution.

Less invasive techniques, to the design phase, are preferred, especially at this early stage of concept maturity. For instance, containment of undemisable components is preferable to material substitution. The introduction of more invasive techniques must be driven from the customers or LSIs, the safety of using tried and tested materials for the optical equipment is something that needs to be overcome. The technology road map and test plans presented will increase confidence in the identified D4D techniques. Initially, these D4D techniques will be used on aspects that do not have a major impact on the optical performance such as the support structures.

Running simulations that follow the procedure of those conducted throughout this study early in the design phase is essential, providing an indication of the criticality of the payload. In particular, the statistical approach to re-entry simulations, in our opinion provides the only representative assessment of casualty risk and measured improvement of D4D techniques, given the current state-of-the-art. Following the guidelines and requirements set out in this report as well as running further iterations of said simulations will lead designers to enhanced demisability designs. Once a system is in place for the marginal cases, it should be transferrable to more critical cases that would currently opt immediately for controlled re-entry. The development of the technologies identified in the technology road map and the validation of D4D techniques through the laid-out test plan will increase payload manufactures' confidence in design for demise.

8 DISTRIBUTION

ESA-ESTEC Antonio Gabriele

FGE Contract No C798

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