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TECHNICAL NOTE

DIVE - Guidelines for Analysing and Testing the Demise of Man Made Space Objects During Re-entry

APPROVAL

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1 INTRODUCTION

1.1 Scope and Objectives

This document aims at providing guidelines to support the verification of requirements related with on-ground casualty risk and demise during the atmospheric re-entry of a space object.

These guidelines are applicable to different users as presented below:

- **System level:** the document provides guidance on how to model and verify the compliance with the re-entry casualty risk requirements for all systems going through an atmospheric re-entry at the end of life. At this level, this document is applicable for system integrators, re-entry simulation modellers, systems engineers & re-entry analysis reviewers. For these users the verification process is described in Section 2.1.
- **Equipment Level**: the document provides guidance on how to define equipment level demise requirements, as well as how to verify these requirements, defining guidelines for their modelling and test. At this level, this document is applicable to equipment developers, re-entry simulation modellers, demise test designers & operators, re-entry analysis reviewers and R&D activities technical officers. For these users the verification process is described in Section 2.2.
- **Material Level**: the document provides guidance on how to characterise the material demise behaviour, through modelling and test. At this level, this document is applicable to materials developers, demise test designers & operators and R&D activities technical officers. For these users the verification process is described in Section 2.3 .

For the correct interpretation, the users of this Technical Note guidelines are strongly advised to involve experts on re-entry analysis.

This document is considered a living document and can be regularly updated in line with results obtained in the scope of system or equipment level analyses and test.

NOTE: The document gives particular attention to use-cases targeting space objects going through an uncontrolled re-entry. For users targeting other applications or re-entry trajectories, special attention shall be placed on the definition of the re-entry conditions and in the consistency of the models used with the range of application for which they have been derived and verified.

1.2 Applicable and Reference Documents

1.2.1 Applicable documents

[AD1]. European Space Agency, ESA Re-entry Safety Requirements, ESSB-ST-U-004, Issue 1 Revision 0, 2017.

[AD2]. European Space Agency, ESA Space Debris Mitigation Compliance Verification Guidelines, ESSB-HB-U-002, Issue 1 Revision 0, 2015.

[AD3]. European Space Agency, Space Debris Mitigation Policy for Agency Projects, ESA ADMIN IPOL(2014)2, 2014.

[AD4]. European Space Agency, ESA Debris Risk Assessment and Mitigation Analysis (DRAMA) Software User Manual, Issue 2 Revision 2, 2019

[AD5]. European Cooperation for Space Standardization, ECSS system: Glossary of terms, ECSS-S-ST-00-01C, 2012

1.2.2 Reference documents

[RD1]. B. Fritsche, T.Lips, and G. Koppenwallner; Analytical and numerical re-entry analysis of simple-shaped objects, Acta Astronautica, Volume 60, Issues 8–9, April–May 2007, Pages 737-751.

[RD2]. H. Klinkrad, B. Fritsche, and T. Lips; A Standardized Method for Re-Entry Risk Evaluation, Proceedings of the 55th International Astronautical Congress, Vancouver, Canada, 2004.

[RD3]. Belstead, R.Tech, University of Strathclyde, AIRBUS, ThalesAlenia Space, CNES; Probabilistic assessment of re-entry breakup analyses and derived quantities, ESA contract 4000125357/18/D/SR, 2019.

[RD4]. M. Fittock, J. Beck, A. Flinton, A. Gibbings, A. Gulhan, V. Liedtke, T. Lips, J. Merrifield, J.C. Meyer, G. Proffe, T. Schleutker and T. Soares; Methodology and results of high enthalpy wind tunnel and static demisability tests for existing s/c structural joining technologies, Proceeding of the 69th International Astronautical Congres, 2018

[RD5]. T. Lips; Equivalent Re-Entry Breakup Altitude and Fragment List, Proceedings of the 6th European Conference on Space Debris, Darmstadt, Germany, 2013.

[RD6]. Lips, T., Wartemann, V., Koppenwallner, G., Klinkrad, H., Alwes, D., Dobarco-Otero, J., Smith, R. N., Delaune, R. M., Rochelle, W. C., and Johnson, N. L.; Comparison of Orsat and Scarab Reentry Survival Results, Proceedings of the 4th European Conference on Space Debris, Darmstadt, Germany, 2005.

[RD7]. Spel M., Rivola V., Plazolles B.; First Spacecraft Demise Workshop – Test Case Description and Results, Proceedings of the 8th European Symposium on Aerothermodynamics, 2015.

[RD8]. J. Beck , T. Soares, L. Innocenti, A. Caiazzo, T. Shleukter, A. Guelhan; Plasma Wind Tunnel Demisability Testing of Spacecraft Equipment, First International Orbital Debris Conference, 2019.

[RD9]. J. Merrifield et al., "Aerothermal heating methodology in the spacecraft aerothermal model (SAM)," 7th IAASS Conference, Friedrichshafen, 2014.

[RD10]. D. Riley et al., "Design for Demise: Systems-level techniques to reduce re-entry casualty risk", 7th European Conference on Space Debris, 2017

1.3 Background

With the adoption of the space debris mitigation guidelines by most space agencies, spacecraft in Low Earth Orbit (LEO) protected regions, must be removed from their operational orbit within 25-year post-mission. This leads to the re-entry of the spacecraft within Earth's atmosphere. During re-entry, even if most of the satellite equipment disintegrates within the atmosphere, several critical components could survive and impact the ground, fragmented or as a whole (e.g. propellant tanks, reaction wheels, magnetorquers and optical payloads). This may pose a great danger when occurring over highly populated areas.

According to safety regulations adopted by ESA, as well as other Agencies, the estimated on-ground casualty risk for any space object upon its atmospheric re-entry, shall be lower than 10^{-4} [AD3]. For this risk estimation one shall consider all objects resulting from the re-entry event and impacting the surface with a kinetic energy equal or above 15J.

For space systems with an expected high on-ground casualty risk, controlled re-entries can be performed in order to comply with the aforementioned guidelines, and ensure these surviving fragments will impact the ground in non-populated areas. This strategy however results in significant impacts on the space system mass, complexity and cost. Alternatively, uncontrolled re-entries may be performed, by ensuring the satellite naturally decays within 25 years post mission and demises within the atmosphere. This strategy has much more limited system impacts, however, it calls for additional measures in order to comply with the on-ground casualty risk requirement. This can be achieved by designing the spacecraft with the Design for Demise (D4D) approach, which means designing the spacecraft in such a way that it will disintegrate during re-entry.

The D4D methods are usually classified into two main categories, depending on whether they impact the entire spacecraft, i.e. system level, or focused on a specific equipment, i.e. equipment level. The assessment of the demise of space systems and equipment implies computational tools, i.e. simulations, on-ground facilities testing and re-entry flight experiments. The computational tools attempt to capture the physical processes during re-entry, and thus are thoroughly based on the thermal properties of the typically used materials. Tests are performed using on-ground facilities, often attempting to reproduce the aerothermal and mechanical phenomena occurring upon re-entry, thus enabling, to some extent, the validation of models used in the computational tools. As much as these means are complementary, there are still large gaps and approximations, which require further understanding.

As the demise process is highly complex, and not yet fully understood, this Technical Note is based on lessons learnt and best practices that have been developed during various R&D activities. Building on this, guidelines and criteria for demise verification at system, equipment and material levels are established in this Technical Note.

1.4 Acronyms and Definitions

1.4.1 Definitions

Adopted from the ECSS Glossary [AD5]: Spacecraft, Qualification, Verification, Validation

Aerothermodynamics coefficients
The aerothermodynamics coefficients are dimensionless numbers that measure specific phenomena related to the aero-thermo-dynamics field (e.g. the Stanton number coefficient is a dimensionless number that measures the ratio of heat transferred into a fluid to the thermal capacity of fluid and it is used to characterise heat transfer in forced convection flows).

Ballistic Coefficient
The ballistic coefficient (BC) of a body is a measure of its ability to overcome air resistance in flight. It is defined as BC=M/(CD*A) where M is the object's mass and CD is drag coefficient of the object and A is the cross sectional area of the object in the direction of the object's motion relative to the atmosphere.

Critical Elements
Equipment and/or parts of spacecraft that are typically identified as surviving re-entry in system level re-entry simulations, or that have been confirmed by in-situ observations as surviving the re-entry event.

Component based model
DRAMA-like model.

Demise
The result of an ablation processes acting on an element during a re-entry event to the extent that the resulting fragments no longer pose a casualty risk.

> NOTE: An element is a whole space object (e.g. spacecraft, launch vehicle orbital stage) or part thereof (e.g. tank, reaction wheel, magnetorquer).
>
> NOTE: The hyper-surface in a phase space which defines the region of full demise for an object shall be denoted as the demise surface (e.g. the altitudes and re-entry corridor parameters for which an equipment is fully demisable).
>
> NOTE: A melt-based demise event occurs when an object has become molten and melted away. For metal alloys this is the baseline demise process.

Equipment
Any component, sub-system, part, or element being combined to a space system.

> NOTE: In the scope of this document, equipment covers general sub-systems, e.g. reaction wheels, tanks, electronic components, etc., but also structural joints.

External equipment
An external equipment is a space system unit or sub-assembly mounted entirely outside the primary or secondary structure of the space system and which is immediately exposed to heating at the beginning of the space system re-entry event.

Fragmentation
The end of existence of a physical connection between spacecraft parts caused by interaction with the re-entry environment.

NOTE: Fragmentation can be caused by a melting event. This process can be used at structural level, when a bracket melts and leads to a system level or equipment structural fragmentation.

NOTE: Fragmentation caused by a melting event cannot be used at material level, as a melt events will not create fragments but only droplets. This is considered to be an ablation process and hence constitutes a demise event.

Internal equipment
An internal equipment is a space system unit or sub-assembly contained **within** the primary or secondary structure of the spacecraft and which is not immediately exposed to heating at the beginning of the space system re-entry event.

Nest-level (of an equipment)
The number of blocking elements between an equipment and the aerothermodynamical flow field responsible for the potential demise during a re-entry event

NOTE: An equipment on the outside of a spacecraft has nest-level 0, an equipment on the inside of an outer panel of a spacecraft has nest-level 1.

NOTE: In component based models, such as the DRAMA tool, nest-level corresponds to level of depth of the “included in” relation but is unaffected by the “connected to” relation. In panel based models, the nest-level can also be affected by the modelling of supporting structures for equipment, e.g. reaction wheel brackets.

Panel based model
SCARAB-like

More detailed model[1]
For the purpose of this document, any simulation model which extends the capability of ESA’s re-entry break-up simulation software DRAMA is referred to as “more detailed”

NOTE: More detailed does not necessarily imply more accurate or precise when it comes to representing the physical reality.

NOTE: More detailed models are also referred to as “higher fidelity models” in chapter 3.1

Re-entry corridor or trajectory bundle
The set of trajectories of an undemisable sphere, with area to mass ratio varied uniformly representative for the population of spacecraft known to undergo uncontrolled re-entry, for a variable inclination range, starting at a geodetic altitude of 120km from a circular orbit.

NOTE: These set of trajectories are used to define the demise or fragmentation regions of a space object, and as such can be limited to representative ranges in inclination.

Release altitude (of an equipment)
Altitude involving separation of the item (equipment) from the main (parent) object and its full exposure to thermal fluxes during re-entry

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[1] In [AD1] more detailed model is referred to as higher fidelity tool. Both definitions could be used.

Significant fragmentation event
A significant fragmentation event is an event that affects the demisability of the fragments generated by the fragmentation.

> NOTE: For example, complex mechanical assemblies can include sub-assemblies that provide a level of shielding to other sub-assemblies. The break up would expose these sub-assemblies separately to the heat flux.

Structural element
A structural element (e.g. sandwich panel, metallic bracket, insert, bolt, etc.) ensures the structural integrity of the spacecraft during its lifetime (including launch environment), providing a mechanical interface between parts of the space system.

> NOTE: During re-entry, the failure of a structural element will lead to a fragmentation event (e.g. failure of main spacecraft panels' structural joints)

> NOTE: for the purpose of this document, the structural elements definition shall include all physical connections that may prevent the separation of the parts from each other, i.e. it shall include harness, piping, etc.

1.4.2 Acronyms

Acronym	Explanation
3 DoF	3 Degrees of Freedom covering translational movement only
6 DoF	6 Degrees of Freedom covering translational and rotational movement
BBU	Ball Bearing Unit
CFD	Computational Fluid Dynamics
CFRP	Carbon Fibre Reinforced Polymer
COPV	Composite Overwrapped Pressure Vessel
DIL	Double Pushrod Dilatometer
D4D	Design for Demise
DRAMA	Debris Risk Assessment and Mitigation Analysis
DSC	Differential Scanning Calorimeter
DTA	Differential Thermal Analyser
ECSS	European Cooperation for Space Standardization
ESTIMATE	European Space maTerIal deMisability dATabasE, available at https://estimate.sdo.esoc.esa.int/
FEM	Finite Element Model
LFA	Laser Flash Analysis
MTQ	Magnetorquer
NIST-JANAF	National Institute of Standard and Technology - Thermochemical Table

Acronym	Explanation
PWT	Plasma Wind Tunnel
RW (or RWL)	Reaction Wheel
SADM	Solar Array Drive Mechanism
SAM	Spacecraft Aerothermal Model
SCARAB	SpaceCraft Atmospheric Re-entry and Aerothermal Break-up
TG	Thermo-Gravimetry
WTM	Wind-Tunnel Mode

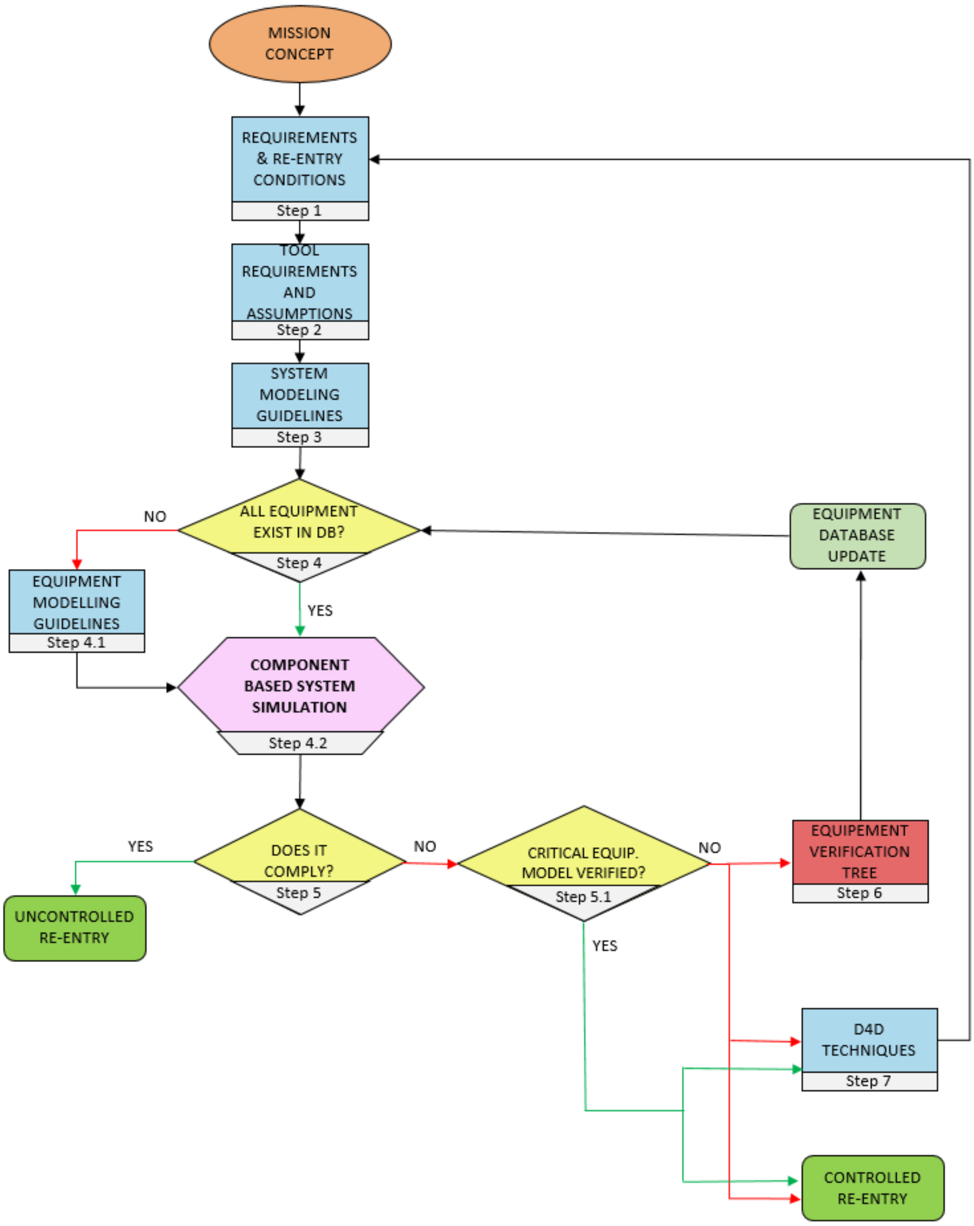
2 DEMISE CHARACTERISATION AND VERIFICATION PROCEDURE TREES

In this section logical flow-charts (trees) for the demise verification are proposed, respectively at:

- System level, section 2.1
- Equipment level, section 2.2
- Material level, section 2.3

For each flowchart, a brief step-by-step description of the process is given.

2.1 System level Verification Tree

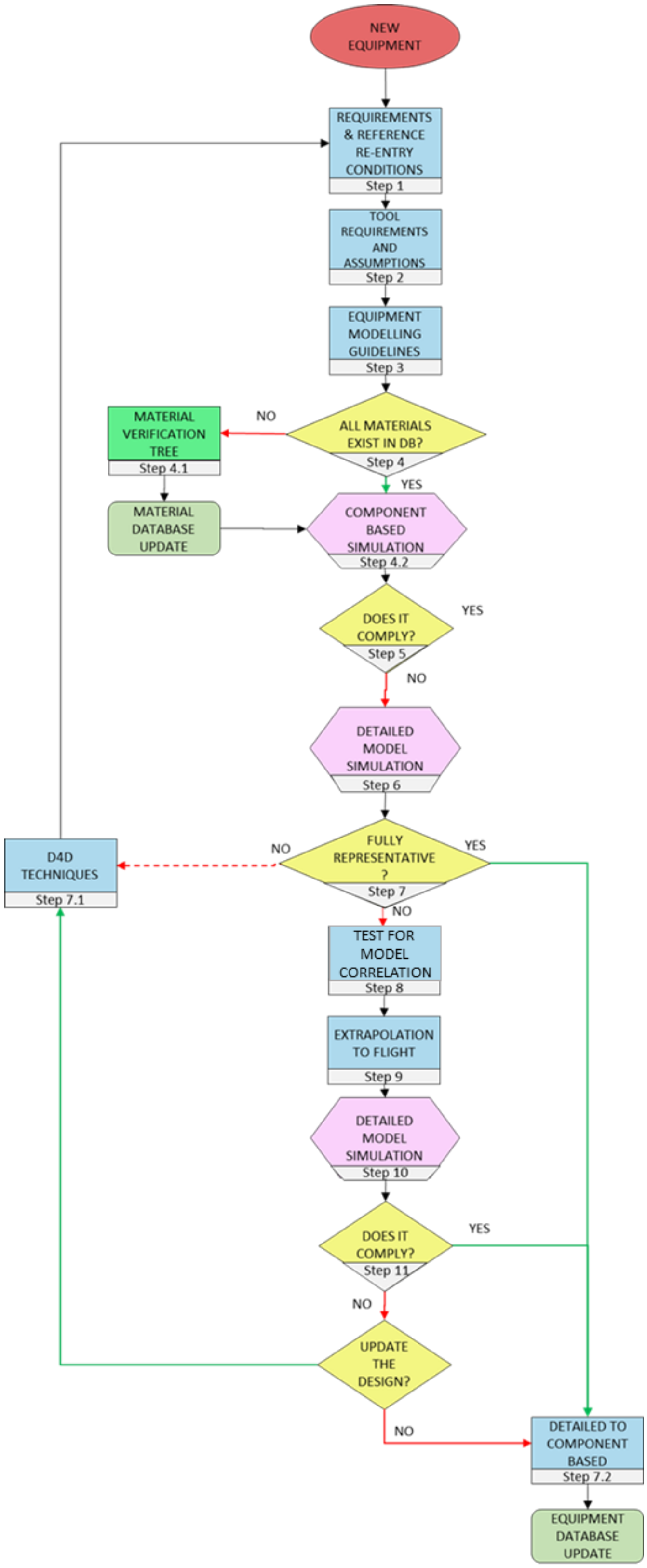


STEP	DESCRIPTION
1: REQUIREMENTS & RE-ENTRY CONDITIONS	The re-entry conditions are derived from the mission concept. The requirements and the guidelines of the re-entry conditions needed for the verification at system level are provided in this document. Please follow chapter 3.1.
2: TOOL REQUIREMENTS AND ASSUMPTIONS	The re-entry analysis shall be performed with the ESA tool DRAMA. The use of tools other than the ESA tool DRAMA shall be compliant with the requirements and assumptions provided in this document and approved by the ESA relevant authority specified in the Space Debris Mitigation Policy of Agency Projects. In case the user is using re-entry tools other than DRAMA the considerations provided in chapter 4.1 shall be taken into account.
3: SYSTEM MODELING GUIDELINES	Guidelines for the system modelling in order to perform the simulations in the frame of this verification process, are provided in this document. Please follow chapter 4.2.1.
4: ALL EQUIPMENT EXIST IN DB?	The modelling of the overall system includes the modelling of the equipment. Two possible cases are foreseen: • Validated models of all equipment exist and are available in the database (YES) - please skip step 4.1 and proceed to Step 4.2. • Not all equipment exist in the database (NO) – please proceed to step 4.1.

4.1: EQUIPMENT MODELLING GUIDELINES	Not all the equipment have validated models available in the database. In this case, the verification process foresees the use of the equipment modelling guidelines in order to model the new equipment. Please follow chapter 4.2.2. This chapter provides modelling guidelines based on materials available in the database and primitive shapes with the appropriate relations/connections between them.
4.2: COMPONENT BASED SYSTEM SIMULATION	All the equipment are available in the database, or modelled through step 4.1. After completing the system modelling, a component based simulation execution is required at system level.
5: DOES IT COMPLY?	Does the simulation show compliance with the system level requirements defined in Step 1? The casualty risk shall be estimated following the Risk estimation guidelines provided in chapter 3.4. If YES- an uncontrolled re-entry is possible. If NO- please proceed to step 5.1.

5.1: CRITICAL EQUIP. MODEL VERIFIED?	An equipment can be considered critical in this frame, if its impact at system level is significant, therefore if it is impacting on the compliance with the system level requirements (these can be found in chapter 3.3.). If the critical equipment has been verified (YES), i.e. can be found in the database or has been verified through the equipment tree (chapter 2.2), then two options are available: 1. Consider improving the design taking Design for Demise Techniques into account, please proceed to step 7. 2. Perform controlled re-entry. If the critical equipment has been verified (NO), then three options are available: 1. Consider improving the design taking Design for Demise Techniques into account, please proceed to step 7. 2. Perform controlled re-entry. 3. Verify the equipment model by going through the steps of the Equipment Verification Tree, please proceed to step 6.
6: EQUIPEMENT VERIFICATION TREE	Please follow the equipment verification tree that can be found in chapter 2.2.
7: D4D TECHNIQUES	A short description and recommendation of Design for Demise Techniques can be found in [RD10].

2.2 Equipment level Verification Tree



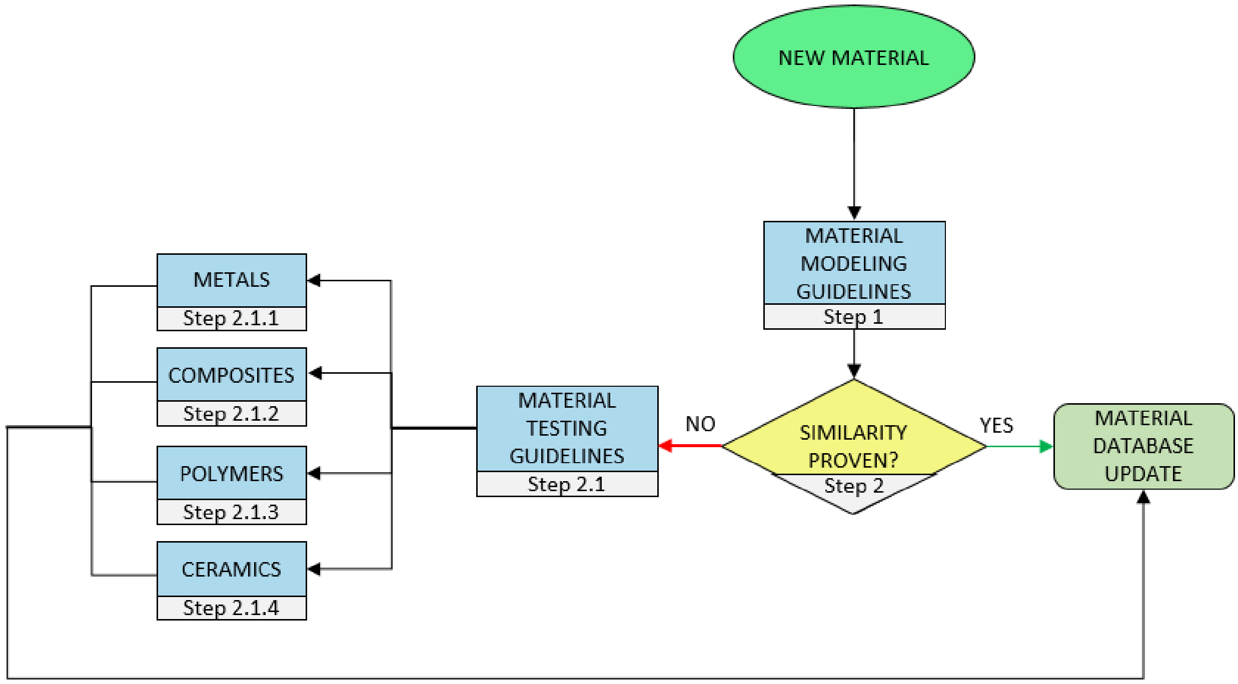
STEP	DESCRIPTION
1: REQUIREMENTS & REFERENCE RE-ENTRY CONDITIONS	At equipment level, the logic for the verification of the demise starts from the requirements and the range of reference re-entry conditions at which the verification at equipment level has to be assessed. The guidelines on how to define the equipment level demise requirements and re-entry conditions are provided in chapter 3.2.
2: TOOL REQUIREMENTS AND ASSUMPTIONS	The re-entry analysis shall be performed with the ESA tool DRAMA. The use of tools other than the ESA tool DRAMA shall be compliant with the requirements and assumptions provided in this document and approved by the ESA relevant authority specified in the Space Debris Mitigation Policy of Agency Projects. Please follow chapter 4.1.
3: EQUIPMENT MODELLING GUIDELINES	The verification process foresees the use of the equipment modelling guidelines in order to model the new equipment. Please follow chapter 4.2.2. This chapter provides modelling guidelines based on materials available in the database and primitive shapes with the appropriate relations/connections between them.
4: ALL MATERIALS EXIST IN DB?	The modelling of a new equipment is based on primitive shapes and database materials. Two possible cases are foreseen: 1. All the materials exist and are available in the database (NO) – please proceed to step 4.1. 2. Not all materials exist in the database (YES)- please skip step 4.1 and proceed to step 4.2.
4.1:MATERIAL VERIFICATION TREE	Please follow the equipment verification tree that can be found in chapter 2.2.
4.2: COMPONENT BASED SYSTEM SIMULATION	All the materials are available in the database, or verified through step 4.1. After completing the modelling, a component based simulation execution is required.
5: DOES IT COMPLY?	Does the model comply with the equipment level requirements? These can be found in chapter 3.2. If YES- the model is verified and has to be updated as a database entry. (if the process has started at system level, please proceed to follow the system level tree from the "EQUIPMENT DATABASE UPDATE "box).

<table>
<tr><td></td><td>If NO- please proceed to step 6.</td></tr>
<tr><td>6: DETAILED MODEL SIMULATION</td><td>For detailed model simulation guidelines, please follow chapter 4.2</td></tr>
<tr><td>7: FULLY REPRESENTATIVE?</td><td>In order to assess whether the more detailed model is representative the user shall address the following questions:
o Are the significant fragmentation events only melt driven?
If yes,
▪ There aren’t any thermo-physical effects that can prevent significant fragmentation events?
o Is the heat flux distribution correctly simulated by the detailed model?

If the answer is YES (for the three bullets) - the detailed model has to be “translated” into a component based model – please proceed to step 7.2.
If the answer is NO (for at least one of the bullets)- two options are available:
1. Consider to improve the design taking Design for Demise Techniques into account, please proceed to step 7.1.
2. Perform equipment testing using on-ground test facilities, please proceed to step 8.</td></tr>
<tr><td>7.1: D4D TECHNIQUES</td><td>A short description and recommendation of Design for Demise Techniques can be found in [RD7].</td></tr>
<tr><td>7.2: DETAILED TO COMPONENT BASED</td><td>Detailed model has to be “translated” into a component based model, please follow chapter 4.3
The output of following this chapter would result in a new database entry.
(if the process has started at system level, please proceed to follow the system level tree from the “EQUIPMENT DATABASE UPDATE “box).</td></tr>
<tr><td>8: TEST FOR MODEL CORRELATION</td><td>For equipment testing guidelines, please follow chapter 5.3. More details for model correlation are provided in 5.3.2</td></tr>
<tr><td>9: EXTRAPOLATION TO FLIGHT</td><td>For modelling of test results using a detailed model, please follow chapter 4.4</td></tr>
<tr><td>10: DETAILED MODEL SIMULATION</td><td>For detailed model simulation guidelines, please follow chapter 4.3</td></tr>
<tr><td>11:DOES IT COMPLY?</td><td>Does the model comply with the equipment level requirements? These can be found in chapter 3.2.</td></tr>
</table>

	If YES - the detailed model has to be "translated" into a component based model – please proceed to step 7.2. If NO - Consider to improve the design taking Design for Demise Techniques into account, please proceed to step 7.1.

2.3 Material level Characterisation Tree



STEP	DESCRIPTION
1: MATERIAL MODELING GUIDELINES	Materials can be first modelled based on similar materials existing in the database. Please follow the guidelines in chapter 4.2.3.
2: SIMILATIRY PROVEN?	Is the new material modelled “similar” to the ones existing in the database to the extent defined in chapter 4.2.3.
2.1: MATERIAL TESTING GUIDELINES	Depending on the type of material, guidelines for test can be found in chapter 5.2. Following these guidelines would result in a new material database entry.
2.1.1: METALS	Please follow chapter 5.2.2.
2.1.2: COMPOSITES	Please follow chapter 5.2.3.
2.1.4: CERAMICS	Please follow chapter 5.2.5.

3 DEMISE REQUIREMENTS DEFINITION AND GENERAL VERIFICATION GUIDELINES

This chapter aims at supporting the users to define demise requirements and provide guidance on how to interpret and verify these requirements.

The requirements on re-entry safety for a Space System are defined in [AD1]. Guidance on the interpretation and verification of these requirements, within the scope of this document, is provided in 3.1.

Nevertheless, also the definition of bottom-up requirements is necessary, e.g. applicable to a new equipment design to mitigate its contribution to the re-entry casualty risk. These requirements can either result from a system level need, or be defined within an equipment development as a way to improve its demise and support its integration in several systems. Guidance for the definition of demise requirements at equipment level and its interpretation is provided in section 3.2.

The release altitude of an equipment is one of the key parameters considered in the assessment of its demise. Spacecraft equipment or parts are typically released as a consequence of a fragmentation event (or a series of fragmentation events). The definition of the conditions in which a fragmentation event occurs will be key to understanding its demise process and establishing interfaces between different elements, e.g. between the system and its equipment. Guidance for the definition of fragmentation event requirements at equipment level and its interpretation is provided in section 3.3.

3.1 System Level Re-Entry Casualty Risk Requirements

The following requirements coming from [AD1] are highlighted:

- *[REQ] The space system shall be designed and operated such that the re-entry casualty risk does not exceed 10^{-4} for all re-entry events.*
- *[REQ] In the case of an uncontrolled re-entry of the space system, the re-entry casualty risk analysis for impacting fragments shall demonstrate for the nominal and non-nominal re-entry scenarios that the maximum casualty risk is lower than the maximum allowed re-entry casualty risk.*
- *[REQ] The re-entry casualty risk analysis shall be performed with the ESA tool DRAMA.*
- *[REQ] In case the analysis with the ESA tool DRAMA shows non-compliance with the re-entry casualty risk requirement or the geometry of the space system is not suitable for analysis with the ESA tool DRAMA, a more detailed model[2] shall be used.*
- *[REQ] The use of tools other than the ESA tool DRAMA for the re-entry casualty risk analysis shall be approved by the ESA relevant authority specified in the Space Debris Mitigation Policy of Agency Projects.*
- *[REQ] For a space system with mass less than 5 kg, compliance with the re-entry casualty risk may be demonstrated by review of design.*

[2] In [AD1] more detailed model is referred to as higher fidelity tool.

Additionally, further recommended requirements can be considered in order to successfully link equipment level to system level requirements:

- *[REQ]* The casualty risk of the system shall be presented as a casualty risk budget.

  Note: the casualty risk budget shall associate the casualty risk of each object reaching the ground to the respective piece of equipment of the space system.

- *[REQ]* Structural elements shall fragment and guarantee the release of the included equipment in line with the demise requirements for these equipment.

  Note: Where necessary the system design shall define the release altitude of each piece of equipment from the spacecraft. This value shall be used either to establish demise requirements at equipment level or to support their verification.

- *[REQ]* The re-entry corridor resulting from the system design shall be used to verify equipment level demise requirements that flow down from the system re-entry casualty risk requirement.

It is important to note that the process linking system level verification and equipment level verification is done in the tool itself, i.e. as baseline DRAMA. In case of other tools being used, care should be taken to ensure that the modelling assumption between system and equipment level are compatible, in line with Section 4.1.

3.2 Equipment Level Demise Requirements

The following recommended requirement formulation can be used as a template for an equipment level demise requirement:

- *[REQ] The equipment shall demise when released at geodetic altitude of **B** km or above assuming an initial release temperature of **A** K, with a 5% significance level based on Monte Carlo analysis for the defined **re-entry corridor**.*
  - The level **A** shall be assumed 300 K unless properly justified.

    Note: different value can be justified depending on the nest-level of the equipment, particularly external equipment is considered. Indicatively, reference initial temperatures for external equipment are provided in ANNEX E – Initial Temperature of External Equipment.

  - The level **B** shall be defined as the minimum release altitude for which the equipment is required to demise, this altitude can be derived based on system level analyses.

    Note: As a function of B, the initial velocity, flight path angle, and geodetic angles will be defined in accordance with the reference re-entry corridor.

    Note: The definition of B shall also consider the nest-level of the equipment, i.e. an equipment with higher nest-level will probably have a lower release altitude. Some background information to support the selection of the target release altitude is provided in ANNEX I – Equipment Release Altitude Assessment.

The **re-entry corridor** shall be defined and justified in accordance with the target system(s) for which the equipment demise is being verified. A reference re-entry corridor for ESA Earth Observation missions is defined in ANNEX C – Reference Re-entry Corridor

Note: The reference re-entry corridor defined in ANNEX C – Reference Re-entry Corridor is defined for encompassing uncontrolled re-entries from circular LEO orbits with high inclinations (covering different Sun-Synchronous Orbits).

Note: Examples for reference re-entry corridors for controlled re-entry are defined in [AD2].

Note: In case of internal equipment, a tailoring for the initial ballistic coefficients for the re-entry corridor can be proposed.

- The uncertainties considered shall be in accordance to 4.2.4 , unless proven to be more constrained by test and numerical simulation.

  Note: the steps below identify actions to reduce the uncertainties which are generally to be considered:

  - The appropriate material demise characteristics verification shall be carried out, in agreement with 2.3.
  - The fragmentation characteristics and phenomenology shall be confirmed based on test in addition to numerical simulation.
  - A database of experimental and numerically derived aero-thermodynamic coefficients, and fragmenting parts thereof, shall be established.

Furthermore, in full generality, the following requirement is to be considered for equipment, as it is derived from [AD1][AD2] and the definition of demise:

- *[REQ] The impact energy of any surviving fragment of an equipment shall be less than 15 J .*

It shall be noted that this formulation of equipment level demise requirement may imply the definition of fragmentation requirements on enclosing structures to guarantee that the system fragmentation results in the necessary equipment release altitude.

3.3 System and Equipment Level Fragmentation Requirements

At system level, fragmentation requirements will be driven by equipment level requirements, i.e. if a reaction wheel needs a release altitude of 80km in order to demise, this shall be translated as a system level fragmentation requirement. Nevertheless, the current knowledge of joint fragmentation is at an exploratory level. Such events are approximatively estimated to occur between 90 km and 65 km altitude (according to past re-entry observations and analytical/numerical models [RD1]). However, the exact values are not known a priori with a reasonable accuracy. This needs to be accounted for when verifying requirements. System level fragmentation requirement needs to be validated stochastically given the high amount of uncertainty.

Fragmentation events, can drive the demise of equipment and sub-equipment during a re-entry event. Dependencies and/or limitations regarding the prediction of fragmentation events (e.g. when performing an analysis to derive potential effects on a specific item to identify possible demise trigger) should be assessed at system level and correlated with:

- Main (parent) object structure, i.e. space system assembly with thermo-mechanical mass (inertia) properties consistent with the design baseline;
- Nest-level of the item in the main (parent) object, e.g. how many layers need to demise before the item is fully exposed to the flow (released);
- Level of confidence associated to the prediction model (analytical/numerical model uncertainties, test data correlations, etc.) and the input parameters (usually known stochastically and/or in ranges);
- Identification of possible fragmentation triggers (e.g. thermal, mechanical, etc.) in the main (parent) object and its derived fragments.

The following requirement formulation can be used as a template for a fragmentation requirement (that may lead to the definition of a release altitude):

- *[REQ] Given a range of physical conditions* ***A*** *at geodetic altitude range of* ***B*** *km, the equipment shall fragment at a 5% significance level based on Monte Carlo analysis for the defined re-entry corridor.*
    - The range **A** shall be defined in line with the fragmentation mechanism, which shall be specified.

      Note: the fragmentation mechanism may be driven by one or by the combination of several physical conditions. These physical conditions include: temperature effects, heat-soak, mechanical loads, etc.

      Note: the achievement of the required conditions **A** at the range of geodetic altitudes **B** for a specific system can be assessed by simulation and analysis.

    - The range **B** shall be defined by the minimum and maximum altitude as a function of velocity, flight path angle, and geodetic angles in accordance with the re-entry corridor above which the equipment fragments.

      Note: As a function of **B**, the initial velocity, flight path angle, and geodetic attitudes will be defined in accordance with the reference re-entry corridor.

      Note: The definition of **B** shall also consider the nest-level of the equipment, i.e. an equipment with higher nest-level will probably have a lower release altitude. Some background information to support the selection of the target release altitude is provided in

ANNEX I – Equipment Release Altitude Assessment

- The re-entry corridor shall be defined and justified in accordance with the target system(s) for which the equipment demise is being verified. A reference re-entry corridor for ESA Earth Observation missions is defined in ANNEX C – Reference Re-entry Corridor

  Note: The reference re-entry corridor defined in ANNEX C – Reference Re-entry Corridor is defined for encompassing uncontrolled re-entries from circular LEO orbits with high inclinations (covering different Sun-Synchronous Orbits).

  Note: Examples for reference re-entry corridors for controlled re-entry are defined in [AD2].

- The uncertainties considered shall be in accordance to 4.2.4, unless proven to be more constrained by test and numerical simulation.

3.4 Risk Estimation

System level requirements from [AD1], and extensions in this document, make reference to the 10^{-4} threshold for risk verification. In case of controlled re-entry, [AD1], [AD2] specific Monte Carlo parameters to be considered for the establishment of the declared and safety re-entry area with convergence criteria. This logic could be extended to the casualty risk estimate itself.

Under the uncertainties defined in Section 4.2.4, applied at system level and to each piece of equipment modelled, the resulting empirical distribution function of casualty area can be multimodal. As a result, verifying the casualty risk requirement assuming a known distribution for the casualty area, such as Gaussian, is deceptive and hence not advisable as a general recommendation. The following can be considered as guidelines to casualty risk estimation compatible with this document and [AD1]:

- A Monte Carlo analysis should not be based solely on a maximum amount of samples, but be executed until convergence of the percentiles under the uncertainties stated or derived when following this document.
- In view of the a-priori unknown re-entry casualty risk distribution, the median value should be considered as initial estimate for the verification step. In case of a large spread when comparing the tails of the distribution, an appropriate estimator should be justified.
- The average projected area of a fragment used for the casualty area formulation should be based on the DRAMA methodology, i.e. the mean area associated uniform rotational motion.
  - For convex shapes this implies the Cauchy theorem on average projected area. Using the mathematical mean can be higher or lower than using the arithmetic mean based on a limited amount of projections.
  - DRAMA provides a conservative estimate in case of “connected to” primitives which should be adjusted for risk verification in case of large over-estimation when used in risk estimation.

- In case of a porous compound object, e.g. interface rings, where the size of the holes are large w.r.t. the solid parts but similar or smaller than 0.36 m^2, their convex hull area should be used as part of the casualty risk verification.

4 GUIDELINES FOR ANALYSIS

This section intends to guide the reader through the modelling and analysis aspects necessary to assess the compliance with the requirements defined in section 3, both at system and equipment level.

4.1 Tool Requirements and Assumptions

General Rationale

The baseline for the software requirements, essentially the process linking equipment and system level, are fixed by the use of a specified tool and version thereof: in this case ESA's DRAMA software (see [AD4]). The requirements coming from [AD1] enable the use of different tools other than DRAMA only in the following cases:

1. The DRAMA analysis shows non-compliance with the re-entry casualty risk requirement. A non-compliance implies that a critical element is found during the system level assessment. A critical elements may result from:
    a. Having an entry in the equipment and material database with large associated uncertainties,
    b. Or having no appropriate model, nor similarity class, in the object or material databases.
2. The geometry of the space system is not suitable for analysis.

It is important to note that when multiple tools are used, the process linking system to equipment might be lost, and any conclusions gained must thus be brought back in line with the base process e.g. an equivalent DRAMA model to capture the processes analysed with more detailed tools and/or testing, needs to be established. As such, any tool needs to list similarities and differences with the DRAMA baseline prior to the start of an analysis.

In the following sections, recommended requirements formulations have been presented which can be used as a template for a tool to assess the compliance with the requirements defined in section 3, both at system and equipment level.

Minimum capabilities required in order to be comparable to DRAMA

- *[REQ] The tool shall have shape dependent aerothermodynamics modelling, with a reference performance. This includes aspects such as the ability to account for nest-level, (partial) shielding, and mimicking of demonstrated demise and fragmentation criteria.*

The software tool needs to have a coefficient database for the aerothermodynamic heating for a range of basic shapes which is justified using CFD or test data. The use of these component specific-coefficients shall be transparent and can be incorporated in the DRAMA database.

The software tool needs to have a verified trajectory capability using DRAMA as a baseline. A three-degree-of-freedom or six-degree-of-freedom simulation of a sphere is recommended for comparing the capabilities. The tool needs to implement a suitable atmosphere model, including oxygen content when treating oxidation effects as part of the simulation. The US76 reference atmosphere is the baseline under average space weather conditions.

As a minimum, a tool shall have a nested modelling (contained-in) capability for sequential demise processes to capture observed test results e.g. magnetorquers are a good example of an associated layered demise process (see [RD8]). This shall be extended with a method to partially shield equipment from the flow, e.g. to account for heating earlier than the classical demise criteria at 78km. This enables the analysis of external equipment such as telescopes. The tool shall also have an option to switch from local to global length scales for the continuum heating.

The software tool should implement at least fragmentation criteria based on melting temperature, heat soak and dynamic pressure.

- *[REQ] The tool shall implement a temperature based material model including a distinction between metals and composite based objects and dependency on oxidation for those, compatible with the findings stored in ESTIMATE.*

The baseline demise criterion for metals shall be complete melt of an element. As composite materials such as CFRPs are essentially equipment dependent in terms of demise or fragmentation behaviour, an individual demise criterion is required. A fully charred matrix is likely to be insufficient for this, but full demise of carbon fibres is too stringent. Examples on how to model composite materials are included in section 4.2.1.

It is of paramount importance to systematically use vetted material properties as part of both system and equipment level modelling, as in many cases the exact representation of the materials used in an equipment will not be available or various materials will be mixed together. This enables the use of unified material properties, including thermo-physical ones. The following order of preference shall be used to model materials:

1. Material properties derived from testing under the representative conditions, as stored in the ESTIMATE database. Uncertainties can be derived from the test data.
2. Material properties derived from testing, if needed extrapolated to be suitable for demise analysis. Uncertainties can be derived from similarity classes if available.
3. Interpolation or first order assessment of material properties based on engineering or scientific reasoning, in absence of testing or appropriate material demise model. This includes data from manufacturer data sheets where there is no accompanying test data. Uncertainties are significant and selected to be conservative (see 4.2.4).

- *[REQ] The tool shall have the capability to model the re-entry corridors as defined in Annex C with the relevant uncertainties listed in section.*

The point above implies a parametric simulation capability and a full Monte Carlo capability, including both initial conditions and physical parameters, in particular fragmentation criteria and aerothermal heating.

Verification of compatibility with the baseline and extensions

- *[REQ] A reference run on the spacecraft model to demonstrate the integrated effect in comparison to the DRAMA tool shall be provided.*

A reference spacecraft model is provided in ANNEX B - Test Facilities Description. As minimum, large difference shall be explained. The same material properties need to be used across the tools.

Some physical effects, that can be simulated as part of more detailed models, have shown to be useful under certain conditions, e.g. to explain phenomena observed in testing or to tackle specific demise or fragmentation issues. A more detailed tool can have the following relevant capabilities:

- Six-degree-of-freedom force analysis for assessment of mechanical loads through components and joints. In this field a rigid body analysis is still state of the art, and methodologies inclusive of strain effects in high temperature objects are desirable.
- Fragmentation criteria based on temperature and mechanical loads criteria. The capability to model a delay heat soak after an event to capture test data where fragmentation occurs after melt or reaching critical temperatures is desirable.
- Material catalycity model.
- A melt-based fragmentation model where some latent heat is required before separation occurs, e.g. this has been observed consistently in tests for aluminium objects.
- A connected-to capability (via specific joints or adjacent objects) and a conduction model. A 3D conduction model is the most desirable, with a 1D model important for capturing of test data and a thermal network approach useful for flight modelling.

4.2 Modelling Guidelines

The modelling guidelines described in this section are intended to be in line with the verification trees presented in section 2, i.e. wherever a validated fragmentation mode, equipment model, or material model exist in the relevant database, it shall be used. The default fragmentation model is described by the tool, i.e. full melt of a geometric primitive in DRAMA. It is intended that the baseline equipment models and the baseline material models will be provided with the DRAMA software, based on ESTIMATE database. Specific uncertainties can apply to any of these models in addition to those laid out in section 4.2.4.

In case an assessment needs to be made outside of the validated models or similarity classes, a set of general modelling guidelines applies. These models shall then be properly justified and documented, and will in all cases be subject to review. Reviewed equipment, fragmentation, and material models may be included into ESTIMATE database as validated models for future use.

4.2.1 System Modelling Guidelines

The standard [AD1] only describes the system level requirement and the methodology, i.e. the DRAMA tool, required for its verification. Section 3 introduces the relation between system level and equipment level requirement. To ensure consistency of the process at system level, conclusions derived based on more detailed modelling and testing need to be converted in a DRAMA compatible model before being applied.

As stated before, accurate and complete prediction of the physics associated with destructive re-entry is beyond the state of the art. From a risk verification point of view, a simplification is applied to systems and any equipment contained therein by assuming that it interacts with the flow as if it were in a 3 DoF random tumble average manner for all aerothermodynamic aspects. Generally conservative considerations are to be taken when making these averages. 6 DoF simulations and analyses, coupled with force and heating models, can indicate more realistic demise and fragmentation behaviour, but these needs to be justified and their applicability range indicated. These considerations imply the following modelling guidelines:

- System level modelling should minimise mass deviation at sub-system and equipment level.
  - A complete list of objects at equipment level needs to be established, including their nest-level and their location.
  - Structural panels are to be accounted for by the overall volume they describe, e.g. the outer shape of a service model is to be modelled as a single box even though it in reality is a collection of single panels, unless a dedicated joint model is available. On the other hand, a web, bracket, or shear panel is to be accounted for as plate (box with one reduced dimension).
  - When modelling structural panels, the material density should not be modified to reach the real thickness. Instead, the thickness may be adapted while it remains between 10% of the real.
  - In the case where the reduction of thickness is far greater than 10% (e.g for honeycomb which uses a single material) the equipment can be represented in a model by reducing the density.
  -
- Materials or equipment which can't be represented faithfully and aren't considered critical, are merged based on mass conservation with a larger component. Some examples are:
  - Spacecraft panels which are combined by structural joints can have the mass of those joints considered as part of the panel.
  - The demise of CFRP face-sheets are an active research topic implying they can delay the heating into a structure, but not necessarily form a separate critical element. The mass of such face-sheets are recommended to be included in the mass of the support structure, i.e. the sandwich panel.
  - Currently in DRAMA the baseline CFRP model is designed for use with COPV tanks only. It is not recommended for now to use these models for brackets or other equipment using CFRP.
  - Harness and cabling, when not impeding fragmentation of equipment, can have their mass accounted for in the supporting structural element.
  - Screws and bolts, when not designed with a specific fragmentation function, which are below the radiative survival limit, are recommended to be included in the mass of the support structure (see [AD4]).

- Materials properties are a driving factor in the risk estimation and as such they shall be selected for modelling based on their closeness to tested sample materials.
    - An order of preference is established in section 4.1, and the use of averaging material properties into a single material for use in the model is discouraged except as a last resort. Instead an approach of using nested component of individual material with known properties shall be used to the extent possible.
- As a conservative baseline, demise of a component is only achieved at full melt. When the nest-level of an element or equipment is established, it shall use the “included in” relation.
    - The classical risk assessment methodology, for uncontrolled re-entries from LEO, which saw all modelled equipment released at a break-up altitude of 78km based on the observed fragmentation of large spacecraft can be thought of as single, conservative example of 1 nest-level ([AD4]). This methodology is extended here, but based on full melt fragmentation rather than a fixed altitude.
    - The “connected to” relation implies heating is passed on, at local length scale, to a component and hence far less conservative than “included in”. It should only be used when modelling the effect of mutual component shielding in the 3 DoF averaging sense of only large components.
    - Between “connected to” components the fragmentation occurs when one of them melts fully.
- Uncertainties on material, trajectory, and modelling should be considered as laid out in Section 4.2.4. When detailed known uncertainties exist but can’t be represented individually, they can be grouped conservatively.
    - E.g. uncertainties on aerothermodynamic coefficients which differ across flow regimes can be grouped by adopting the largest one.

Based on more detailed modelling or test data, specific demise and fragmentation phenomenology can be uncovered. At a system level, these can, when duly justified, be accounted for by means of modelling them representatively and hence amending the default baseline physics model. This implies:

- A set of connections between elements needs to be mapped in order to determine expected fragmentation events defined by insert failure, component melt, mechanical fragmentation, fragmentation altitude, etc. For those a fragmentation or demise trigger, with identified uncertainties, can be set.
    - These uncertainties can be lower than the baseline from Section 4.2.4.
    - When converting detailed models, separate objects must have a connection and not be modelled as one object.
        - E.g. for items such as the connection between silicon carbide mirrors and optical bench. When the “connected to” relation is used in such a way, it shall be assessed if also the aerothermodynamic properties of the component need to be provided in DRAMA explicitly.
    - Fragmentation criteria are required to be set for all connections. The first met criterion will cause fragmentation when not using the baseline fragmentation model.

    - E.g. insert-based joints are required to have an insert failure condition and joints with an adhesive connection (possibly via unmodelled bipod) are required to have an adhesive failure condition.
    - E.g. to mimic joint fragmentation events: Unless clearly demonstrated by test, epoxy adhesives used in potting material or adhesive connections shall not use failure temperatures under 400°C (673K).

Any deviations from the guidelines above and/or specific fragmentation criteria must be justified for use in DRAMA, e.g. more detailed models have used "reaching melt temperature criteria" as fragmentation condition.

4.2.2 Equipment Modelling Guidelines

Extension of Database

A spacecraft or equipment thereof might have been designed to demise or accepted in previous re-entry risk analyses compatible with the guidelines in this document, in which case a similarity class can be constructed out of it. To establish such a class of objects the following should be achieved:

- The appropriate material characteristics shall be used in accordance with Section 4.1.
- The fragmentation characteristics and phenomenology shall be based on the holotype(s) of the class.
- A database of aero-thermodynamic coefficients or correlation coefficients based on extrapolation from experimental and numerically setups can be used.
- Class similarity needs to be defined and justified, e.g. by reviewing the design in view of the compatibility with the database models.
    - Class similarity breaks when different materials are used for critical elements, different fragmentation phenomenology may occur, or different critical elements need to be included in the model
    - Class similarity is not necessarily broken by geometric scaling of the object dimensions.
    - Similarity should not be established without the detailed analysis of the points above by an Equipment design expert.
    - Establishing class similarity requires approval from the approving agent, in lines with the review established in [AD1].
- Uncertainties associated with objects in a similarity class shall be established in accordance to Section 4.2.4, unless proven to be more constrained by test and numerical simulation.

New Equipment Modelling

A spacecraft or equipment which is not present in the equipment database or not accepted in previous re-entry risk analyses compatible with the guidelines in this document, needs to be modelled starting from the system level guidelines. In addition the following should be achieved:

- Inclusion of all parts or sub-parts of known critical elements that could have a terminal energy greater than 15J when separated from all other parts in a significant fragmentation event. Approximate limits are provided in ANNEX H – Approximate Size Limits for 15J Elements.
- Ensuring that none of the potentially critical elements are deleted from the simulation due to their potentially small size or mass.
- Preference is given to using nested models before considering equivalent materials, or demonstrating that equivalent material model is necessarily conservative.
- Modelling of any approximate shape with a representative primitive shall be done with a matching convex heating area.
- Thermal conduction between different parts of an equipment or the equipment and the system can occur in practice. For a component based model, no conduction between modelled components should be assumed as baseline unless justified otherwise.

When accounting for all equipment level guidelines above, which apply with preference, all system level modelling guidelines apply to equipment level modelling as well.

4.2.3 Material Modelling Guidelines

The following applies when modelling materials:

- All material properties included in the DRAMA software for metal alloys, excluding heat of oxidation, should be defined and used.
- To reduce critical elements to non-critical status, reducing the uncertainty associated with the materials may be considered. In this case, the level of the material model should be raised based on testing.
- Where ESTIMATE data is not available for a similar material, it is recommended to take data for the key species (base metal for alloys) from the NIST-JANAF tables, and to use an emissivity of 0.8.

The influence of catalycity on the demise of metal alloys and other materials is part of current research. It is expected to be important, particularly for ceramics and possibly for some metal oxides. When data is available in ESTIMATE, it shall be used.

In analogy with equipment, metal alloys can be grouped in similarity classes. E.g. for Aluminium and Titanium alloys the variation among them in terms of demise behaviour and composition is limited. In case of steel, nickel and copper alloys, greater variability has been observed in test and a comparison against the ESTIMATE and DRAMA baselines should be included before usage.

Composites, CFRP or GFRP, models for demise or fragmentation are an area of active research and do not generalise well outside their tested and experimental ranges, e.g. the CFRP model included in DRAMA allows to fit experimental results at the expense of having the parameters tuned to those. Therefore, equipment or structural elements containing a majority of CFRP or GFRP are to be treated on case by case bases unless specified otherwise in Section 4.2.1 or Section 4.2.2.

Generally, ceramic materials have a high melting temperature and are hence unlikely to demise. They can be modelled based on the SiC baseline in DRAMA unless they have a significantly lower temperature or are known to be prone to fracturing at temperatures associated with the re-entry event.

4.2.4 Uncertainties to be Applied

The following parameters are, in addition to the re-entry corridors considered, a set of justifiable uncertainties to be applied as baseline uncertainties on both system, equipment, and material level. They are derived and listed only in cases where a sufficient body of scientific evidence is available to justify both distribution and its defining moments Table 4-1. Far more physical uncertainties are expected beyond those listed here, but in absence of firm parameters they could skew an uncertainty analysis and hence produce results which can't be interpreted consistently.

Parameter	**Uncertainty**	**Comments**	**Uncertainty reduction methods**
Aerodynamic drag Continuum	±10% uniform	Could be systematically low for slender objects at low AoA	Delivery of a dedicated CFD, panel based, or test analysis for a specific shape
Aerodynamic drag and heating, Free molecular	±10% uniform	Errors introduced by speed ratio and mutual shading	Delivery of a dedicated CFD, panel based, or test analysis for a specific shape
Heat Flux Continuum	±30% uniform	Still very limited data available with which to make assessment. 30% is a conservative estimate	Delivery of a dedicated CFD or test analysis for a specific shape
Transitional drag and heating	±50% on characteristic length scale used for Knudsen number definition, uniform	Provide reasonable variation in transitional heating and aerodynamics whilst remaining continuous	Delivery of a dedicated CFD or test analysis for a specific shape
Oxidised Emissivity	±25%, triangular. Maximum does not exceed 1	Based on characterisation of demisable materials in ESTIMATE When Oxidised Emissivity is unknown the recommended value for metals is 0.8.	Delivery of a dedicated test analysis for a specific material for inclusion in ESTIMATE
Specific heat capacity	±5% normal three sigma limit	Effect likely to be insignificant w.r.t. heating uncertainty	Delivery of a dedicated test analysis for a specific material for inclusion in ESTIMATE
Latent heat of melt	±5% normal three sigma limit	Effect likely to be insignificant w.r.t. heating uncertainty	Delivery of a dedicated test analysis for a specific material for inclusion in ESTIMATE

Parameter	Uncertainty	Comments	Uncertainty reduction methods
Alloys melt temperature	±30 K uniform	Capture non-eutectic effects based on the current tests in ESTIMATE	Delivery of a dedicated test analysis for a specific material for inclusion in ESTIMATE
Atmospheric density	±10% normal one sigma	Based on seasonal variations not captured in a static model such as the recommended US76	In absence of dedicated atmosphere models it is not intended to be reducible for the time being,

Table 4-1: Uncertainties associated with physical properties.

Parameter	Uncertainty	Comments
Critical joint temperature	±100K uniform	[RD4]
Critical joint dynamic pressure	±25% uniform	Consistent with observation [RD4]
Critical joint break-up altitude	±10km uniform	Consistent with observation [RD4]

Table 4-2: Uncertainties associated with simplified joint-based fragmentation properties.

Parameter	Uncertainty	Comments
Aerodynamic moments, free molecular and continuum	±10% uniform	Analogy with space capsule studies. Uncertainty should be at least as large as for aerodynamic forces.
Adhesive joint	Force: ±5N +20N, asymmetric triangular Temperature ±100K, uniform	[RD4]
Insert joint	Force: -5N, +20N, asymmetric triangular Temperature: ±100K, uniform	[RD4]

Table 4-3: Uncertainties associated with joint-based fragmentation properties for more detailed models.

The uncertainties in Table 4-1 are designed for component level modelling, such as DRAMA, and are subject to the detailed model uncertainties. Table 4-3 Models can be calibrated to use some or all of the above thresholds (with suitable uncertainty) which exist in DRAMA.

Further uncertainties shall only be considered on a case by case basis. Examples include concave shapes or materials where a validated fragmentation model is absent, such as for ceramics.

4.3 Guidelines for the Extrapolation of DRAMA Component Based Models from Detailed Models

4.3.1 Detailed Modelling Options

Different tests and simulations require the use of different tools in order to produce a good simulation of the data. Tools which may be used include:

Tool Type	Usage	Notes
CFD	Wind tunnel conditions verification Heat flux profiles to test samples	Subsonic/transonic test cases shall be rebuilt using CFD tools to provide the input heat fluxes to demise simulations CFD rebuilding of the nozzle and calibration probe flow fields is recommended for anchoring of the test conditions in all cases.
Finite Element Analysis	Strain analysis Capture of forces required for fragmentation	Simulation of forces in fragmentation where rigid body analyses are insufficient
Detailed Demise Tools (SAM, SCARAB, ADRYANS, etc.)	Test rebuilding Extrapolation of test results to flight conditions Provision of correlation data for DRAMA model construction	Heat flux mapping from CFD to tools at surface is required for subsonic/transonic tests Capturing of criteria for determination of fragmentation/demise events Verification of applicability of material models

Table 4-4: Tool types and usage

CFD or FEM based models are considered an input to both component and panel based models in conjunction with test data, even though overlaying heat flux or pressures/strain maps are certainly considered as added value. The process for mapping the test results through to a DRAMA model is provided in the next section. Some examples of the process of mapping the detailed model flight results to a DRAMA database entry are given here.

4.3.2 Detailed Models Extrapolation

The following process should be followed when deriving a DRAMA component based model from a more detailed model:

1. Significant fragmentation events and their phenomenology should be identified:
    a. An event description should be established, e.g. identifying the most probable number of fragments driving the casualty area, as function of the equipment release altitude. This enables to track the parts of the more detailed model responsible for creating critical fragments.
    b. In case of fragmentation phenomenology with various distinct fragments arising caused by the input uncertainties, the most probable events are to be identified.

2. Material and trajectory properties should be as close as possible to DRAMA, and divergences noted as uncertainties and justified on the DRAMA model.
    a. Where updated material properties are required, these should be submitted for potential inclusion in ESTIMATE.

3. The critical elements, for both fragmentation and impact on ground, should be mapped to unique geometric primitives following the modelling guidelines of Section 4.2.
    a. When an alternative model is already component based, this mapping can be done by ensuring model compatibility, (reference to chapter 4.1) e.g. geometric primitives are faithfully mapped by ensuring comparable aero-thermodynamic models.
    b. When the more detailed model is panel based, partial fragments should be linked to a nested parent primitive in DRAMA.
        i. Note: Panel based methods allow fragments of arbitrary shape but mimicking such individual fragments is discouraged as it breaks the logic compatible system and equipment level simulation [RD5]. Instead, the source of these fragments shall be used in the model as a parent primitive (see modelling guidelines of Section 4.2).
    c. As figure of merit, 3DoF drag–driven trajectory and heating histories between the more detailed and DRAMA model are to be compared prior to the start of a demise process. Achieving similarity within the uncertainty levels indicated in Section 4.2.4 is the goal, but it is noted that due to modelling difference this cannot be achieved in all cases.

4. The aerothermodynamics coefficients of the critical elements in DRAMA shall be adjusted to fit the heating, demise, and trajectory profiles of the more detailed simulation.
    a. The aerothermodynamics coefficients can be considered as a shape dependent correlation function, not necessarily a full database.
    b. The creation of an aero-thermodynamic coefficients database is preferred over scaling factors since it potentially increases the accuracy of the heating history and the applicability to different scenarios.

5. Significant fragmentation events simulated shall be captured approximately by using break-up triggers, and divergences noted as uncertainties on the DRAMA model.
    a. In case of multi-fragmentation behaviour on similar trajectories, the conservative estimates should be fitted as baseline.
    b. In case of multi-fragmentation behaviour on distinct trajectories, different models should be applicable within limited trajectory bundles.

After creating the DRAMA model its performance should be compared against the more detailed model and differences identified.

4.4 Guidelines for the Extrapolation of Test Results to Re-Entry Simulations

The current means for testing demise on-ground do not allow for a fully representative re-entry test. Therefore they cannot be used as a demise verification method by itself. The tests shall be used to anchor the modelling in observable data and raise confidence on the re-entry simulations and on the modelling of the different phenomena. It is therefore essential to be able to extrapolate re-entry simulation models from the ground tests.

As DRAMA was not designed to simulate test data, nor should it be used as such. These simulations require the use of a more sophisticated simulation tool, or tools, to be used to capture the test output and provide a set of correlation data, against which a DRAMA database entry can be constructed as stipulated in section 4.3. Construction of representative models for the re-entry process from test data should consider the following guidelines:

- In the ideal case, the representative model is constructed using elements from within the capability set of DRAMA such that the adaptation to a DRAMA model is essentially trivial (production of aerodynamic/aerothermal databases and event thresholds).
- The material properties shall be consistent with those used to rebuild the test.
  - Updated material properties to capture specific phenomena observed shall be included. For example: at the melting point, the magnetic core of a magnetorquer has demonstrated significantly lower emissivity than the solid object. This resulted in an updated material model.
  - Where justified from test numerical rebuilding work, material models derived from the test results may be used. Examples are:
    - Battery cells are well represented using a steel model as the demise has been verified in the test rebuilds to be driven by the melt of the steel can.
    - Electronics cards demise behaviour in testing has been captured by a proxy model for a GFRP material which has been demonstrated to be applicable in two separate test rebuilds.
- A model which suitably captures all the significant demise and fragmentation processes shall be constructed:
  - It shall be determined whether a bulk heating model is sufficient to capture the demise events. A bulk heating model is preferred in flight models where justified, as this is the model used for the majority of materials in DRAMA. Examples from previous tests include:
    - Demise of CFRP magnetorquer housing could not be captured using a bulk heating model. Therefore, a model which includes capability for capturing temperature gradients is required.
    - Demise of the magnetic coils layer demonstrated low conductivity in the test, but the demise event is well captured using a bulk heating model. Therefore, a bulk heating model is acceptable for the copper layer.
    - Demise of primitive shapes of bulk metal materials (including aluminium housings) have been shown to be equivalent for demise to conduction models [RD6].
  - Critical assessment of the fragmentation event is required in order to determine whether the event is similar to that which would be observed if the equipment is

tumbling in flight. Full demise models are required to be used unless there is a clear justification to use a less conservative model from the test data. An example is:

        - The copper coils are observed to break in the magnetorquer test such that full demise of the coils is not required. It is not clear that this effect is not due to the heat flux at fixed attitude causing the break, and so this is not justified for inclusion in the flight model.
    - The ability to capture temperature data does not verify by itself the fragmentation and/or demise processes of a model.
        - The model can be tuned to match the temperature profile in a sample, but this does not imply that it captures the demise phenomenology of this piece, e.g. when testing under slightly different conditions, given the large amount of free parameters when rebuilding the tests.
    - Where the demise process is not specifically melt driven, a suitable fragmentation event model is required. Examples include:
        - For electronics boxes, a test has demonstrated that the electronics cards separate, such that they will be released on the failure of the aluminium housing. Therefore, a nested model releasing separated cards on the complete demise of the aluminium housing can be used.
        - For the CFRP magnetorquer housing, the failure of the CFRP material is a mechanical fragmentation. More than one test condition is required in order to provide a good assessment of a fragmentation condition. Note that composite materials are currently not well characterised in terms of demise conditions.
- A model which suitably captures the heating to the equipment shall be constructed. This shall include:
    - Shape effects, inclusive of mapping of fluxes from primitive modelling or CFD.
        - The model for the heating to the flight model shall be consistent with the flux map produced and the test results. Where these differ, the test data takes precedence in the application of the heat flux model.
        - A set of heating coefficients shall be derived. Where possible, this shall be linked to the shape and the curvature of the shape such that they are generally applicable and can be used for similar items. It shall be noted if the heating is tuned without physical basis.
    - Capture of the heat flux shading to the different parts of the model using a set of primitives in order to capture the heating observed in the test. Examples include:
        - The heating to different parts of a reaction wheel on demise of the housing depends on the shading. This shall be captured by either:
            - Using a set of primitives for the different parts in order to ensure the correct heating to the motor and flywheel.
            - Using a panel-based geometry which is demonstrated to capture the heat fluxes to the different parts.

5 GUIDELINES FOR TEST

This section intends to guide the reader through the testing aspects necessary to support the analyses required to assess the compliance with the requirements defined in section 3. These guidelines are derived in relation to the capabilities of existing test facilities and therefore are focused on equipment and material level testing.

5.1 Facilities Description

The demise process may result from a wide range of aspects, there is a wide range of conditions of interest. An example of the characteristic events during the re-entry is shown below Figure 5-1. The main events and their driving parameters (heat flux, flow effects, etc.) during an atmospheric re-entry, highlighting the impact on internal, structural or external equipment.

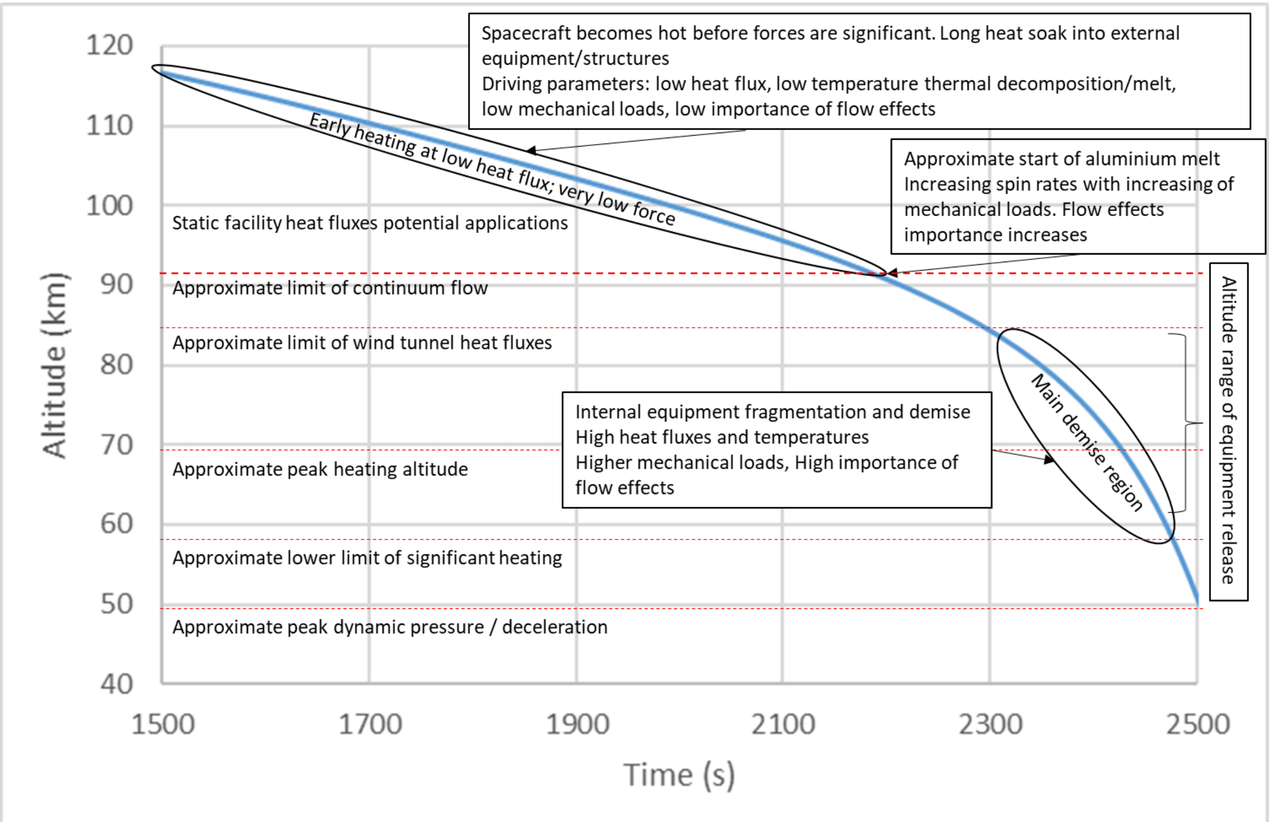


Figure 5-1: Main events of interest within the scope of demise verification, occurring along the standard re-entry trajectory

Ground test facilities are however not capable of representatively simulating all the effects occurring during a re-entry. Current facilities limit the generation of hypersonic flows fully representative of re-entry either in scope and/or duration. This results in a wide range of facilities being required in order to capture the conditions of interest.

Figure 5-2 shows the main classes of facilities of interest for assessing the demise of equipment and materials during an atmospheric re-entry.

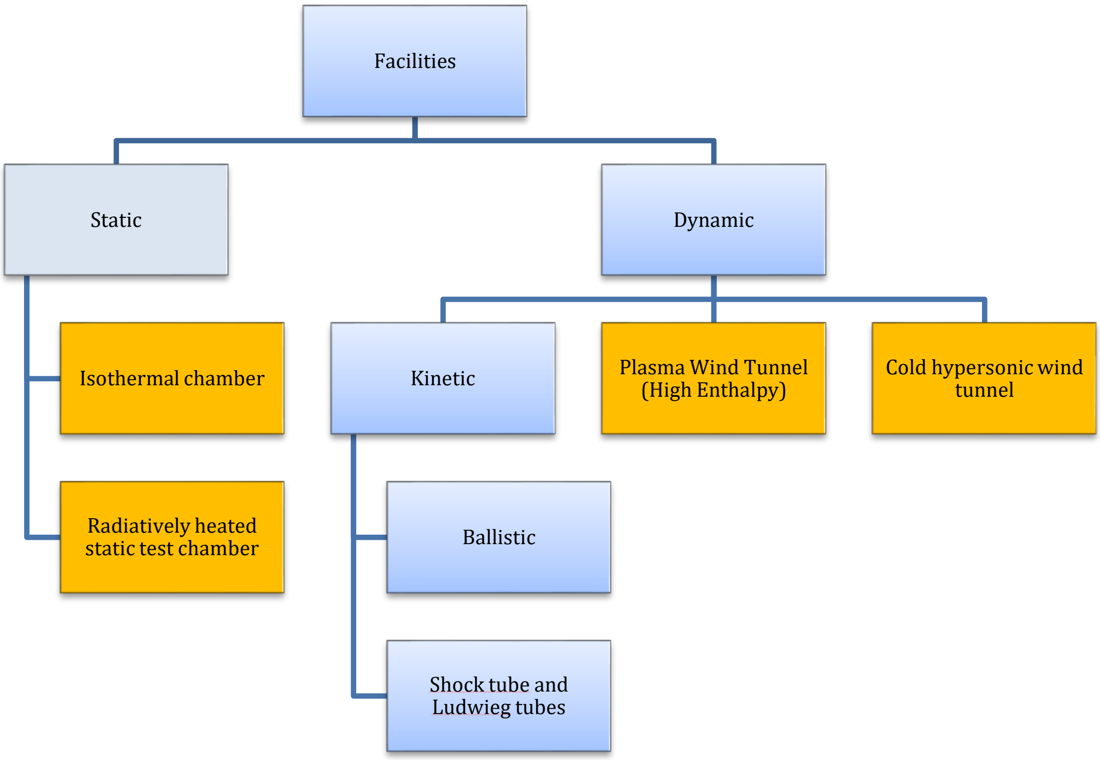


Figure 5-2: test facilities available in Europe (in yellow are highlighted the ones of interest within the scope of demise verification)

The primary interest is in high enthalpy testing facilities where a high heat flux in a representative flow-field can be applied in order to generate a representative material response. This is useful for assessing the demise of materials and equipment. However, where fragmentation events are not expected to be driven by melt, but are mechanical in nature, or where events are expected before the flow is expected to be of high importance, static radiatively heated facilities can provide more relevant data. Further, if a specific demise mechanism is dependent on high heat flux being received in a particular location based on a particular shape, then this is best verified using infra-red thermography in a cold hypersonic wind tunnel.

The main aspects of the different facility types are summarised in Table 5-1. The facilities are presented, with an insight on their capabilities and limitations as well the driving parameters that can be expected to be verified in the test, for the event of interest (e.g. if the event to test is mainly temperature and mechanical loads driven, with negligible impact of heat flux effects and flow effects, the most suitable choice would be running the test in an isothermal chamber). This approach is further detailed in section 5.3. Further information about facilities is available in ANNEX B - Test Facilities Description.

Facilities	Driving Parameters	Test Complexity	Capabilities and Limitations
Isothermal chamber	Temperature, Mechanical loads	Low	- Capture events which are temperature driven - No dynamics in terms of heating profile - Easy mechanical load application - Mechanical fragmentation observations - High temperature material property database generation.
Radiatively heated static test chamber	Temperature, Mechanical loads, Heat flux effects	Low/ Medium	- Representative heating and timescale (trajectory simulation) - Easy mechanical load application - Suitable to test external fragmentation at high altitude and low flux. - Internal fragmentation under load. - Mechanical fragmentation observations - Low Heat flux level
Cold hypersonic wind tunnel	Mechanical loads, Heat flux effects	High	- Heat flux and heat transfer coefficient mapping - Aerodynamic database generation - Mechanical loads obtained from dynamic motion - No demise observations
High enthalpy wind tunnel (Plasma Wind Tunnel)	Temperature, Heat flux effects, Flow effects	High	- Representative oxidizing plasma environment - Not representative dynamic pressure and/or flow velocity - Useful for (melt driven) demise observations. - Representative heat flux distribution. Steps in heat flux can capture demise threshold. - Representative thermochemistry - Not easy application of mechanical loads - The heat flux profile can only be re-built at discrete trajectory points. - High Heat flux level

Table 5-1: Main aspects of different test facility types

The use of the facilities shall not be considered only in isolation and the combination of their capabilities can provide a more optimal outcome. Figure 5-3 shows how the outputs from cold hypersonic wind tunnel tests, in terms of heat flux mapping (e.g. heat flux coefficient, aerodynamic coefficients, etc.) can be used as inputs for tests to perform in plasma wind tunnel and/or static facilities. This combination allows to assess the appropriate test conditions a-priori, leading to an accurate test re-building in the models in the post-test analysis phase.

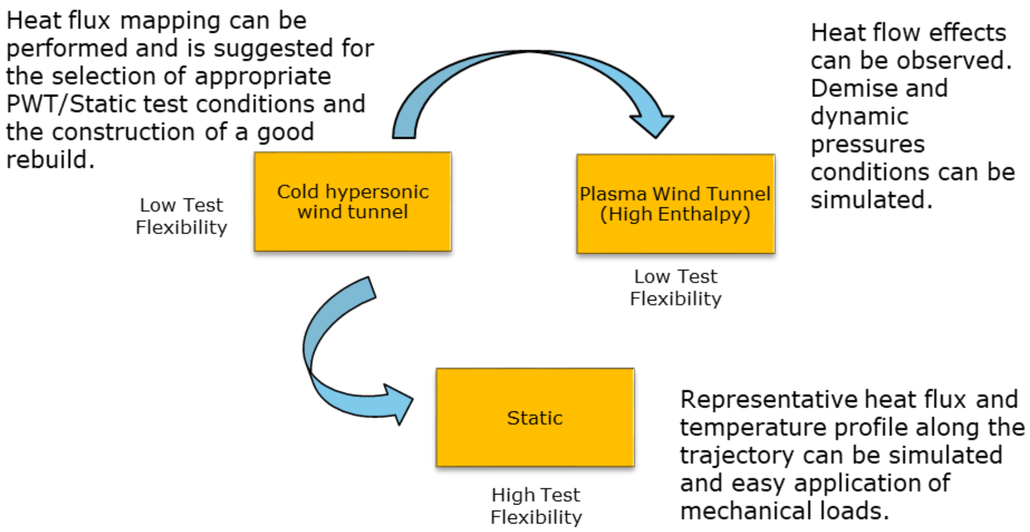


Figure 5-3: Potential logic for the set-up of a test campaign for demise verification

Materials laboratory test facilities

For determining material properties that are relevant for the demise process other laboratory facilities may be considered. Table 5-2 lists relevant facilities and properties measured. Application ranges and test approaches used are further detailed in section 5.2.

Test Facility	Properties	Material family
Different Scanning calorimeter (DSC)	Heat capacity	Metals, composites, polymers, ceramics, glasses
Different thermal analyzer with Thermogravimetry (DTA/TG)	Heat of fusion	metals
Different thermal analyzer with Thermogravimetry (DTA/TG)	fraction solid in the melt	metals
Different thermal analyzer with Thermogravimetry (DTA/TG)	Mass loss by chemical reaction	Composites, polymers
Scale	Density	Metals, composites, polymers, ceramics, glasses
Laser flash apparatus (LFA)	Thermal diffusivity	Metals, ceramics
Dilatometer, optical imagery, pulse heating	Linear thermal expansion	Metals, composites, polymers, ceramics, glasses

Table 5-2: Material laboratory test facilities

5.2 Material Level Testing

5.2.1 Thermo-Physical Properties Measurement

Thermo-physical properties to be measured in laboratory

For metals and thermoplastics, the upper testing temperature of the following properties is referred to as melting point while for thermoset and ceramic materials the upper temperature will correspond to a degradation temperature.

The **heat capacity** from room temperature to the melting range of a specimen is measured with a Differential Scanning Calorimeter (DSC) in a protective inert gas atmosphere or ultra-high vacuum (as required by material) with a heating rate of 20°C/min in comparison with sapphire. The measured temperature range can be extended or the DSC replaced by other measurement techniques if necessary for fulfilling the room temperature to melting point criterion (e.g. pulse heating calorimetry).

The **heat of fusion and the fraction solid** in the melting range is measured with a Differential Thermal Analyser with thermogravimetry (DTA/TG) in a protective inert gas atmosphere or ultra-high vacuum (as required by material) where possible. Other measurement techniques are applied if necessary (e.g. pulse heating calorimetry).

The **linear thermal expansion** is measured with a Double Pushrod Dilatometer (DIL) in a protective inert gas atmosphere or ultra-high vacuum (as required by material) at 5°C/min where possible. The measured temperature range can be completed or the DIL replaced by other measurement techniques if necessary for fulfilling the room temperature to melting point criterion (e.g. pulse heating shadowgraph technique). This quantity is currently unused in any demise simulation tool. The most likely use for this is in the case that a fragmentation event is identified in test to be driven by differential thermal expansion of neighbouring parts. However, no observation of such an event has been made in tests so far.[3]

The **thermal diffusivity** is measured with a Laser Flash Analysis (LFA) in a protective inert gas atmosphere or ultra-high vacuum (as required by material) where possible and it allows to calculate the thermal conductivity, directly impacting demise. The measured temperature range can be completed or the LFA replaced by other measurement techniques if necessary for fulfilling the room temperature to melting point criterion (e.g. calculation of thermal diffusivity from heat capacity, density and electrical conductivity).

The **density** at room temperature is measured with an Archimedean balance. The density at elevated temperatures is calculated from room temperature density and thermal expansion.

Thermo-physical properties to be derived from PWT test

[3] The SMA used in the demisable joints study (see [RD4]) makes use of this principle but this is a rather extreme example.

The **emissivity** measurements should be performed both on virgin and degraded samples (post Plasma Wind Tunnel testing) on the temperature range of interest (Material dependent). Emissivity measurements will be challenging for material suffering from structural degradation after long heating time (e.g. composite materials). The emissivity measurements shall be performed in an inert atmosphere or ultra-high vacuum as required by material in order to avoid further reaction/degradation of the samples during the emissivity test itself.

The spectral (narrow band) emissivity measurement shall be performed using the same spectral pyrometer and its corresponding optical set-up than the one used for the PWT test campaign or a pyrometer operating at the same wavelength). A spectral emissivity can also be derived from two-colour pyrometer measurements in steady state conditions. Having an accurate value of the emissivity will be more relevant for high melting point alloys where a steady state condition could be observed before reaching melting point. The total emissivity measurement is more relevant for modelling purposes.

The **catalycity** is the gas-material interaction occurring at the surface of the material. Specifically of interest is the recombination of dissociated air atoms at the surface of the material as this releases heat to the surface. The heating rate correlations used in the simulations generally assume complete recombination at the surface (fully catalytic), resulting in a high heating rate. The heating to the surface is reduced if the recombination to air molecules is incomplete (partially catalytic).

5.2.2 Metals

Among all materials, metals are the ones for which the demise behaviour and associated simulation are understood the best. Their simulation and failure are driven by a melting phenomenon.

The key thermo-physical properties for demise of metals are the **melting point, the heat capacity, the heat of fusion and the thermal diffusivity.** A single value for the heat capacity or the thermal diffusivity is insufficient. A full temperature dependent set of data up to the melting point is necessary as the heat capacity increases significantly with temperature.

For simulation purposes, density shall be known too.

For low melting point metals such as aluminium alloys, the surface properties (emissivity and catalycity) will not be the driving demise parameters. Nonetheless, for higher melting point metals, the surface properties (**emissivity and catalycity**) have to be characterised. The oxidation of metallic surfaces will impact emissivity and catalycity and could lead to a steady state (temperature equilibrium) below the melting point of the alloy.

The most common metallic materials used on spacecraft can be classified in the following families: Aluminium alloys, Steel alloys, Nickel alloys, miscellaneous alloys (e.g. Titanium), Copper alloys.

Metallic materials are most of the time coated or protected by a surface treatment in order to improve their corrosion behaviour or their tribological properties (e.g. alodine, black coating, molybdenum disulfide, tartaric sulphuric anodising). Coatings can modify virgin material emissivity and might have an impact on the demise behaviour of the virgin materials.

Testing logic

The following test logic could be applied when an alloy not referenced in ESTIMATE database is considered.

1. A literature review of the thermo-physical properties relevant for demise of the new alloy should be performed. Values found should be compared with ESTIMATE database.
2. When the new material is coming from a known family (e.g. aluminium alloy), object oriented simulation should be performed with the most conservative properties (in terms of demise) of the family or alternatively from the most tested material (better confidence) of the family. Where data is obtained which differs significantly from other data in the material family ,this shall not be used as it is almost certainly in error.
3. When the new material is not linked to a known family, then at least the thermo-physical properties should be tested.
4. When the thermo-physical properties are not available up to melting point, then they should be tested.

With the current state of the re-entry simulation tools, the mechanical properties are not to be considered. Even if the demise simulation of metals are repeatable and understood, the current amount of alloys tested in ESTIMATE database among the alloy families is rather limited. Material properties can vary even among the same family, in order to reduce the uncertainty thermo-physical properties shall be tested.

5.2.3 Composites

Composite materials are made of a reinforcement and a matrix. In space applications composites are mostly used on the main structure of the spacecraft as face skins of the sandwich panels and as thicker monolithic parts (e.g. structural booms) and for composite overwrapped pressure vessels. The most common reinforcement for space application are carbon fibre and glass fibres. The most common matrices are epoxy and cyanate ester.

Due to the broad range of potential combinations (e.g. reinforcement, matrix, reinforcement lay-up, manufacturing process, etc.) the simulation of the demise behaviour of composites materials is very challenging. Classifying composites in families for demise purpose is therefore not possible as of today.

The following materials properties can be derived from a test campaign in PWT combined with a test case rebuilt using CFD:

- Heat of pyrolysis (resin decomposition)
- Activation energy for pyrolysis
- Chemical reaction rate factor(s) for resin decomposition

- Blocking factor, blowing factor
- Heat of oxidation (fibre oxidation)
- Chemical reaction rate factor(s) for fibre oxidation

A factor of thermal diffusivity[4] or ablation is then used at spacecraft simulation level.

The range of **emissivity** of composites materials will vary less than for metals and a high emissivity value can be assumed for both virgin and exposed surfaces.

The **Catalycity** is significantly less important for carbonaceous surfaces as the arriving air atoms react with the surface rather than the surface acting as a catalytic medium for the recombination to molecules. Therefore, this property is not normally used in heat shield analysis of ablators.

For glass based reinforcement (GFRP) the failure of the material (reinforcement) is due to the reduction in the viscosity to the point where the material is able to shear. To model this effect, knowledge of critical temperatures for the glass at different viscosity levels is required, in order to establish a melt point (say 10Pa.s). This requires different measurement techniques. (e.g. viscometer)

Testing logic

Due to the current knowledge of the composite materials, plasma wind tunnel tests should be performed to derive simulation parameters for demise simulation at equipment or spacecraft level.

Thermal conductivity and thermal degradation profile (TGA) and DSC, allowing to know the Tg (glass transition), are important for simulation purposes.

Given their variability, the extrapolation of demise tests done at material sample level to equipment or system level is not advisable. Depending on the criticality of the components considered with regards to their associated casualty risk, an appropriate test campaign should be performed at equipment or part level.

5.2.4 Polymers

Polymers are widely used on spacecraft as adhesives, tapes, matrices for composite materials and potting agents for insert bonding in sandwich panels.

Understanding the behaviour of potting agents used for structural inserts bonding in sandwich panels helps simulating the fragmentation behaviour of equipment, systems and spacecraft.

Testing logic

Testing in isothermal chamber at equipment level allows the understanding of the degradation mechanisms of the tapes, adhesives and potting materials.

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[4] The factor of thermal diffusivity is one of the inputs to fit an ablation mode to the data.

Thermal conductivity and thermal degradation profile (TGA) and DSC, allowing to know the Tg (glass transition temperature), are important for simulation purposes.

5.2.5 Ceramics

Ceramics are used for high temperature applications (e.g. propulsion) or for structures requiring high thermal stability such as optical payload. Therefore parts made of these materials are often found to survive re-entry and to contribute to the on-ground casualty risk.

In order to understand the behaviour of these materials during re-entry their heat capacity and thermal conductivity shall be measured.

Generally, ceramic materials have a low catalycity for the recombination of air molecules resulting in significantly reduced incoming heat fluxes. The resistance to fragmentation caused to internal stresses induced by quick temperature increase should be assessed at component level.

Active oxidation of ceramic materials can occur under specific environment. This should be assessed through a PWT campaign.

Testing logic

Depending on the criticality of the components considered with regards to their associated casualty risk, an appropriate test campaign should be performed at equipment or part level to understand their potential fragmentation behaviour. This may have a significant impact on the calculated casualty risk.

5.2.6 Glasses

Glasses are mainly used on spacecraft for optical payloads (e.g. lenses). They can be coated to improve optical performances. Their demise behaviour is currently not well understood. A melting demise behaviour is expected once the glasses reach critical temperature. Glasses shall be tested in PWT to derive key properties and their demise behaviour.

5.3 Equipment Testing Guidelines

5.3.1 Equipment Level Test Objective(s) and Key Parameters Measured

With the current state of the art, verification of demisability at equipment level by test only is not feasible. The differences between the possible test conditions and the actual environment during re-entry are too large and not sufficiently quantified to define a credible all-encompassing test case.

Therefore, the objective of equipment level assembly or subassembly level tests is twofold:

- Observe and quantify the demise phenomenology and correlate the simulation models accordingly
- Verify significant fragmentation events occur as expected and quantify their behaviour and uncertainty.

In order to satisfy the first objective, it is imperative to test equipment as close as possible to the full mechanical configuration of the actual flight hardware. The purpose is to either validate that the models perform adequately for extrapolation to re-entry conditions, or to provide data for the necessary correlation of the models before they can be considered suitable for extrapolation to re-entry. Some figures of merit for the model correlation are proposed in section 5.3.2.

The second objective aims at characterising significant fragmentation events, included in the equipment on purpose to affect its demise behaviour or not. For example, complex mechanical assemblies can include sub-assemblies that provide a level of shielding to other sub-assemblies. The break up would expose these sub-assemblies separately to the heat flux. Such a fragmentation event can be a thermo-mechanical event where mechanical forces, e.g. centrifugal forces, aerodynamic forces or thermo-elastic forces, are the cause of the break-up of a certain interface. Verification of a thermo-mechanical fragmentation event requires a test that represents both the thermal environment and the mechanical loads.

Equipment level testing also provides useful data regarding the material property models within the tools and measurements of particular properties, such as emissivity and melt/fragmentation temperatures. This data should already be available in ESTIMATE and validated by material level tests. However, it is recommended to double check the material performance at equipment level. The rebuilding of the tests, particularly where steady state conditions are achieved, can be used to estimate thermal conductivity and catalycity and to capture the point at which the material melt is observed, where there is a large difference. Depending on the alloys there could be a large difference between liquidus and solidus temperatures.

The exception to this, as expressed in section 5.2.3, is that the current material modelling capability of composite materials, particularly CFRP materials, is not sufficient to properly capture the complex material failure processes. Therefore, composites testing is recommended to be performed at equipment (strut, optical bench segment) level, and a specific demise model is to be derived from the test results.

Key parameters that can be assessed in the tests, validation methods and data requirements for validation are provided in Table 7-2. It needs to be highlighted that the possible correlation actions depend on the specific tool to be used in the simulation. Table 7-2 also provides a comprehensive list of correlation actions possible in the different tools. Some of these correlation actions may not be possible for all tools. Good model correlation can be achieved by performing certain correlation actions, as per the table below. However, the physical validity of the correlation actions implemented shall be justified.

Model	Possible Validation	Data Requirement	Correlation Actions
Heat flux inputs including hot wall correction (shape/size effects)	Steady state condition *[Is the test understood?]*	Surface temperature (pyrometer, thermocouples)	• Adapt the flow conditions. Ensure correct (cold and hot wall) heat flux rebuilding • Note: CFD can be used to recreate the flow conditions, which provides the enthalpy and therefore hot wall conditions. • Assess input heating levels relative to existent shape correlations. Determine corrected input heat flux length scale and apply to heating correlation for use in flight database.
Material emissivity/catalycity	Steady state condition *[Are the material properties consistent?]*	Surface temperature 2-colour pyrometer	• Adapt emissivity (temperature and/or oxidation dependent) • Adapt catalycity
Material thermal conductivity	Temperature matching *[Are the material properties consistent? Are there significant heat losses in the test set-up?]*	In-depth thermocoupling	• Adapt thermal conductivity (temperature dependent) • Note: Thermal conductivity is a material property. However, the conductivity may also depend on mechanical interfaces. Changes to the conductivity with respect to measured and validated material properties in order to better suit the tests is therefore deemed acceptable.
Change in heating on geometry change	Temperature matching *[Is there a significant change in the behaviour due to geometry changes during the demise process?]*	IR camera temperature, pyrometer	• Adapt heating input to capture the shape specifics as the shape changes • Note: The changes require a justification related to actual physical events or behaviour.
Demise validation	Increase in flux via steady state to achieve	Visual observation (video)	• Improve heat flux input correlation (particularly to individual parts of the model at a local scale)

Model	Possible Validation	Data Requirement	Correlation Actions
	demise condition Order of events *[Are the key events captured?]*	Temperature data (pyrometer, thermocouples)	
Fragmentation validation	Increase in flux via steady state to achieve fragmentation Order of events *[Are the key events captured?]*	Visual observation (video) Temperature data (pyrometer, thermocouples)	• Improve the representation of the fragmentation criteria (trigger events)
Composite Component Behaviour	Test at a range of heat fluxes to capture the failure behaviour [Can a reliable model for CFRP component demise be established?]	Visual observation (video) Temperature data (pyrometer, thermocouples)	• Derive a material model a posteriori from the data produced. • Use, as far as is practical, standard CFRP material properties for the temperature rebuilding, with trigger events, based on physical parameters (such as temperature), correlated over at least three different heat flux conditions. • Note: Ensure that the results are not dominated by the edge effects of thin CFRP layers which have been observed in test.

Table 5-3: Key parameters assessed through equipment level test procedure

The following steps should be followed in order to perform a test at equipment level:

- Extract the phenomena and sequence of events from simulation
- Definition of test object(s)
- Selection of test facility
- Test definition
- Model correlation

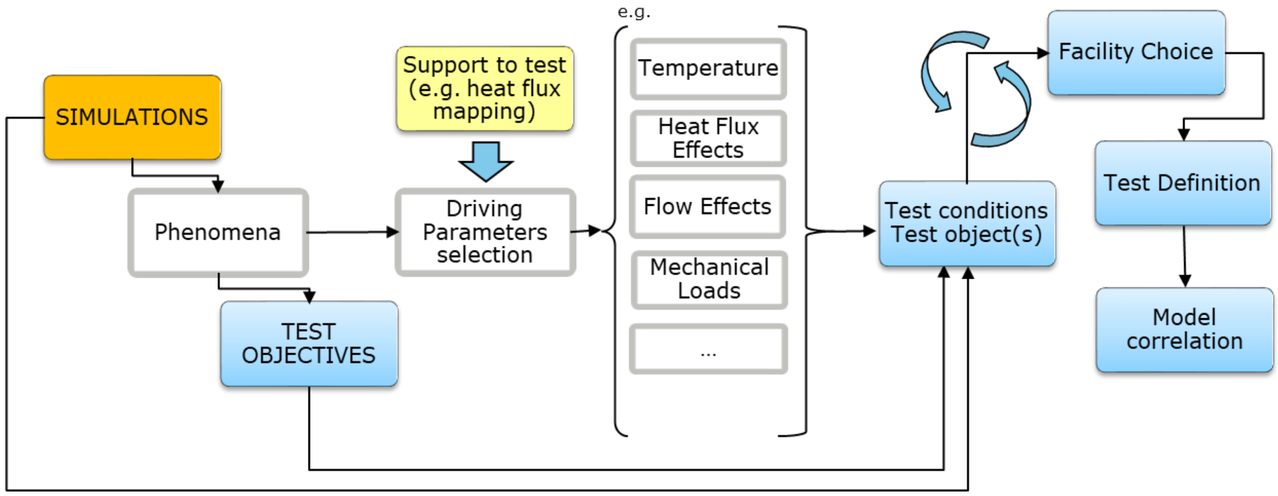


Figure 5-4: Equipment test - proposed steps

Detail on these steps is provided below, followed by an example based on a demisable reaction wheel.

Extract the phenomena and sequence of events from simulation

- A clear mapping of the events expected in flight (e.g. fragmentation) to the events expected in the test facility is required. This is particularly important as the heat flux profile and the object orientation as per flight is not expected to be reproduced in test
- A physical explanation of the expected sequence of events is required
- A specific test is required for the demonstration of any claimed specific fragmentation and/or demise behaviour
- Tests are required for the demonstration of the overall demise behaviour.

Definition of test object(s)

- Test requirements
    - The test campaign shall be designed to capture the demise phenomenology.
    - The test campaign shall be designed to capture any significant event (e.g. fragmentation). It is recommended to design separate tests/test conditions for every single significant event.
    - It is required to include a steady state condition on the critical low demisability material/part within the equipment, then to increase the heat flux in order to achieve demise. This may not be possible within one test in some facilities, if the expected radiative emission makes it impossible to achieve the demise of the equipment. This demonstrates the need for equipment calibration tests to understand the heat fluxes, emissivity and facility enthalpy levels.

- Test object
    - The test object shall be thermally and mechanically representative (all mechanical and material properties).

- The test object shall contain all parts that have the possibility to have a terminal velocity resulting in kinetic energy of more than 15J on the ground.
- The test object can be at sub-equipment level where there is sufficient evidence that this part is a realistic fragment.. In addition, sub-equipment level tests could be valuable to verify fragmentation events that happen at a later stage.
- Representative sections of an object which is large (e.g. magnetorquer, tank sections) are acceptable.
- Test samples to be tested in a radiatively heated test facility shall by sprayed with graphite to ensure that the reflectivity of the surface is sufficiently low.

Selection of test facility

In order to select the test facility type, the following guidelines shall be considered:

- For use of an isothermal facility:
  - The phenomenon to be observed is predominantly temperature driven and independent of dynamic pressure forces or other demise processes.
  - There is sufficient separation between the temperatures of separate events that they can be considered independent. Where interactions are possible as events can overlap in time, this type of facility is not appropriate.
  - Application of mechanical loads can generally be performed more flexibly in these facilities.

- For use of a static (radiative heat flux) facility, at least one of the following must be true:
  - The process to be observed is driven by heat fluxes below those that can be obtained in a high enthalpy wind tunnel.
  - The process to be observed requires a force application set-up, which currently cannot be achieved in a high enthalpy wind tunnel. Note that wind tunnel capabilities are under development/investigation, but that the application of forces can generally be performed more easily and more precisely in static facilities.
  - The process to be observed requires a specific (trajectory) heat flux profile in order to be observed. For example, the heat soak to inserts in sandwich panels cannot be captured without the correct timescales for the re-entry being reproduced in the test. This is critical to the chemical decomposition observed in insert failures. For example, the heat soak to inserts in sandwich panels cannot be captured without the correct timescales for the re-entry being reproduced in the test. This is critical to the observed insert failures.
  - The process to be observed is independent of the dynamic pressure of the flow, either due to the low dynamic pressure of the dominance of other force effects.
  - This type of facility can also be considered where the test object required to be tested is too large for a high enthalpy wind tunnel. In this case, a justification and/or demonstration of the expected observation differences from the different facility type is mandatory.

- For use of a high enthalpy wind tunnel:
  - This is the default facility type where the overall demise process is best demonstrated.
  - The flux levels and dynamic pressure levels shall be relevant to the expected behaviour. These facilities are generally not appropriate for early (>80km) break-up phenomena as the heat fluxes are too high.

Test definition

- Test predictions
  - Test predictions shall be derived by simulation in order to identify the expected test conditions necessary to observe a given phenomenon.
  - Depending on the phenomena to be observed, the simulations to support the conditions selection can vary. For steady state predictions, an equilibrium assessment is sufficient, whereas a transient simulation is required for demise prediction.
  - As fragmentation processes other than pure melt are rarely modelled physically in demise tools, an expected temperature and/or time of fragmentation is to be provided. These events are often modelled using triggers, e.g. a trigger temperature for a SMA used in a demisable joint, a failure temperature for an insert failure, a failure temperature of a glued connection failure, etc. A time delay beyond the failure temperature may be required.

- Test conditions
  - A methodology for mapping the heat flux from a standard probe to the test object must be detailed. This is critical to the selection of the correct test conditions.
  - It is highly recommended to calibrate a range of test conditions to be stepped through during the test. This allows for errors in the calculation of the heat fluxes, facility conditions (enthalpy in particular) and in material property estimates (emissivity in particular) whilst still allowing capture of the demise threshold. Correct estimation of the heat flux level at which demise is observed provides significant confidence in the methodology. At least one steady state test shall be used for demonstration of the understanding of the test conditions through the capture of steady state temperatures by the model.
  - For thermo-mechanical failure, forces need to be applied in the test set-up. Depending on the magnitude of the force as derived from simulation or supplementary analyses, the test set-up can include forces based on gravity, actuators, springs, centrifugal forces by spinning the test object or shaking.

- Facility calibration test
  - The calibration of a wind tunnel shall include a measurement of the heat flux on a standard probe (flat-faced cylinder or hemisphere) and a measurement of the pitot pressure.
  - This calibration is required for every test condition used – inclusive of intermediate steady state conditions.

  - The calibration of a static facility includes use of a high thermal conductivity calibration block (graphite is acceptable) in order to confirm the heat flux levels received by the sample. This is particularly important in cases where the flux levels can be reduced by outgassing contamination of the heating elements during the test.

- Test equipment (sensors)
  - A video recording of the test shall be made. This is the key diagnostic for fragmentation and demise event information.
  - An infra-red video recording is highly recommended.
  - The sample shall be thermocoupled as far as is practically possible. There are some objects which cannot be effectively thermocoupled (e.g. battery cells) and some fragmentation tests where thermocouple wiring could result in inhibition of the desired phenomenon to be observed. However, it should be expected that most samples can be effectively thermocoupled.
  - Thermocouples should be added to the sample holder in order to quantify the conductive heat loss due to the test set-up.

- Test set-up and define success criteria
  - The test shall be designed to minimise the heat losses from the test object by thermally insulating the sample from the sample holder as much as practical. Both insulating materials and air gaps are acceptable.
  - The test set-up is recommended to have sufficient space behind to allow demised parts to be separated from the test object without becoming stuck on the sample holder as this can produce significant heat losses.
  - The sample holder is recommended to hold the test object by the least demisable part in order to capture the sample fragmentation effects.
  - The orientation of the test object shall be selected to capture the important phenomena. Examples include:
    - Electronics cards tested with the flat face perpendicular to the flow.
    - Layer-by-layer demise of a magnetorquer is best captured with the axis perpendicular to the flow, where the melt through the layers is captured.
    - Battery modules have been tested at an angle of 45 degrees to the flow in order to reduce the moment effect on the connection to the GFRP baseplate whilst still ensuring that the cells can be removed when fragmentation events occur.

Reaction wheel parts have been tested with the symmetry axis in the flow direction

  - Care is required in order to ensure that the gravitational forces on the object do not drive the fragmentation events observed, or are used intentionally to capture particular effects.
  - Success criteria shall be defined.
    - Correctness of test conditions used
    - Capture of all the diagnostic data
    - Capture of the intended event occurrence / non-occurrence

        - Quantify fragmentation events

- Testing
    - Where a set of increasing flux conditions have been selected in order to achieve a sequential fragmentation, or a steady state condition prior to demise, it is recommended to allow 30 s at the steady state prior to shifting to the next flow condition.
    - Flow condition changes should be achieved as fast as possible, ideally within 10s.
    - The test stop condition should be pre-selected, based on time, observation of a specific phenomenon (can be complete demise), or between phenomena (to understand an intermediate state).
    - All required safety assessments, or required pre-tests to ensure the equipment is safe to test in the facility, shall be performed prior to testing.

- Post Test Analysis
    - All the remaining fragments shall be identified and photographed.
    - Particular fragmentation/demise features which can be seen on the recovered fragments shall be recorded. Improved understanding of the demise processes of more complex parts (e.g. battery cells) can be understood more clearly.
    - The justification of a fragmentation event is enhanced by evidence from the post-test analysis.
    - Considerations and guidelines to assess the tests uncertainty are provided in ANNEX G – Test Uncertainties Evaluation.

- Test conclusions
    - Provide test success criteria compliance
    - Certificate of conformance, list non-conformance reports and mitigation actions.
    - Compliance verification matrix
    - Update of compliance with Demise requirement, and identify main uncertainties.
    - Development of equivalent model for DRAMA equipment database
    - Highlight potential open points and knowledge gaps.
    -

Examples of the test procedure followed at equipment level for Reaction Wheels and for Structural joints are described in ANNEX M – Equipment Test Procedure Examples.

5.3.2 Model Correlation

- The test results shall be rebuilt numerically, with the end goal to provide a model suitable for inclusion in DRAMA (Section 4.4). Model correlation as described here is assumed to take place in the detailed model only. Model simplification is recommended to enable easier extrapolation of the test rebuild to a DRAMA model.
- A clear demonstration that the test conditions are well represented is required.
    - For wind tunnel tests, a CFD simulation of the stagnation probe shall be performed in order to demonstrate the cold wall heat flux and stagnation pressure can be rebuilt.

- For static facilities, a calibration block is required for verification of potential changes in the heating due to blockage of the radiative heat flux by outgassing.
- The methodology for mapping the heat flux to the test object shape shall be provided. In wind tunnels, if the Mach number of the test is below 3.0 and/or the shape cannot be represented well by primitive then a mapping by CFD is mandatory. Identification of the driving length scales for the heating is necessary for extrapolation to flight.
- For wind tunnels, a steady state condition shall be used to ensure that an energy balance can be captured.
- Correlation actions from the Table 5-3 shall be applied to capture the energy balance. This is mandatory before extrapolation to flight (Section 4.4) is performed.

- The macroscopic processes observed (fragmentation, material melt removal, material recession) shall be captured and compared with the expected fragmentation and/or demise processes used to establish the test conditions. Correlation actions shall be performed in line with Table 5-3.
- The thermocouple temperature data shall be rebuilt. It is expected that a 1D conduction model is the minimum requirement for this. Correlation actions may include adaptation of heat conduction properties in line with Table 7-2.
- Material properties shall be double checked with respect to ESTIMATE data using steady state data. It is worth noting that a good estimate of the heat input is required to achieve this. Demise analysis tools (e.g. SCARAB, SAM) can be used for supersonic flows, but this will require an intermediate step with a CFD model to provide the input heating if a subsonic facility is used.
- The rebuild is required to capture:
  - Surface temperature data to within 100K for all steady-state conditions.
  - In depth thermocouple data to within 100K (some further deviation based on smooth rebuild curves and less smooth data is acceptable).
  - Demise events to within 10% of demise timescale observed.
  - Observed changes in heating rates to demonstrate understanding.
  - As a minimum, the correct trends demonstrating that the necessary physics is present shall be demonstrated.
- Guidelines for extrapolation to flight are in Section 4.4.

5.3.3 Considerations for Test of Structural Elements

Structural elements cover a reasonably wide range of components, including:

- Sandwich panels
- Struts/bipods
- Joints

Tests of these structural elements have two specific areas of interest. Firstly, the demise of the component itself in the case of panels and struts, and secondly the separation of the component from attached parts. Reference to dependencies on nest-levels.

The testing of the demise of these structural elements follows either the internal equipment procedure (for internal structures) or the external equipment procedure (for external structures). This section provides the guidelines for the assessment of the separation of attached objects, inclusive of the connection of external equipment to the spacecraft.

The key diagnostic data required for model verification is the capture of the separation of the structure from a connected part. The correct test to be performed is dependent upon the nest-level of the structural element considered and the temperature level of the expected separation.

For the case of structural elements mounted on external panels for which failures at relatively low temperature levels are expected (e.g. inserts and epoxy-based adhesive joints, this is expected at approximately 400ºC, and where aluminium material failure is the driver about 600ºC is required), static facilities are generally adapted for demise tests (radiatively heated, see ANNEX B - Test Facilities Description). These elements are expected to fail at higher altitudes and therefore the effects of the low heat flux profile and low mechanical loads are predominant. Analysis performed in past studies (see [RD4]) showed that the forces on the spacecraft external panels at altitudes between 97km and 78km were of the order of 250N – 700N, which suggests a force of 10N – 35N per insert given the expected number of inserts per panel.

For structural elements with higher temperature failures or higher nest-level (e.g. mounted on internal panels), the selection of the facility(ies) depends on the driving parameters of the predicted demise phenomena, expected at lower altitudes. Therefore, the relevant loads vary significantly and the range of force levels needs to be assessed for the specific case. In addition, in the case of late exposure (e.g. high nest-level), other effects become relevant such as high heat flux levels and high flow field effects. For these tests the use of high enthalpy wind tunnel (see ANNEX B - Test Facilities Description), instead of static facilities, may be necessary.

The output data shall include video recording for observation of the separation event, and thermocoupling of the expected separation location.

5.3.4 Considerations for Test of Internal Equipment

The differentiation between internal and external equipment is defined in terms of the heat flux profile, flow effects and mechanical loads associated. Internal equipment will be exposed at later stages during the re-entry, therefore these effects will be more significant.

The majority of internal equipment is to be tested in a high enthalpy wind tunnel (see ANNEX B - Test Facilities Description), in order to achieve relevant heat flux levels and flow-field conditions.

Where a mechanical failure, due to rotational motion or other effect, is expected, the testing is required to be augmented by a high temperature radiatively heated test where external forces can be applied, or preferably, the test item can be spun in order to verify the fragmentation event at the temperature and force claimed.

5.3.5 Considerations for Test of External Equipment

The differentiation between internal and external equipment is defined in terms of the heat flux profile and flow field effects associated (see chapter 5.3.1). Connections of external equipment to the spacecraft is considered within the structural elements part (section 5.3.3).

Testing is required to consider the effects on the demise phenomena expected of the exposure of the external equipment (test object) to the re-entry flow from the beginning of the atmospheric re-entry. The main events related to the demise and their driving parameters (heat flux, flow effects, mechanical loads, etc.) during an atmospheric re-entry, have to be critically assessed:

- For demise phenomena predicted to occur at high altitudes (relatively low temperatures, low heat flux levels, low flow effects, low mechanical, etc.) static facilities are generally adapted and re-entry heat profile is recommended to be used.
- For demise phenomena predicted to occur at lower altitudes (relatively high temperatures, high heat flux levels, high flow effects, high mechanical loads, etc.) high enthalpy wind tunnel are suitable. For these tests an assessment of the impacts (e.g. changes in material properties, changes in mechanical integrity, etc.) of the equipment exposure to the re-entry flow from the beginning of the re-entry shall be performed.

At the moment, ground test facilities are not capable of representatively simulating all the effects occurring during a re-entry (see chapter 5.3.1). Therefore a combination of facilities may be required to capture all the conditions of interest for given demise phenomena.

6 IDENTIFIED KNOWLEDGE GAPS

During this work several knowledge gaps have been identified that are important to mature the Demise verification process. They are listed here below:

- Knowledge gaps identified on materials demise and fragmentation physics:
    - Understanding the impact on the demise and fragmentation process of materials mechanical properties under re-entry conditions;
    - Understanding of the impact on demise of different surface treatments.
    - Develop knowledge on ceramics and glass materials behaviour under re-entry conditions.
    - Understanding of impact in demise and fragmentation of the interaction with material ejectas in re-entry conditions.

- Updates required to verification tool:
    - Update of verification tool (DRAMA) to meet the required verification functionalities defined in this Technical Note.
    - Development of a database of aerothermodynamic correlation factors for more complex shapes (e.g. boxes, rings, etc.).
    - Development knowledge on length scale effects (e.g. the case of small objects on large objects such as boxes on plates, reaction wheels on a central tube, etc.).
    - Development of cavity flows models (e.g. box with a missing side): this is highly relevant to the fragmentation altitudes where a panel has been removed, but other panels remain in place.
    - Develop an equipment level database verified following the methodology established in this Technical Note to support system level demise verification.
    - Development of a system level reference case for tool comparison.

- Knowledge gaps identified in test definition and analysis:
    - Development of guidelines for scalability and sectioning to support definition of test objects.
    - Development and validation of fragmentation models to improve higher fidelity re-entry simulation predictions.

- Development of design methods to establish a more predictable break-up sequence analysis, to have the system guaranteeing that the equipment is separated from the spacecraft at the required altitudes.
- Validation of re-entry model predictions through observation of re-entry events and/or dedicated re-entry experiments.
- Study advanced models for the on-ground casualty risk calculation taking into account factors such as population shielding.

7 ANNEXES

7.1 ANNEX A - ESTIMATE Database Description

The ESTIMATE database compiles thermo-physical properties of the most commonly used metallic alloys in space and Silicon Carbide.

Plasma wind tunnel measurements performed on these materials are also available.

Materials thermo-physical properties can be used by re-entry tools for analysis while PWT tests results and tests conditions can be used for test case rebuild and material properties derivation.

The database will be regularly populated in the future when additional tests are performed.

Registration procedure, limited to users affiliated with entities in ESA member states and on a need to know basis:

1) You'll need a general account which can be created at https://account.sdo.esoc.esa.int/ (but you might already have one as it is the one used on https://sdup.esoc.esa.int)

2) You then use this account to login at https://account.sdo.esoc.esa.int/sdo-user-management/toolsRegistration?toolId=estimate where you will have to request access.

3) Afterwards, the request is manually processed and you'll be informed on the outcome.

4) If accepted, you can use your account to login at https://estimate.sdo.esoc.esa.int/

The table below shows several material properties that were measured for aluminium alloys in different test campaigns. There is not enough data to draw conclusions on what distribution they follow. However, the properties stay within limited ranges, meaning that it is reasonable to consider aluminium alloys as a similarity class, as shown below:

- Density: 2750 +/- 2.5%
- Melting temperature: 864.5 +/- 5.4%
- Specific heat: 942 +/- 6.9%

Material	Density [kg/m^3]	Melting temperature [K]	Specific heat [J/kg/K]
AA2219	2820	818	953
AA2050	2720	911	1007
AA5028	2680	887	919
AA7075	2813	906	940
AA2195	2685	906.15	877

7.2 ANNEX B - Test Facilities Description

In this Annex the descriptions of the main facilities considered in chapter 5.1, are presented.

Static Test Facilities

Static test facilities usually consist of a vacuum chamber with means to heat the test sample to temperatures that are relevant to re-entry conditions.

The instrumentation typically used in these facilities is for temperature measurements, such as pyrometers. Emission spectroscopy might also be used to determine concentration and temperature profiles.

In general, the facilities are useful to obtain information about material properties at high temperatures, and the thermochemistry of the surface of the sample if the facility permits. In the specific case of the AAC chamber, mechanical loads (static and dynamic) can also be applied, making it possible to study the thermo-mechanical behaviour of the sample.

Applications in this case include thermal shock testing, thermal cycling and gas cycling tests, thermos-mechanical test and combinations. In other facilities, the thermochemistry of the surface can be studied by exposing the surface to oxidising plasmas. The most obvious limitation is that there is no flow velocity.

It is usually possible to control the temperature and pressure of these chambers independently and with high accuracy, as opposed to plasma wind tunnels.

In general they are useful to obtain information about material properties at high temperatures. This information can then be used on the models to give more accurate predictions.

Cold Hypersonic Wind Tunnel

Hypersonic flow is a flow for which speeds are much larger than the local speed of sound. In general hypersonic flow is defined as the flow at Mach 5 or greater at which physical properties of the flow changes rapidly. A test facility designed or considered for hypersonic testing simulates the typical flow features of this flow regime. These flow features include thin shock layer, entropy layer, viscous interaction and most importantly high total or stagnation temperature of the flow.

For the sake of completeness a brief description of shock tube is also presented. In this facility a valve is placed between the driving tube and the nozzle. The driver tube is pressurised until the valve breaks, creating two waves. One propagates towards the nozzle, and goes through it to the test section, where hypersonic flow is reached. The other wave is propagated in the opposite direction, into the tube. It travels through the tube until it reaches the end, and it is reflected back. The hypersonic conditions are maintained in the test section until the second wave reaches it, so the test time corresponds to the time it takes this wave to travel twice the length of the driver tube approximately. For optical measurements, it is possible to use IR spectrometry, (and other kinds of spectrometry according to DLR), shadowgraphy, and schlieren as well.

The test time is very short, ranging in the order of milliseconds to a few seconds. In this amount of time it is not possible to reproduce the heat conditions the object would experience in re-entry.

These facilities are able to create flow fields with Reynolds and Mach numbers which are relevant to re-entry conditions, so they are useful to study the aerodynamics of the object and the shock behaviour.

Dynamic Test Facilities - Plasma Wind Tunnel

In a plasma wind tunnel, a continuous stream of plasma is created and passed through a nozzle and into the test section. These kind of wind tunnels can be classified according to the method used to create the plasma, which will affect the characteristics of it and its recommended use.

Firstly, a plasma wind tunnel can be equipped with magneto-plasma-dynamic plasma sources (MPG). They are used to simulate re-entry conditions with high specific enthalpies and low pressure levels. They are useful to simulate the first phase of re-entry, where the temperature of the sample reaches its maximum.

The plasma can also be created using an arcjet, making it possible to test at high dynamic pressure levels. They have a more limited reachable specific enthalpy, but higher pressures can be obtained together with higher Mach numbers. The gases reach high temperatures and hypersonic speeds when they pass through an arc jet between an anode and a cathode. This kind of PWT is better suited to study the late phase of re-entry trajectories.

The last kind is the inductively heated plasma wind tunnels. These type of plasma wind tunnels are used to generate plasma flow that does not create any unwanted chemical reaction in front of the test sample, with the objective to study its catalytic behaviour. For this reason, inductively heated plasma wind tunnels have no electrodes. In addition, they can be operated on more reactive gases, which could be useful to simulate the atmospheres of other planets.

Usually the instrumentation is used for thermal and optical measurements. For thermal measurements, the possible instrumentation includes thermocouples, IR pyrometers and radiometry. Pyrometers are remote-sensing thermometers, and radiometry is just another technique to measure the temperature of an object. For optical measurements, it is possible to use emission spectroscopy, or laser induced fluorescence in addition to HD and IR cameras. Infrared thermography can therefore be used as well. A very important parameter that can be measured is the emissivity of the test sample.

A critical limitation is that there is no wind tunnel that can emulate all the phases of re-entry. Usually a choice has to be made between testing with a representative total pressure (arc heater) or a representative enthalpy (MPG) for the peak heating phase.

In addition, usually the way the heat flux is applied to the test sample does not correspond exactly to the way it would happen in flight. An example implementation is based on using the stagnation point heat flux profile which is integrated over the re-entry trajectory, and this value is used to compute the average constant heat flux. That should be applied over a determined amount of time in order to subject the sample to the same amount of energy. This way the entire process during the trajectory cannot be resolved but the final result should be representative. Several different combinations of time duration and average heat flux can be used, but this last value must be above a certain amount in order to reach melting temperatures.

Another important limitation has to do with the way the sample is placed inside the test section. Usually it is supported by a holder and is held still throughout the test, while during re-entry the object would be tumbling, which makes the heat flux received 4 times lower than the stagnation point heat flux. Additionally, the support for the test sample can use as a heat sink during the test, making the results less representative. Therefore, to minimise this effect, the use of thermal insulation is recommended. Finally, the flow velocities achieved do not match the ones experienced during re-entry. For this reason, testing is conducted via Local Heat Transfer Simulation, by which the enthalpy, stagnation pressure and velocity gradient at the stagnation point are reproduced.

Facility type	**Plasma Wind Tunnels (in Europe)**	**Shock Tubes and Ludwieg Tubes *(kinetic)***	**Ballistic Facilities *(kinetic)***
Examples in ESA member or associated countries	• L2K & L3K (DLR, DE) • PHEDRA (ICARE, FR) • Plasmatron (VKI, BE) • PWK1-4 (IRS, DE) • SCIROCCO & GHIBLI (CIRA, IT) • SIMOUN (Airbus, FR)	• ESTHER (IPFN, PT) • HEG (DLR, DE) • HWK (ZARM, DE)	• Terminal Ballistics facility (DREV, CA)
Test duration	~ 1 h	~ 1 ms	~ 100 ms
Total pressures	< 1.7 MPa (SCIROCCO, constricted arc plenum pressure)	< 150 MPa (before expansion)	< 480 GPa (assumption of isentropic kinetic energy transfer)
Mach number	< 12	< 25	< 20
Reynolds number	$10^3 - 10^4\ m^{-1}$	$< 10^7\ m^{-1}$	$< 6.5 \cdot 10^6\ m^{-1}$
Sample size	< 0.3 m (typical), < 2 m (SCIROCCO)	< 0.5 m	< 0.5 m (typically cm range)
Sample mass	(limited by size)	(limited by size)	< 10 kg (typically g range for hypersonic velocities)
Specific enthalpy	< 220 MJ/kg (air) < 5 GJ/kg (H_2)	< 25 MJ/kg	< 30 MJ/kg
Primary drawbacks (as compared e.g. to flight experiments)	• No Reynolds or Mach number analogy • Academic reduction of reference object and trajectory required • Challenges concerning representation of large-scale structure-material interactions (e.g. for anisotropic materials) • Trade-off usually required between representative specific enthalpy and representative total pressure (see also Table 5)	• Very short test durations • Unsuitable for material heating response tests • Typically, thermochemically non-representative test gases distorts boundary layer shaping	• Very short test durations • Unsuitable for material heating response tests
Suitable applications	• Material response characterisations (demise phenomenology, catalysis at relevant wall temperatures) • Joint break-off characterisations • Limited verification of thermo-structural responses of small-scale components or mock-ups • Thermochemistry verification cases for ground risk assessment simulation tools	• Simple aerodynamic break-up (e.g. "break-off") experiments • (Multi-body) shock layer formation and interaction • Aerodynamics verification cases for ground risk assessment simulation tools	• Potentially relevant when combined with shock tube or Ludwieg tube for break-up ("break-off" experiments

Table 7-1: Overview of dynamic entry test facility types in ESA member states or associated countries

Types of Plasma Sources	Arc heaters (a.k.a. Thermal Plasma Generators or TPG)	Magnetoplasmadynamic generators (MPG)	Inductively heated Plasma Generators (IPG, a.k.a. Radio-Frequency Generators or IPG)
Subtypes	• Hollow electrode / Huels type arc heater, e.g. L2K (DLR, DE), SIMOUN (Airbus, FR) • Constrictor-design thermal arcjet generator, e.g. L3K (DLR, DE), SCIROCCO (CIRA, IT) • Central cathode design Thermal Arcjet, e.g. RB3 in PWK4 (IRS, DE) • Hot cathode generator • 3-phase AC generator	• Self-field MPG (SF-MPG), e.g. RD5/6/7 in PWK1 (IRS, DE) • Applied-field MPG (AF-MPG), used in Russia only for entry testing	• Inductive plasma generator (IPG) / radio-frequency generator (RFG), e.g. IPG3/4/7 in PWK3 (IRS, DE), Plasmatron (VKI, BE)
Advantages	• High pressure range • Comparatively high Mach numbers → locally representative aeromechanics (stagnation area)	• High enthalpy range • Fairly high plasma purity → locally representative thermochemistry (stagnation area)	• Full working gas flexibility due to electrode-less design • High plasma purity • Moderately high pressure and enthalpy ranges
Disadvantages	• Limited mass-specific enthalpies especially at high-pressure conditions • Typically, some plasma contamination through electrodes	• Limited maximum pressure range	• Only moderate enthalpy and pressure ranges
Best applications for investigation of uncontrolled re-entry aspects	• Late phase (e.g. post-break-up) entry trajectory simulation (material demise) • Investigation of localised aeromechanical effects	• Early phase (e.g. pre-break-up) entry trajectory simulation • High-energy entry trajectory simulation (energy similarity) • Investigation of localised high-enthalpy thermochemistry (oxidation and catalysis)	• Detailed surface thermochemistry investigation, e.g. catalysis and oxidation

Table 7-2: Overview of plasma source type available for plasma wind tunnel facilities in ESA member states or associated countries

Steady state atmospheric entry test facilities for aerothermal testing at flight-relevant heating conditions, commonly referred to as Plasma Wind Tunnels (PWT), are meaningful as a facility for the duplication of a boundary layer environment that is representative of local conditions generated from hypersonic compression in front of an object entering and interacting with an atmosphere.

The environmental conditions ensuring this boundary layer similarity comprise an equivalence of the local mass-specific enthalpy, the total pressure and the velocity gradient at the boundary layer edge. The latter condition is typically met by scaling the effective nose radius of the test article to mimic the given real flight scenario. Scaling approaches exist that enable a direct, meaningful scaling and read-across of stagnation point heating conditions between a given flight reference and an accordingly calibrated PWT test scenario, such that boundary layer conditions near a surface can be considered fully representative within the stagnation area. This ensures local thermochemical similarity and results in representative and comparable gas-surface interactions and heat transfer.

The relative deficiency in kinetic energy of the typically sub-hypersonic simulated flow contributing to compression heating is compensated by an artificial increase of the flow enthalpy through the facility's plasma generator. Through this approach, the definition of Mach and Reynolds analogies as employed in classical fluid mechanics is not useful and the resulting values are misleading. Whereas the localised boundary layer conditions are accordingly inaccurate aside the stagnation point, they can still be relevant and conducive towards a verification of thermo-structural responses of non-trivial objects to entry conditions (e.g. nose structures or mock-ups) and can serve to verify numerical simulation tools via correspondingly implemented test cases.

7.3 ANNEX C – Reference Re-entry Corridor

Definition

The focus of this body of work is on uncontrolled re-entries from low Earth orbits, i.e. for those orbits the mean eccentricity is 0 and the true anomaly can be considered uniformly distributed.

In order to facilitate the validation of fragmentation and demise requirements, it is necessary to define the physical conditions encountered. This is done by defining hypothetical re-entry trajectories which can be considered as input to derive the atmospheric conditions. The objective is to systematically capture all trajectory uncertainty encountered by both equipment and system levels.

The relevant area-to-mass ratio range can be constrained by available statistics on actual values of on-orbit and historical satellites. The data for all intact satellites associated with a civil meteorological or imaging missions were extracted from ESA's Database Information System Characterising Objects in Space (DISCOS). The histogram is shown in Figure 7-1.

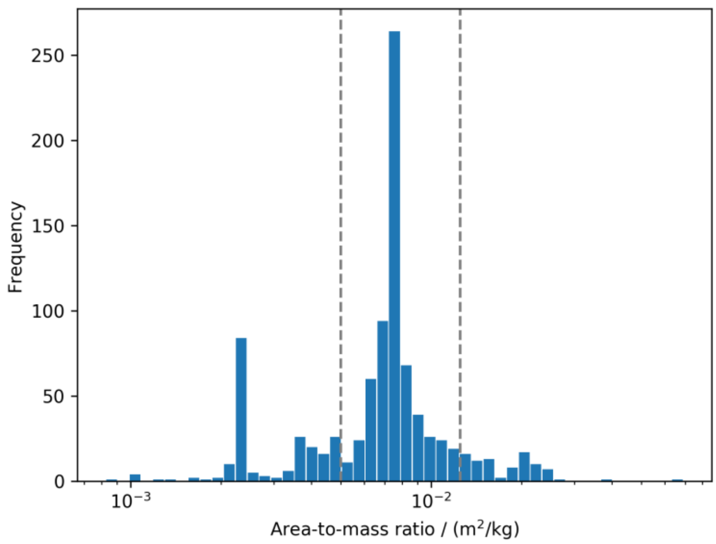


Figure 7-1: Area-to-mass ratio for intact satellites in ESA's DISCOS, as of November 2019. Only civil meteorological and imaging missions shown Dashed vertical lines indicate the region between 1/200 and 1/80 m^2/kg.

It seems that for typical Earth observations missions targeting high inclination orbits, the area-to-mass ratio can be quite narrowly constrained to values approximately around 0.01 m^2/kg. For the baseline, a coverage of the region between 0.005 (1/200) and 0.0125 (1/80) is recommended according to ESA's Earth observation missions. A similar restriction can be applied to the inclination.

The trajectories which can be used of for assessing the demise and fragmentation behaviour at system and equipment level are those:

- Of an non-demisable sphere, with area to mass ratio varied uniformly between 80 and 200,
- With a variable inclination [65 deg, 100 deg] and the position along the orbit [0 deg, 360 deg],
- Released at a geodetic altitude of 120km from a circular orbit,
- Considering the US79 atmosphere model with density variation as in Section 4.2.4,
- An Earth gravity model up till J2.

The trajectories generated in this way shall be referred to as the re-entry corridor or trajectory bundle. Any point on this trajectory, in the phase space defined at first order by velocity, altitude, and flight path angle, is a possible fragmentation point where an equipment is released to the aerothermal flow on its own trajectory.

These trajectories can be tailored for specific needs in case equipment is under consideration. For example, internal equipment is not so much concerned with higher area to mass trajectories, as the solar panels on the parent spacecraft will no longer have a significant influence on the trajectory at the point where the equipment is released to the aerothermal flow field. On the contrary, design for demise technique which aim to detach spacecraft parts at higher altitude, e.g. 95 kilometre and above, would be less concerned with lower area to mass trajectories. Tailoring justifications of the requirements in Section 3.3 can thus be made on a case by case basis, if the full range as laid out above is too broad.

Examples

By varying the orbital inclination [65 deg, 100 deg] and the position along the orbit [0 deg, 360 deg], as well as scaling the heat flux and the drag coefficient, of 150, between 90% and 110% as per in Section 4.2.4, respectively, for any specific satellite modelled in DRAMA, one obtains a map of release conditions in terms of the velocity, flight path angle and release altitude as shown in Figure 7-2.

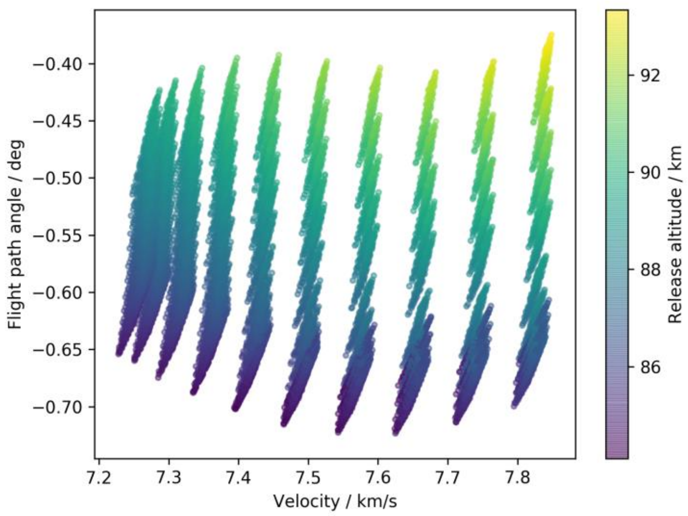


Figure 7-2: Release conditions, in terms of velocity, flight path angle and altitude for a specific satellite mission immediately after the demise of the service module

The inclination variation leads to a spread in velocity direction with higher inclination values resulting in higher release velocities. Varying the position along the orbit results in a distribution along the flight path angle. Heat flux and drag coefficient scaling result in smaller order variations in both flight path angle and velocity. The release altitude tends to increase for higher inclinations.

In Figure 7-3, the results for five different satellites are super-imposed. Again, the conditions at the moment of the demise of the service module of those satellites are shown. It can be clearly seen that the actual design of the service module plays a significant role.

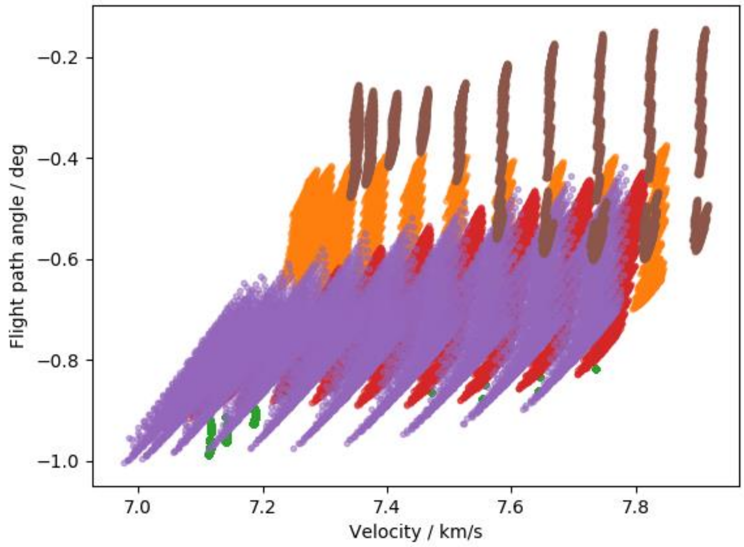


Figure 7-3: Release conditions, in terms of velocity and FPA for a few specific satellite missions immediately after the demise of the corresponding service module

The integrated heat for a non-demisable sphere of 15 cm radius is shown in Figure 7-4. In this case, the orbit was polar (inclination of 90 degrees) and the argument of true latitude (position along the orbit) and the area-to-mass-ratio were varied.

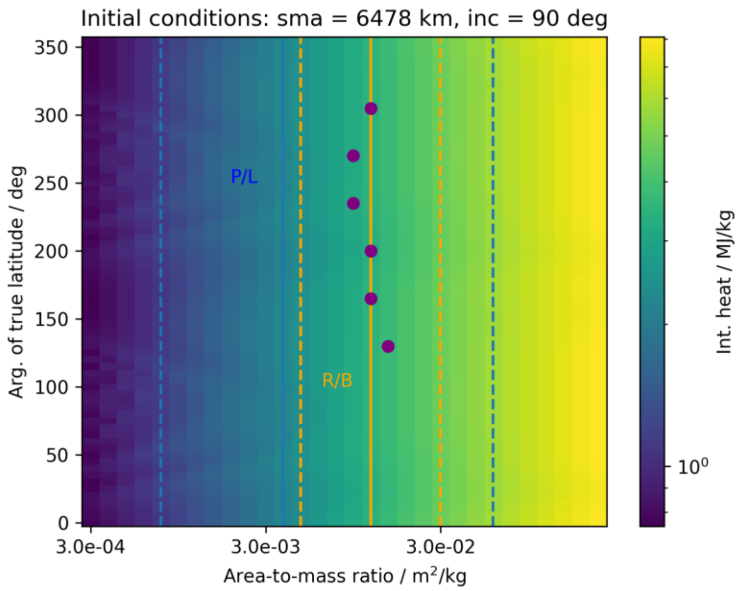


Figure 7-4: Integrated heat as a function of A/m ratio and initial condition for the argument of true latitude and an inclination of 90 degrees (polar). Purple dots show specific satellite missions. Payload (P/L) and rocket body (R/B) area-to-mass range indicated by vertical lines.

Solid vertical lines for payloads (P/L) and rocket bodies (R/B) indicate the typical area-to-mass ratios in the sense of their overall frequency in DISCOS. Beyond the dashed lines, only single objects can be found from all known space missions. Also shown (with purple markers) are a few specific missions, which align closely around the value of 0.01 m^2/kg, as already identified to be a very likely value for Earth observation missions in [RD3].

The same example is shown for a near-equatorial orbit (inclination of 1 degree) in Figure 7-5. The integrated heat tends to be on the order of a few MJ/kg in general with tendency towards increased values for higher inclinations.

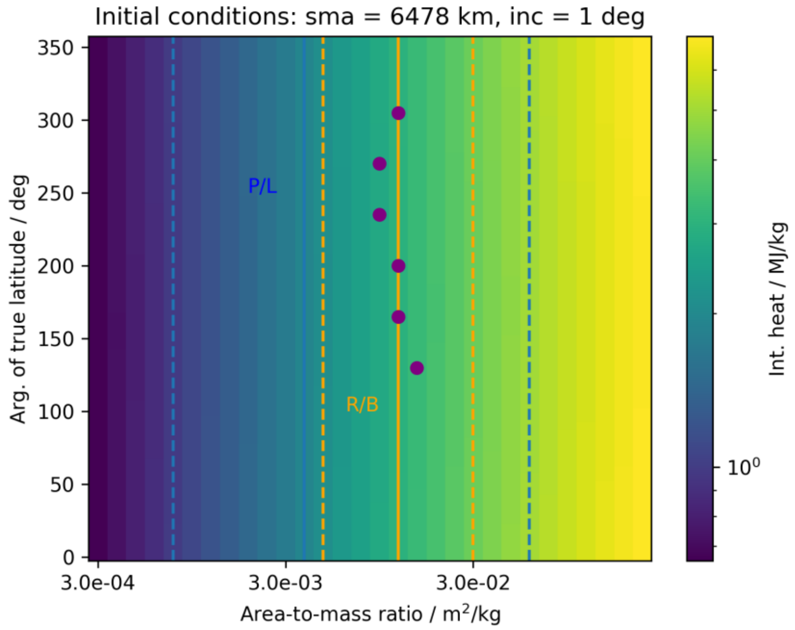


Figure 7-5: Integrated heat as a function of A/m ratio and initial condition for the argument of true latitude and an inclination of 1 degree (near-equatorial). Purple dots show specific satellite missions. Payload (P/L) and rocket body (R/B) area-to-mass range indicated by vertical lines.

Another example using the same non-demisable sphere with a radius of 0.15 m (in order to follow the same trajectory bundle) was run, this time releasing a mock-up reaction wheel model at pre-defined altitudes, in order to assess the reaction wheel's demisability. An example output is shown in Figure 7-5. Again, the inclination and the position along the orbit were varied. In this case, however, the inclination was constrained to values between 80 deg and 100 deg. Demisability heavily depends on the release conditions and is also a function of the release altitude. In Figure 7-6, it is shown exemplarily for a release altitude of 76 km.

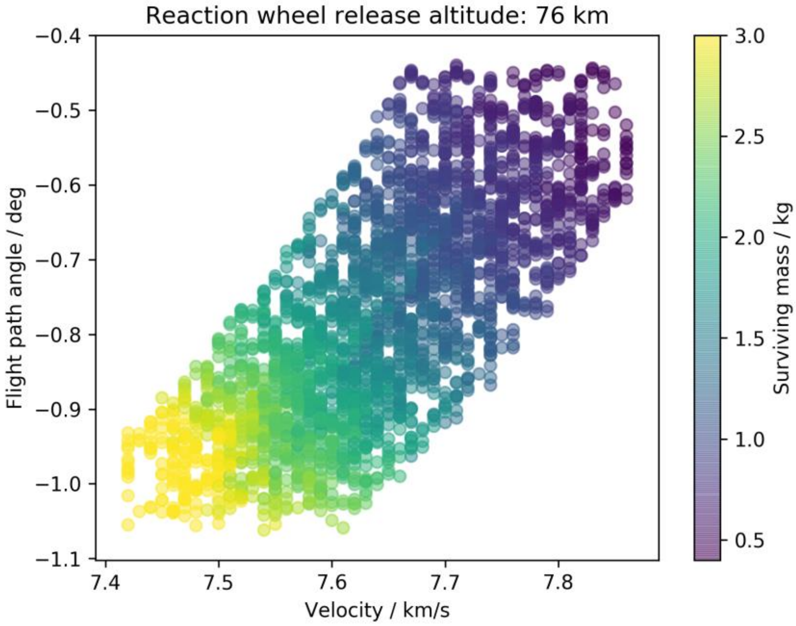


Figure 7-6: Release conditions and surviving mass for a mock-up reaction wheel (total mass of 9 kg) released at 76 km.

7.4 ANNEX D – Material Level Test Samples Definition

Thermophysical characterisation:

The specimens have the following standard dimensions:

- Archimedean balance: diameter, 20 mm; length 50 mm
- DSC (solid phase): diameter, 6 mm; thickness 1.5 mm
- DSC (melting and liquid): diameter, 2 mm; thickness 2 mm
- LFA (solid phase): diameter, 12.55 mm; thickness 3 mm
- LFA (melting and liquid): diameter, 11 mm; thickness 1.5 mm
- DIL (solid phase): diameter, 6 mm; length 25 mm
- DIL (melting and liquid): diameter, 6 mm; length 12 mm
- Pulse heating (microsecond): diameter, 1.6 mm; length 75 mm
- Pulse heating (millisecond): tube; outer diameter, 6 mm; inner diameter, 4 mm; Length 75 mm
- Electromagnetic levitation (before experiment): diameter, 6 mm; length 6 mm.

The specimen dimensions may be different if necessary. The sample definitions, test facilities and test conditions shall be approved by ESA before starting the test campaign.

Plasma Wind Tunnel Tests
The definition of the samples depends on the wind tunnel facility selected and the material itself. Some limitations due to material properties (e.g. brittleness) or the manufacturing process (ceramic and composites) might induce samples shape modification.

Cylindrical shape samples without cap
The samples can have the design specified below. The back face of the sample will be drilled to insert thermocouples at various depths allowing measuring the temperature gradient within the sample during PWT test. The drawback of this sample approach could be for composites material. The shear stresses created at the edge of the sample might induce a fast ablation of the CFRP plies, which might lead to a faster demise. This sample design is well suited for metallic materials, ceramics and material combinations (as the holder can be adapted to various sample dimensions). For the metallic materials, care shall be taken while selecting the material of the screws to avoid reactions/alloying during the PWT test.
Specific attention should be given to the thermal insulation with the support of the sample holder.

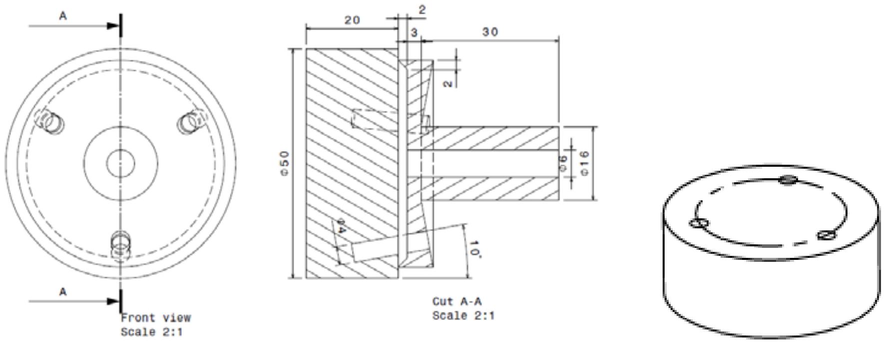
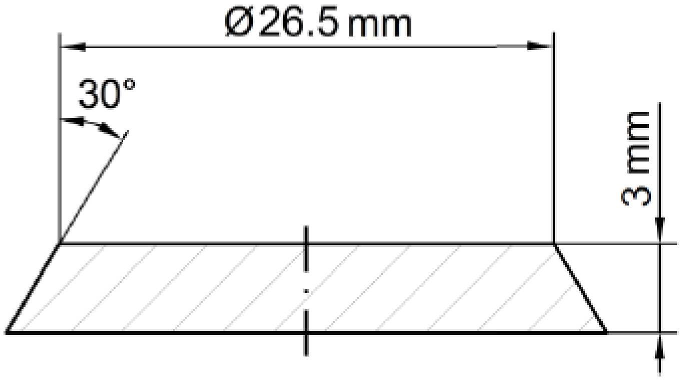


Figure 7-7: Coin Shape sample with SiC cap

If the coin sample strategy is used, the sample shall have the following dimensions.



The sample will then be mounted in a probe equipped with a cap. Silicon carbide caps shall be preferred and Graphite caps shall be avoided. It has been observed that reaction could occur between graphite and some samples materials during PWT tests. Additional heat was introduced inside the sample causing an earlier demise of the sample. This sample shape is not suited for material combination testing (like honeycomb CFRP or COPV). It is important to have a good understanding of the isolating material around the samples and to have a thermal analysis of the system to be able to simulate the PWT test accurately.

7.5 ANNEX E – Initial Temperature of External Equipment

To determine the initial temperature for external equipment, the following procedure could be used. The heat load to a re-entering vehicle is approximated in an average sense in the figure. This can be fit using the following formula:

- If altitude A > 95km, heat load is 1.4 x (115-A)/5
- If altitude A <95km, heat load is 1.4 x (115-A)/5 + 0.9 * (95-A)/5

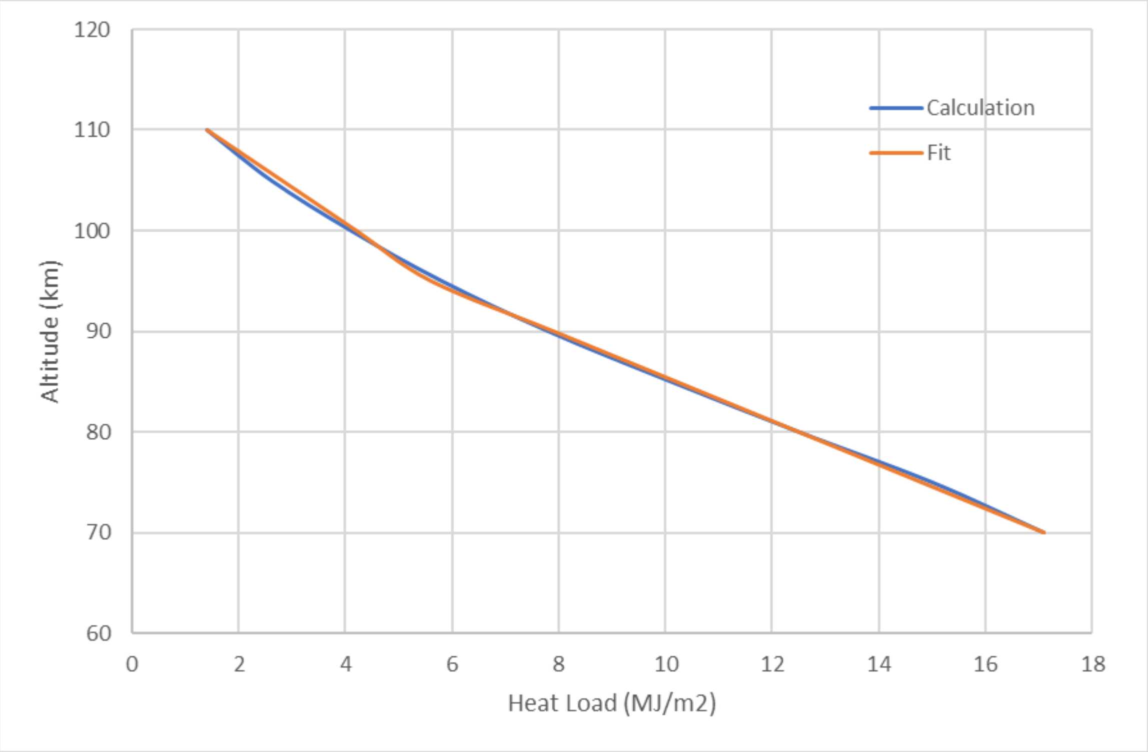


Figure 7-8: Heat load to a re-entering vehicle approximated in an average sense

To convert the heat load, H, per unit area (in J/m²) to the temperature increase of the object, the following formula is used:

- T (in Kelvin) = 300+ H*A/M/Cp/2
- A is projected visible area of object projected on the external structure in m²
- M is the mass of the object in kg
- Cp is the specific heat capacity in J/kgK at 400K for the relevant material from the ESTIMATE database
- A safety factor of 2 is used as the flux distribution varies across the panel surface.

No initial temperature higher than 600K should be used for a release above 80km.

As an example, an antenna pointing mechanism can be considered. Based loosely on an X-band antenna from a current spacecraft, the antenna is modelled as a cylindrical predominantly aluminium structure of 4.5kg mass, 0.4m length and 0.1m radius. The relevant area to consider is the average projected area which is given by one-quarter of the convex area, which in this case is $0.079m^2$. The specific heat capacity of aluminium at 400K is approximately 920J/kgK. The initial temperatures obtained are:

Altitude (km)	Temperature (K)
110	312
105	326
100	341
95	357
90	378
85	396
80	418
75	441
70	466

Table 7-3: Example of the temperature profile on an antenna pointing mechanism, during the re-entry

Figure 7-9 shows mean temperature evolutions for three different types of components: Star tracker (STR) clearly being an external component, magnetic-torque (MTQ) clearly being an internal component, and a solar array driving mechanism (SADM) mounted on the border between internal and external.

Obviously, the STR shows the quickest and most intense temperature increase. However, the differences between SADM and MTQ temperatures needs a deeper understanding of the satellite configuration and its tumbling motion during re-entry. The asymmetric solar array configuration of Sentinel-2 leads an aerodynamic stabilization with the SADM in a leeward position, keeping it shielded down to low altitudes. The MTQs are mounted in two different positions: two on the Baseplate (structure panel where also the launch interface ring is mounted), one mounted on the same panel as the SADM. This leads to two different temperature evolutions, one very close the one seen for the SADM, and two, which are more towards the STR temperature (also very closely mounted to the Baseplate). Although being located on the inside, they are still heated up by thermal conduction through the Baseplate. The average temperature of all three MTQs is in between the boundaries formed by STR and SADM temperatures, which could be interpreted as a “min-max bandwidth”.

Figure 7-10 illustrates the SADM release temperatures extracted from SCARAB simulations for three different satellites, indicating the variability which can be observed for similar equipment on different platforms.

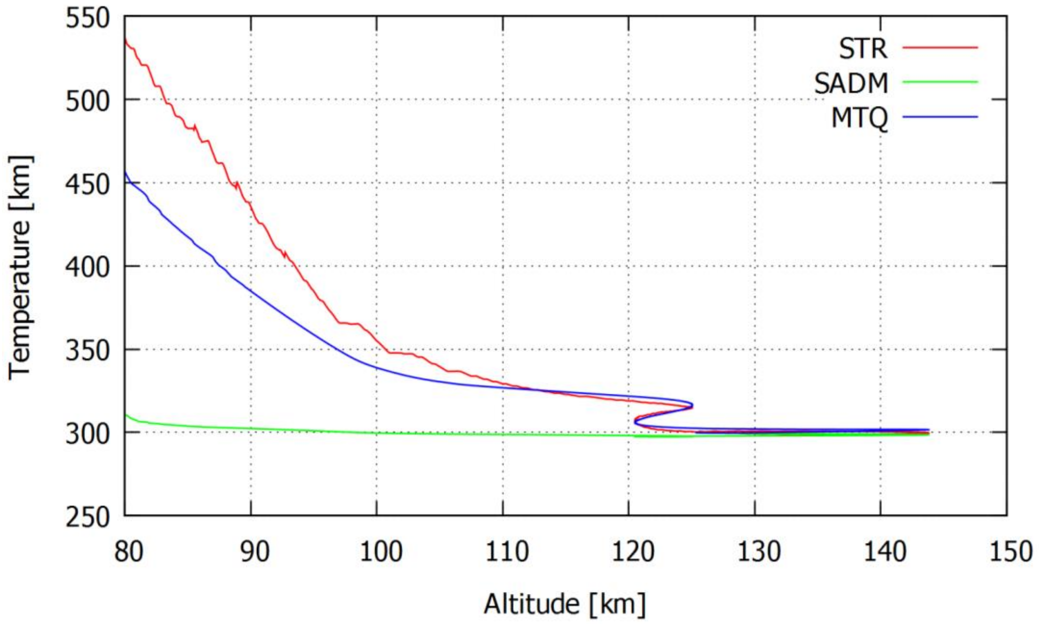


Figure 7-9: Mean temperature evolution [K] for three different types of components on a SCARAB re-entry simulation for Sentinel-2.

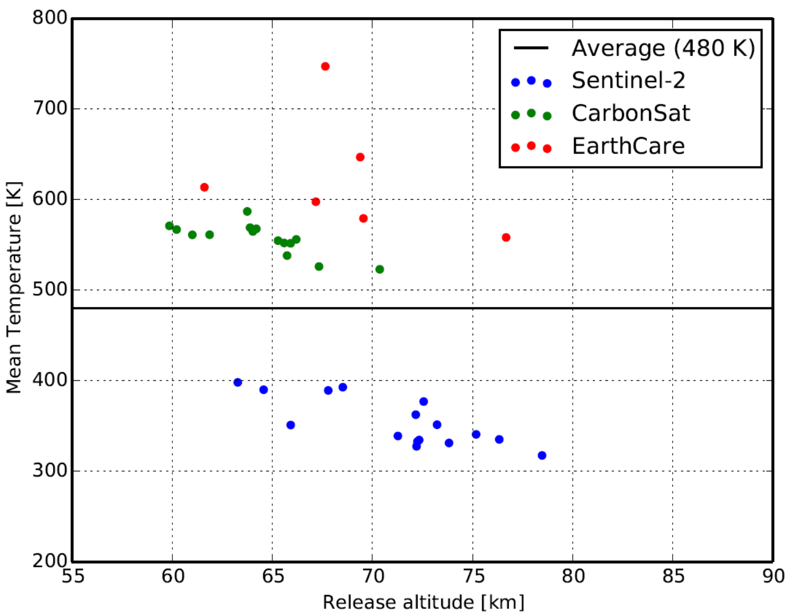


Figure 7-10: SADM release temperatures extracted from SCARAB simulations for three different ESA Earth Observation missions.

7.6 ANNEX F – Plasma Wind Tunnel Test Conditions for Material Characterisation

A wide range of conditions can be relevant to the destructive re-entry of spacecraft. The heat fluxes and dynamic pressures vary significantly dependent upon the ballistic coefficient of both spacecraft and equipment and the object size. In an ideal case, the test conditions would aim at reproducing the aerothermodynamic phenomena on the test objects in a manner which is fully representative of a specific flight condition. This is to be achieved using the Local Heat Transfer Simulation (LHTS) methodology, where the flow conditions match the enthalpy, stagnation pressure and the velocity gradient at the stagnation point. This is very difficult to achieve in practice for the majority of flow conditions. For the majority of material tests, the conditions will be selected with the flow parameters within the below specified relevant ranges, which are dependent upon the material critical temperatures and, potentially, the equipment type for which the material is being tested.

- Relevant peak heat fluxes range from 200kW/m^2 to 1.5MW/m^2 in a tumble average sense, with the peak stagnation point fluxes being approximately a factor of four higher. In general, heat fluxes from 100kW/m^2 for very low temperature materials, to 1.5MW/m^2 are recommended.
- Relevant peak stagnation pressures range from 2kPa-50kPa. Higher stagnation pressures generally relate to higher flux conditions in flight.
- The enthalpy range in flight is 12-30MJ/kg. It should be noted that this range is not generally reproducible at all the relevant heat fluxes in wind tunnels.
- The representativeness of the Mach number is highly facility dependent. Although it is desirable to have a supersonic flow with a shock wave over the test object, this is not mandatory, and subsonic facilities can be used for material testing. This is consistent with the approach used for heatshield material TPS tests.

The test conditions shall be well represented by a simulation tool for material model validation. A good enthalpy estimate is particularly critical.

The test duration is dependent upon the test condition and need to be selected in conjunction with test prediction simulations. Relevant tests have been performed with timescales up to 1000 seconds, which is significantly greater than the timescale of re-entry.

7.7 ANNEX G – Test Uncertainties Evaluation

A further set of uncertainties have been inferred from equipment level tests, and would thus need to translate into equipment level modelling uncertainties for inclusion in the verification. These cover three different areas:

- Instrumentation measurement uncertainties
  - Thermocouple uncertainty is mainly driven by imprecision in the knowledge of the exact placement as the instrument itself is inside 1K. The errors are dependent upon the thermal gradients within the material and are at most a few tens of degrees.
  - Pyrometer temperature measurements are larger as they are dependent upon the emissivity of the material. Generally, where the emissivity is high, the confidence in the measurements are higher. Uncertainties are of the order of a few tens of degrees.
  - Emissivity can be inferred from a 2-colour pyrometer. This narrow band estimate has an error of ±0.1. The error relative to the broadband emissivity, which is the true value of interest is difficult to assess.
  - Inference of temperature from an infra-red camera is more difficult and is of the order of ±50K.

- Input heating uncertainties
  - The heating uncertainty in the cold wall heat flux as measured by the facility on the calibration probe is of the order of ±10%
  - The heating uncertainty in the hot wall heat flux is dependent upon the enthalpy, but can be reasonably large. The uncertainties in the cold and hot wall heat fluxes can be reduced significantly by the use of steady state conditions and rebuilding of the energy balance.
  - The heating uncertainty to the test object is dependent upon the complexity of the object shape. This is of the order of ±10% for a known primitive shape (box, cylinder, sphere) but can be much larger for a complex shape.

- Uncertainties in the model rebuilding
  - The uncertainties in the detailed model rebuild are highly dependent upon the quality of the heat flux mapping. Where the heat flux mapping is good, as confirmed through steady state conditions, the rebuilds should be expected to be under 100K for the surface temperature and thermocouple measurements.
  - Uncertainties in the fragmentation events are likely to be larger, and should be expected to be improved by re-correlation post-test. Fragmentation event indicators (“triggers”) are considered to have relatively large errors, with temperature values at least ±20K, and perhaps as high as ±50K.

7.8 ANNEX H – Approximate Size Limits for 15J Elements

Limit based on terminal velocity

As all elements greater than 15J are to be modelled unless justified otherwise [RD2], the below figure provides an approximate guide for the masses of element which need to be considered. Figure 7-11 gives the 15J limit mass for a solid sphere of the material density, and is thus at the conservative limit. Where the object is not solid, or is a different shape, the allowable masses can be higher.

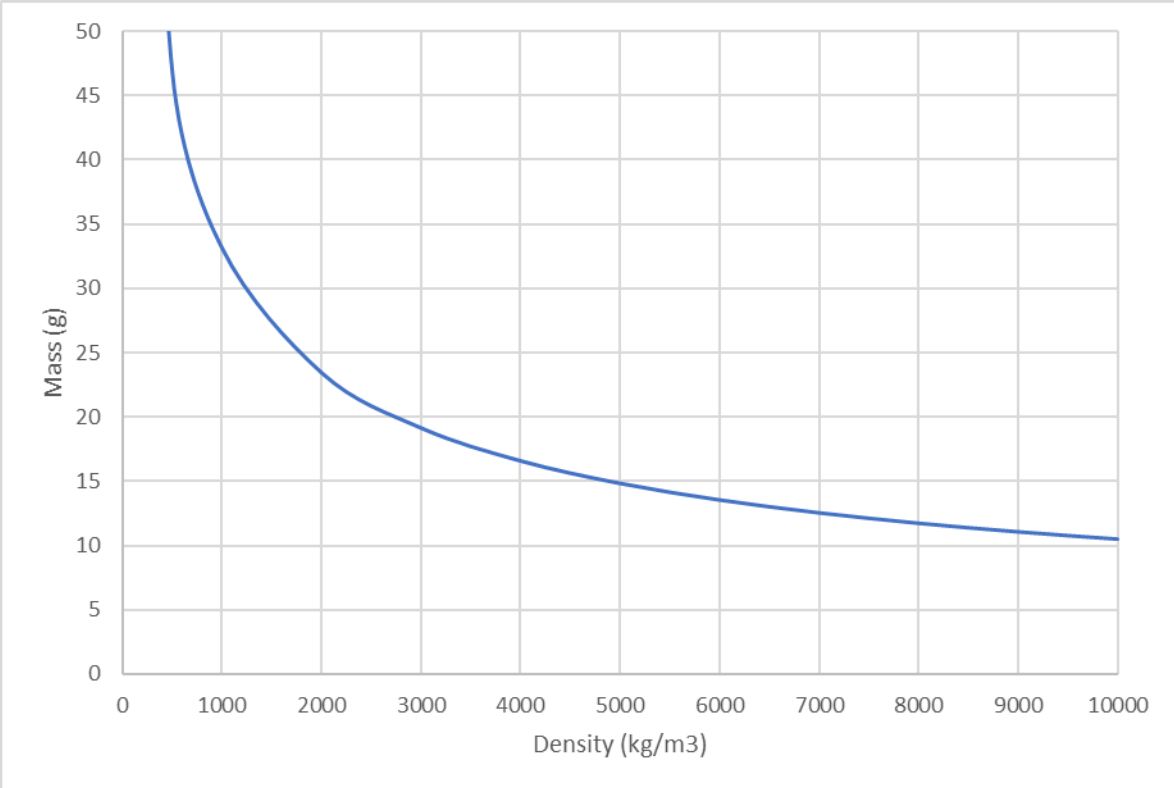


Figure 7-11: 15J limit translated into mass for a solid sphere of the given material density at terminal velocity.

Limits accounting for nest-level

In order to provide information on to which level of details a component has to be modelled, a parametric analysis has been performed using DRAMA 3.0.2. This analysis attempts to set the minimum mass below which an element does not need to be accounted for when modelling using DRAMA. A minimum mass to be modelled is of which the impact energy of its remaining fragment reaching the ground is slightly above the threshold of 15J.

The general approach of the parametric analysis is as follows:

- The subject of the study is a sphere, as an internal sub-equipment. The reason for choosing a sphere is it has the highest ballistic coefficient among primitives with equivalent mass, and thus is more likely to demise. The mass of the sphere is iteratively modified for each DRAMA run, as determined by the Bisection method in order to find the minimum mass which the impact energy of its remaining fragment reaching the ground is slightly above the threshold of 15J .

- The sphere is then contained within a two to three nest-levels – representing housing of, or within, an equipment and the spacecraft structure. A dummy mass is then added to the model, in between the nest-levels, in order to compensate the mass changes of the internal level and thus to have a constant ballistic coefficient. The dummy mass is set to demise together with the nest-level it is nested in. This is illustrated in the following figure.

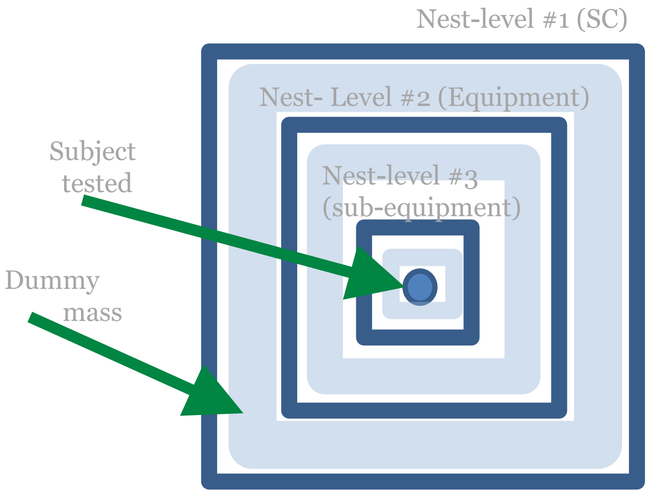


Figure 7-12: Cross-section of the model

- The nest- level representing the spacecraft structure has been modelled as a box with a 150kg/m² mass to area ratio which has been identified as common for Earth observation satellites. In addition, its material has been set to be Titanium, in order to have control over its breakup altitude (as such it will not demise before the set child release is triggered).
- The second nest-level, representing the equipment housing is set to be AA7075, with average cross section ratio between 100 to 200 kg/m².
- The third nest-level representing the sub-equipment housing is set to be either AA7075 or A316.
- Break-up altitudes of the first nest- level, representing the spacecraft structure, are between 60 and 96 km (with the exception of the cases with A316 third nest level, as it did nor demise for break-up altitudes lower than 74 km).

Results:

Below are figures which give the indication of which is the minimum mass to be modelled of sub-equipment with materials of A316, Copper, AA7075, TiAl6v4 and Carbon-Carbon.
For each material, a set of four figures is presented, for four different mass to area ratio of the second nest-level.

Note:

- The case of A316 third nest-level and a send nest-level with mass to area ratio of 100 kg/m² is not presented since the third nest-level does not demise in this case (top-left figure for each set).

- Cases where the resultant minimum mass is greater than the mass that fits the net-level are also not presented, and thus several curves do not cover all the break-up altitude regime.

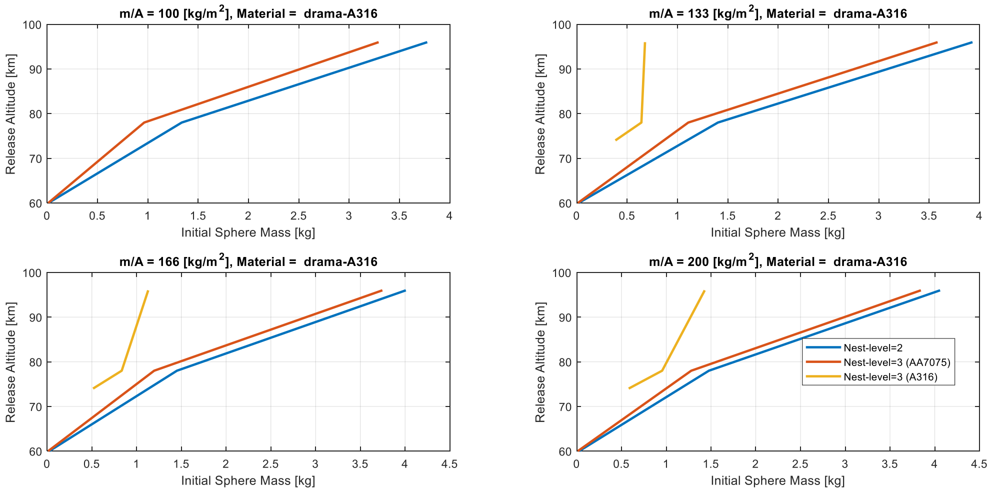


Figure 7-13 - Minimum mass to be modelled for A316 sub-equipment object

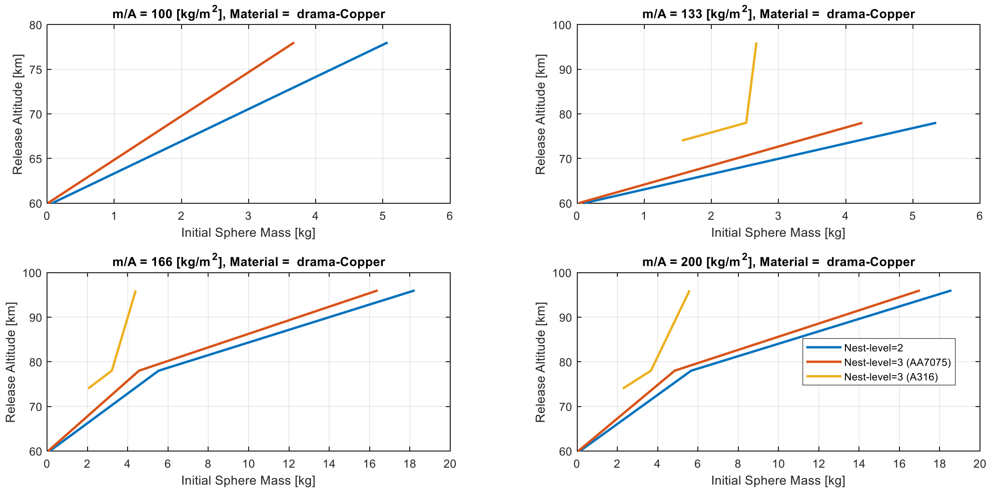


Figure 7-14 - Minimum mass to be modelled for Copper sub-equipment object

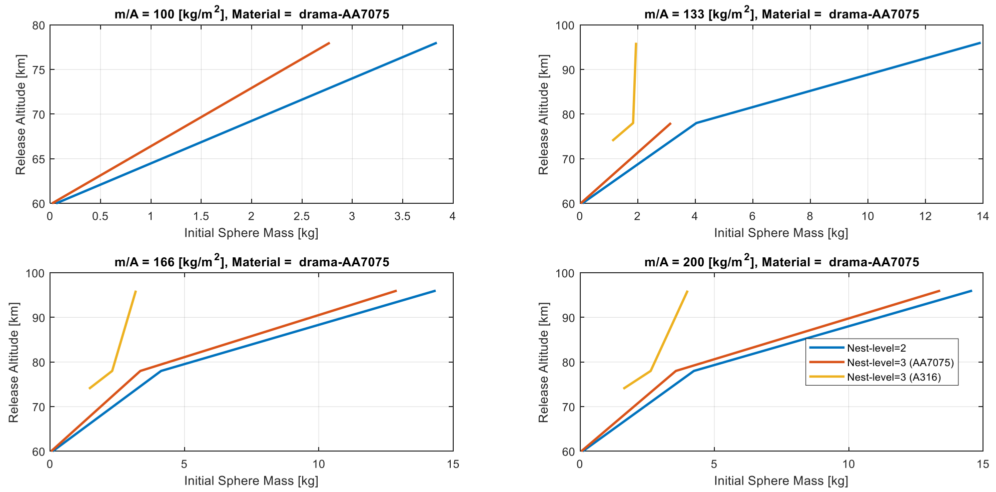


Figure 7-15 - Minimum mass to be modelled for AA7075 sub-equipment object

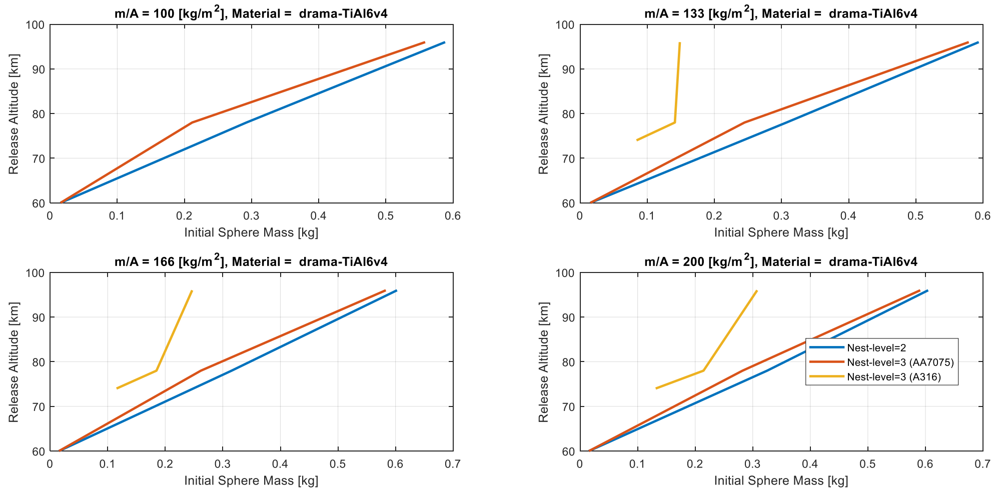


Figure 7-16 - Minimum mass to be modelled for TiAl6v4 sub-equipment object

As for Carbon-carbon, the minimum mass that should be accounted for is 0.0252 kg for all cases.

7.9 ANNEX I – Equipment Release Altitude Assessment

The baseline fragmentation behaviour of a system during re-entry can be modelled as the full demise of large components such as a service module under the assumption of fully ablating it by melt. The altitude where this occurs along the defined re-entry corridors is strongly dependent on the actual spacecraft or launch vehicles orbital stage model, as show in ANNEX C – Reference Re-entry Corridor. This is important to consider when including equipment as part of specific satellite design and hence the casualty risk budget, as for some equipment the demise surface will cross the region where the fragmentation of a system is modelled.

More detailed models can indicated different fragmentation behaviour as it will generally be based on different aerothermodynamical models and fragmentation phenomenology. This stresses the need for the conversion of the modelled behaviour into the baseline DRAMA tool before results can be made compatible. The following system level study depicted in Figure 7-17 shows a statistical assessment of fragmentation data obtained by SCARAB for five different ESA Earth Observation missions. SCARAB is a panel-based model, and fragmentation occurs when a panel no longer connect multiple parts. As such, the density of altitude of fragmentation tentatively correlates with the amount of components exposed to the maximum heating in the flow when looked at on system level. The histogram plot covers more than 10,000 fragmentation events in total. The fragmentation density is normalized such that the total area under the boxes equals unity (box width 1 km).

This plot reveals three different phases of breakup:

1. Early breakup:
   This breakup phase starts below 110 km and remains on a low (almost constant) intensity level down to 90 km. This phase is characterized by external equipment separation, e.g. solar arrays, antenna, star tracker.
2. Main breakup:
   This breakup phase starts below 90 km with increasing intensity, reaching its peak at 83 km, remaining at constant level down to 76 km. This phase is mostly characterized by the breakup of the primary/secondary structure of the satellite. Note: This in agreement to the breakup altitude of 78 km used in a number of risk verification methodologies.
3. Low breakup:
   Below 76 km, another increase in fragmentation density can be seen, reaching its peak at 70 km. This phase is most likely characterized best as “sub-fragmentations”. Fragments created in the previous main breakup phase are breaking up further into sub-fragments. Due to the overall increasing number of fragments, this can be seen as a cascading effect. However, it should be noted that most of the equipment units are finally released in this phase, remaining attached to some bigger structure fragments, which are still posing at least some shielding effects to the units.

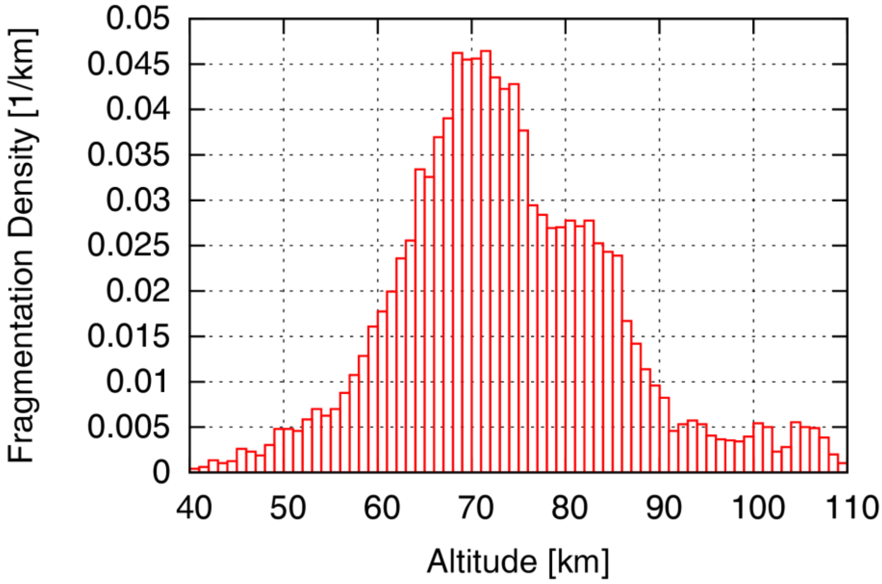


Figure 7-17: Fragmentation density

The general fragmentation of the spacecraft can be linked to the release of individual equipment pieces. The following table shows mean component release altitudes extracted from SCARAB simulations for a single modelled spacecraft (including one sigma of uncertainty). Note: release altitude in a SCARAB system level simulation is defined as the component has become the "dominating" part of the fragment, i.e. more than 50% of the fragment mass is attributed by the component. With regard to the previous paragraph, this demonstrates that equipment release is occurring in the low breakup phase of the system. However, the components are already pre-heated before their final release. Their (partial) exposure to the flow starts already in the main breakup phase.

Component	Mean Release Altitude [km]
SADM	71.2 ± 4.2
RW	70.0 ± 2.6
MTQ	73.9 ± 2.5
Batteries	64.3 ± 2.9
Tank	65.9 ± 2.8

Table 7-4: mean released altitude on SCARAB for the main critical elements

The next figure further illustrates the release altitude distribution of SADMs for three different missions.

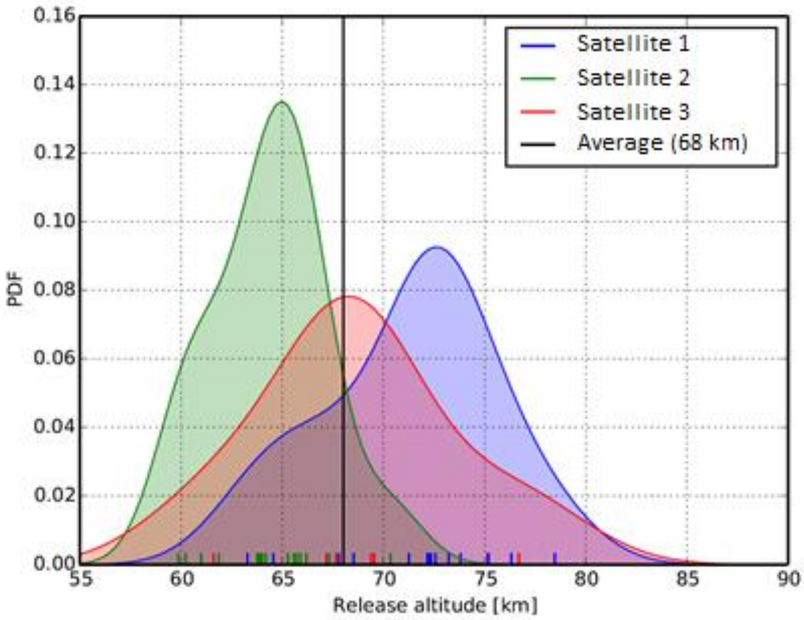


Figure 7-18: release altitude distribution of SADMs for three different missions.

It is worth noting that the distinction between internal and external equipment is not as clear at system level. External equipment is expected to receive heat flux early, but with some spacecraft tumbling expected, it will not receive a continuous heat flux, although it will be modelled as continuous in DRAMA. Internal equipment is considered to be heated from the point of release, but it is likely to experience some heating once the external spacecraft structure has been released/demised, prior to its final release. Therefore DRAMA system-level simulations are likely to heat this component, unless it is nested, prior to release.

7.10 ANNEX L – Creation of a DRAMA Model from a more Detailed Model

Ball bearing unit with SAM

A mock-up ball bearing unit provided by ESA was tested in the DLR L2K wind tunnel. The results showed that the heating to the end surface was significantly enhanced by the ring shape of the equipment. This heating was sufficient to result in fast melting in the test which is not achieved using heat fluxes to a cylinder end. After the first melting of the surface, the heating was seen to reduce as the geometry changed to a different ring shape.

Analysis using SAM demonstrated that the heating could be understood in terms of the different rings. Once this was established, the behaviour of the sample could be understood in terms of a simple one-dimensional heat conduction through a stainless steel material of the correct mass. This allows a simple model application into DRAMA.

The DRAMA model is applied as a steel cylinder of the correct mass. The drag coefficient differs from the tube by under 3% so this is not considered. The heating coefficient is increased by 15% in a tumble-average sense before the shape change, and by 3% thereafter. Therefore, the proposed model is to provide an updated heating database to account for the geometry effects on a standard cylinder DRAMA model. As different heating correlations are required to capture the shape change, the model is constructed as a nested model with a thin outer layer and high conductivity between the connected-to element. This way the bulk heating model with the first heating database is used until melt temperature is achieved. Once melt is achieved, the failure of the thin layer is triggered and the inner part, which has the second heating database associated, is released. This results in the capture of both the heat flux levels due to the shape change in a simplified manner.

Magnetorquer with SAM

The magnetorquer has a layer-by-layer layup with a magnetic core, copper coils, a potting layer and a CFRP housing. The demise of the different component parts have been verified by test, and successfully rebuilt using SAM. For the CFRP failure, the SAM demise criterion for the removal of the material has been correlated to the CFRP back face temperature at the time of failure. Further, SAM has been used to determine that the demise timing of the different parts (feet, coils and core) is well represented by the bulk modelling approach used in DRAMA. An improvement to the material database for the cobalt-iron core, inclusive of a reduction in the emissivity of the material when melting, is also an output of the test data.

Therefore, a model in SAM, which is directly reproducible as a DRAMA-level connected-to model, has been constructed which captures the test data, inclusive of a material model update. The change required is that the DRAMA model does not contain a ring primitive. However, the geometry of the magnetorquer is such that cylinder primitives can be used as the exposed area for a bulk heating model will be captured correctly in this model due to the connections between the components not failing until full demise of the outer layers.

Reaction Wheel with SCARAB

An exercise has been performed on how to reproduce results from SCARAB in DRAMA in case that casualty area curve results exist from a detailed component model. Subject of this exercise was the RWL results shown in the following pictures.

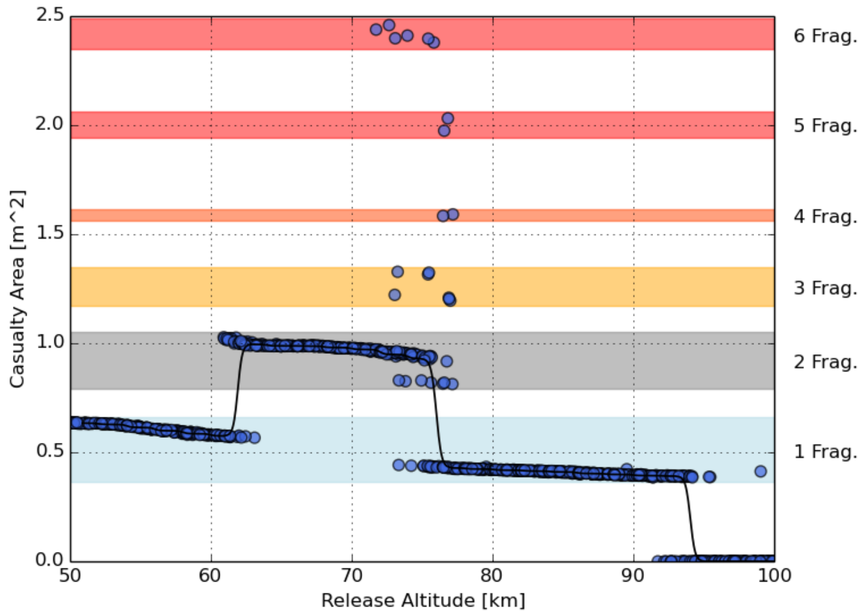


Figure 7-19: Casualty area derived with SACRAB for a reaction wheel model as a function of release altitude, with randomised initial attitude

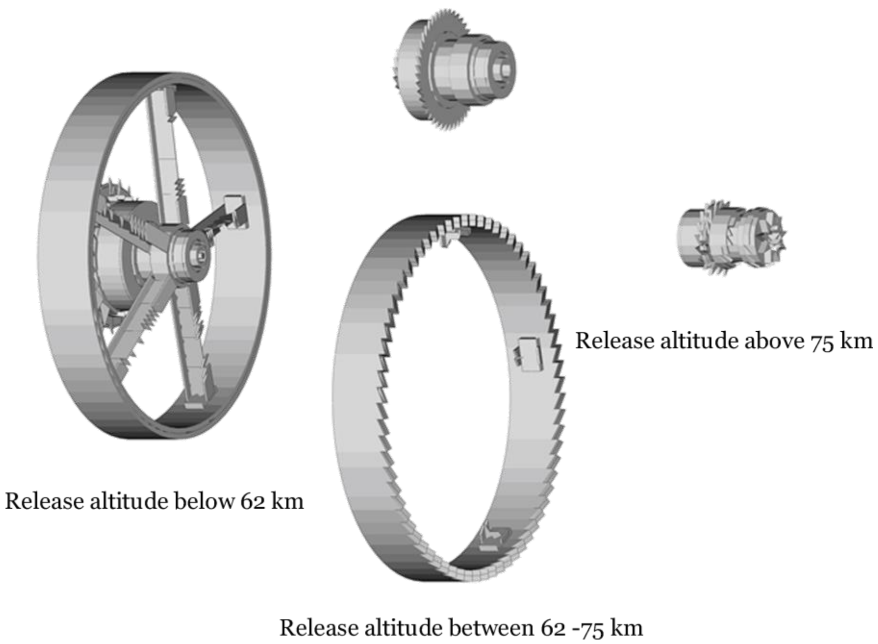


Figure 7-20: Fragments create as part of the analysis shown in Figure 7-19

Steps in line with section 4.2:

1. Identify the maximum number of surviving fragments, i.e. highest level of the casualty area curve. This is the minimum number of objects to be modelled in DRAMA. In this case: 2 (flywheel and ball bearing unit) plus housing.
2. Identify the mass, shape, dimensions, material of these fragments in their virgin state:
    - Flywheel, 6 kg, cylinder, R = 0.165 m, H = 0.05 m, Steel
    - Ball bearing unit, 1.5 kg, cylinder, R = 0.025 m, H = 0.1 m, Steel
    - Housing, 1.5 kg, cylinder, R = 0.172 m, H = 0.11 m, Aluminium
3. Select your included-in or connected-to approach. In this case:
    - Flywheel and BBU included in Housing
4. Check total mass: 9 kg (mass conservation achieved? Yes!)
5. Ensure that all settings in DRAMA are equivalent to the settings used by SCARAB for generating the curve. Examples: Atmosphere model (MSIS), wind model (off), solar/geomagnetic activity (100/6) [Expert mode needed]
6. Use the same reference trajectory settings for the parent body, i.e. semi-major axis 6490 km, eccentricity 0, inclination 98 deg, RAAN 7.3 deg, AOP 0 deg, TAN 12 deg; epoch 2004/01/01 – 00:01:00.000
7. Set parent body mass, shape, dimensions according to the area-to-mass ratio of your reference trajectory, i.e. 141 kg (150 – 9 kg), sphere, R = 0.565 m (A_{prj} = 1 m²) → 150 kg/m²
8. Set up a Monte-Carlo analysis for the parent body breakup altitude (range: 50 -100 km)
9. Iteratively adapt the scaling factors for the average heat fluxes of the objects until the location of the transition altitudes (i.e. where the SCARAB results are switching from zero to one fragment, or from one to two fragments, and vice versa) are met in DRAMA. In this case:
    - Flywheel: 1.9
    - Ball bearing unit: 0.69
    - Housing: 0.22
10. Analyse the physical "truth" in this adaptations:
    - Flywheel: increase from 1 to 1.9 appears reasonable as a ring is likely to see more heating than a closed disk
    - Ball bearing unit: a reduction from 1 to 0.69 appears reasonable as the BBU is partially shielded by the flywheel and other not modelled parts
    - Housing: non-physical adaptation! Reason: the housing is used as non-physical proxy to keep flywheel and BBU together below a certain altitude
11. Verify that your adapted results are also transferable to other reference trajectories

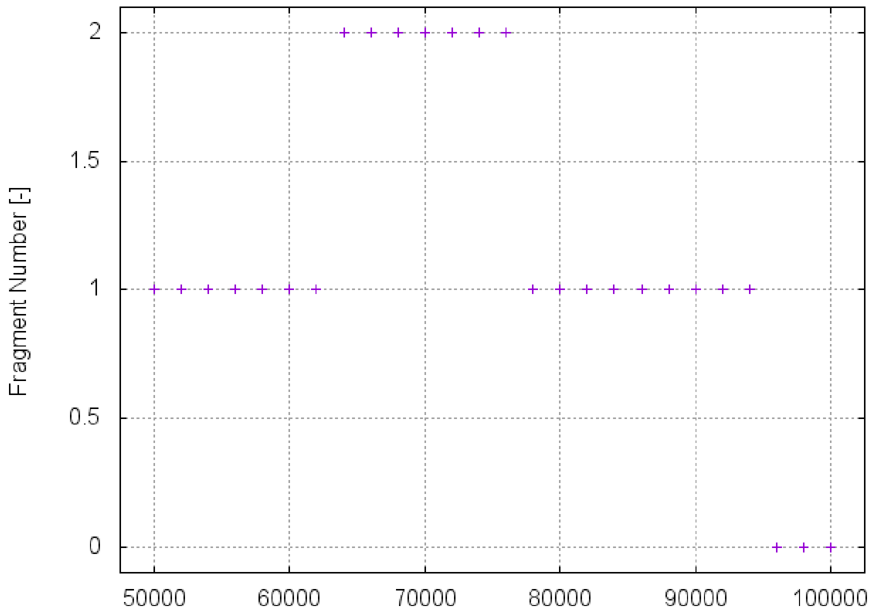


Figure 7-21: Fragment count for the fitted DRAMA model as function of release altitude [m].

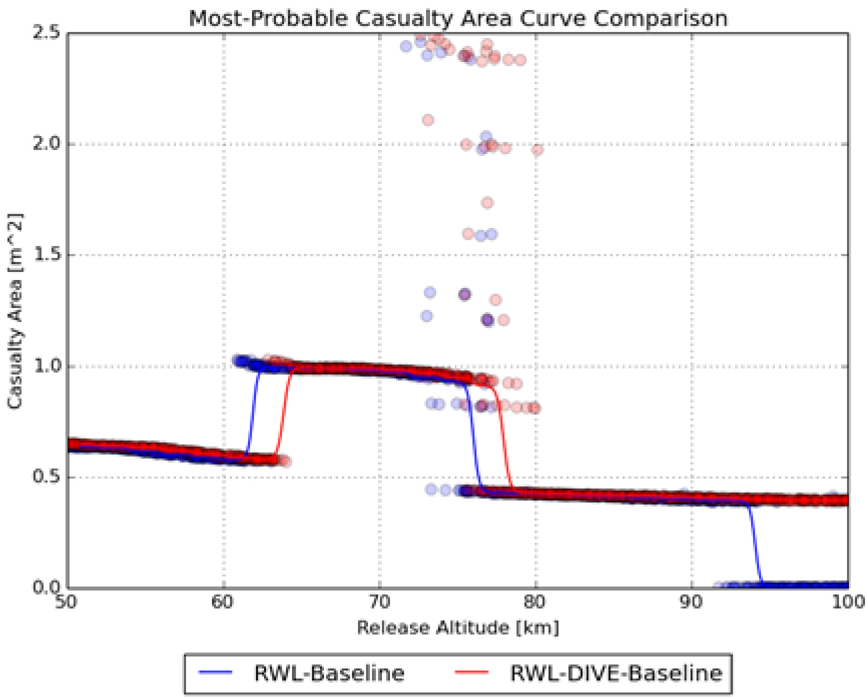


Figure 7-22: casualty area for a RWL as function of the release altitude, depending on size and numbers of fragments.

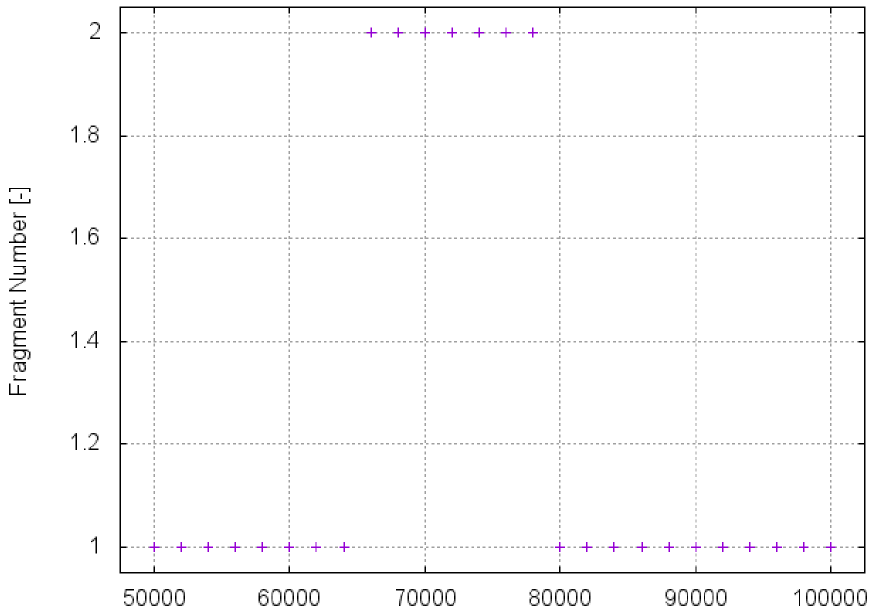


Figure 7-23: Fragment count for the fitted DRAMA model as function of release altitude [m].

The exercise showed that it is in general possible to duplicate the SCARAB result pattern in DRAMA, especially the transition altitudes where the SCARAB results are switching from zero to one fragment, or from one to two fragments (and vice versa).

The main guideline outcome from this exercise is that DRAMA objects of a component model should be of the same size and material as their counterparts in the real component. Artificial deviations are not needed. Parts of the component which have already been demonstrated as demisable in SCARAB can be omitted. Overwriting of the default heating factors (DRAMA expert mode) is needed in this case.

Once a DRAMA model is constructed, it can be subject to the larger set of uncertainties as documented in Section 4.2.4. In this case the results remains fairly stable when comparing the DRAMA result in Figure 7-24 to the original in Figure 7-19. Difference in absolute casualty area are caused by difference in fragment size assessments between the tools.

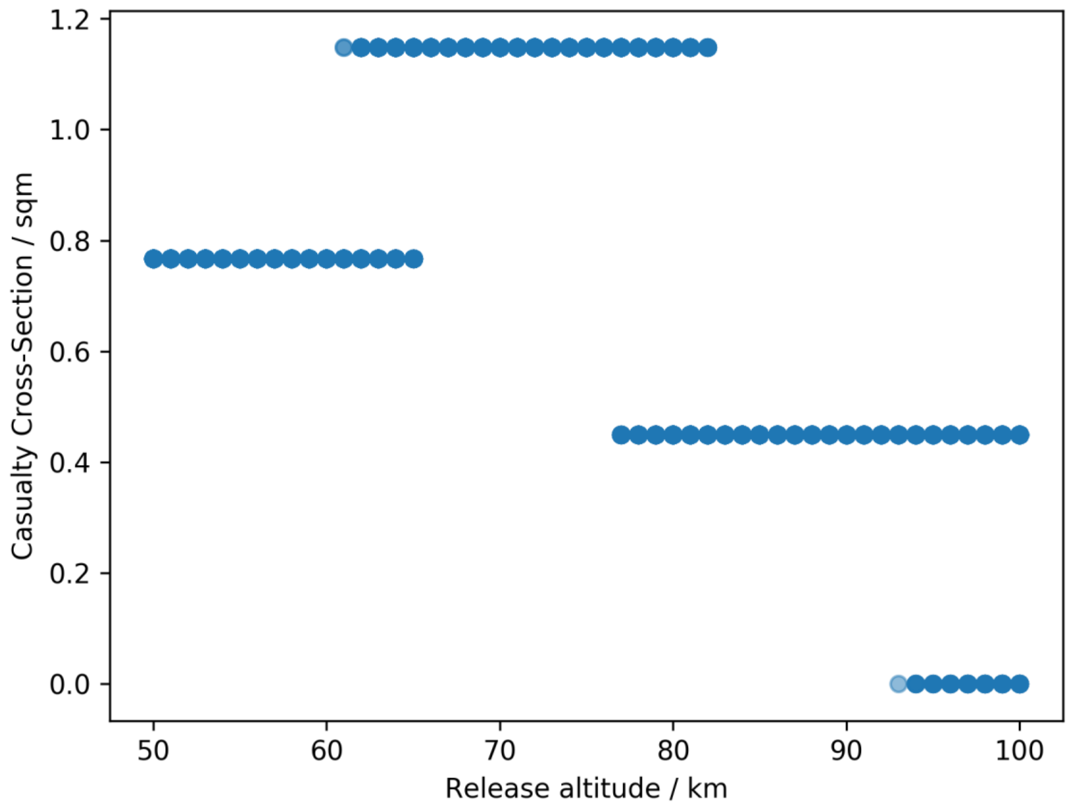


Figure 7-24: Reconstructed DRAMA reaction wheel model based on the SCARAB analysis, subject to the uncertainties listed in this document.

Solar Array Drive Mechanism with SCARAB

It should be noted that the reaction wheel exercise which SCARAB was a single example. The findings can be very different for other components. In fact, a similar exercise attempt for a solar array driving mechanism broke down at step #1/2 of the reaction wheel example.

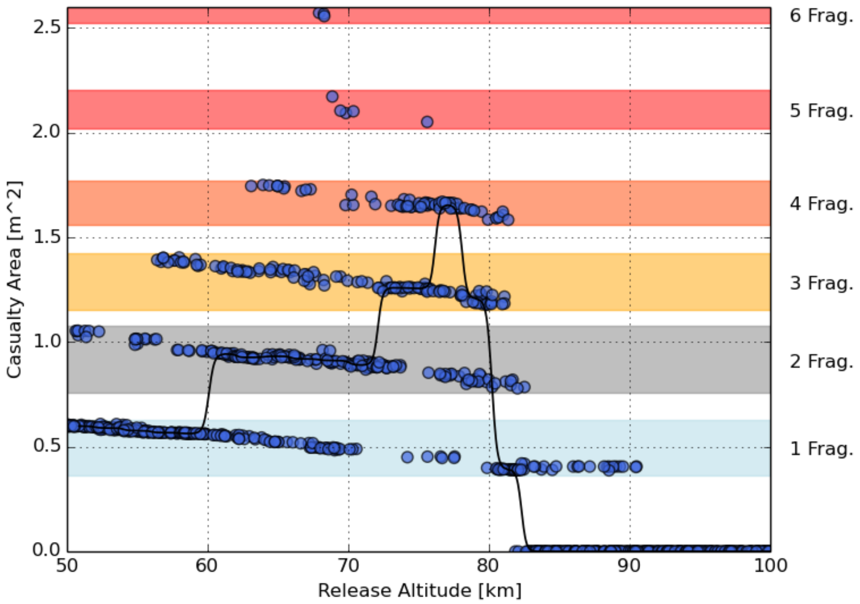


Figure 7-25: casualty area for a SADM as function of the release altitude, depending on size and numbers of fragments.

The maximum number of (statistically significant) fragments was larger (4 instead of 2). The number of transition altitudes was larger (6 instead of 3). The origin/type of fragments varies over the release altitude range within the fragment number bands, e.g. the two fragments in the grey band are not always the same or at least similar fragments even if the release altitude varies only a few kilometres.

To generate an artificial (i.e. with no or limited relationship to real SADM parts) DRAMA model might still be possible, but the achievable level of equivalence and scalability to other re-entry conditions might be limited. As a consequence, the need for procedural steps, subject to review, to capture a single baseline behaviour are laid out in Section 4.3.

Reaction Wheel with SAM

To this end a total of 9000 SAM simulations have been performed across nine scenarios. comprising three orbit inclinations (58°, 78° and 98°), for three parent spacecraft mass/area ratios (75kg/m^2, 150kg/m^2 and 300kg/m^2). Generation of the parent object trajectories and therefore simulation initial state vectors was performed using SAM. The results of this were verified as being in close agreement with the same state vectors constructed in DRAMA using the analytic tumbling method.

The model studied in this analysis is an approximation of a Rockwell Collins spoked reaction wheel. The parts considered are modelled as primitives (cylinders, tubes and boxes) and the fragmentation is determined by a degree of melt approach. 90% melt is required for aluminium failure and 70% for steel failure. These values are tentatively estimated from recent test data. The parts considered are given in Table 7-5, with the local SAM heating on the flywheel, ball bearing unit, motor/stator and spokes shown in Figure 7-26. The total reaction wheel mass is 7.5kg.

Component	Mass (kg)	Shape	Diameter (mm)	Height (mm)	Material
Ball bearing unit	1.1	Cylinder	42	87	Steel
Motor/stator	0.35	Tube	Inner 42; Outer 88	33	Iron
Flywheel ring	4.75	Tube	Inner 230; Outer 266	48	Steel
5 Spokes	0.05	Box	20x20 Square Section	94	Steel
Top cover	0.4	Cylinder	310	60	Aluminium
Bottom cover	0.4	Cylinder	310	51	Aluminium
Base	0.2	Disc	80	12	Aluminium
Printed circuit board	0.05	Disc	97	2	GFRP

Table 7-5: Reaction Wheel Components

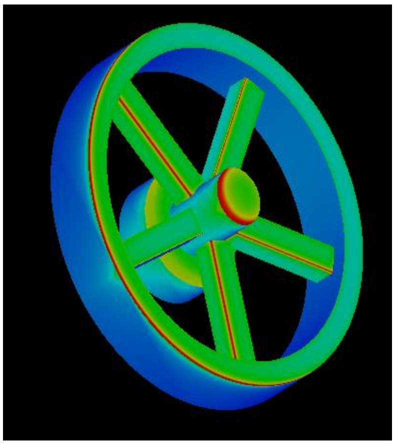


Figure 7-26: Reaction Wheel Internal Parts Geometry and Heating

The reaction wheel is released at a range of altitudes, ranging from 100km to 60km. For each release altitude case, the initial conditions (state vector) were fixed, generating 90 separate cases (10 release altitudes * 3 orbit inclinations * 3 parent spacecraft). The initial temperature of all components within the reaction wheel was 300K in all cases. All the runs are performed in six degrees of freedom for multi-component fragments, switching to three degrees of freedom once a fragment has only one remaining component. A bulk heating model is used for each part.

For each case a small Monte Carlo of 100 runs was performed (giving the 9000 total simulations) with variations according to the recommended uncertainties, as detailed in Table 7-6.

Parameter	Distribution	Range
Aerothermodynamic Heating	Uniform	±30%
Aerodynamic Drag	Uniform	±10%
Material Emissivity	Triangular	±25% (limited to 1)
Material Demise Temperature	Uniform	±30K (maximum liquidus)
Flight Path Angle	Uniform	-0.05° to -0.5°
Initial Attitude	Uniform	Attack -180° to 180° Sideslip -90° to 90°
Atmospheric Density	Normal	10% 1-sigma

Table 7-6: Simulation Uncertainties

DRAMA material properties are used as a baseline, with increased emissivities as determined from testing. The nominal melt temperature has also been adjusted in order to prevent the uncertainty from providing melt temperatures above the liquids value, again an approach justified by test data.

At 98^o orbital inclination, the median landed mass can be seen to be small (but non-zero) at altitudes above 85km, as shown in Figure 7-27. The parent spacecraft ballistic coefficient has little effect above 85km, but the increased atmospheric penetration of the higher ballistic coefficient spacecraft results in significantly more mass loss in the 65-85km release altitude range.

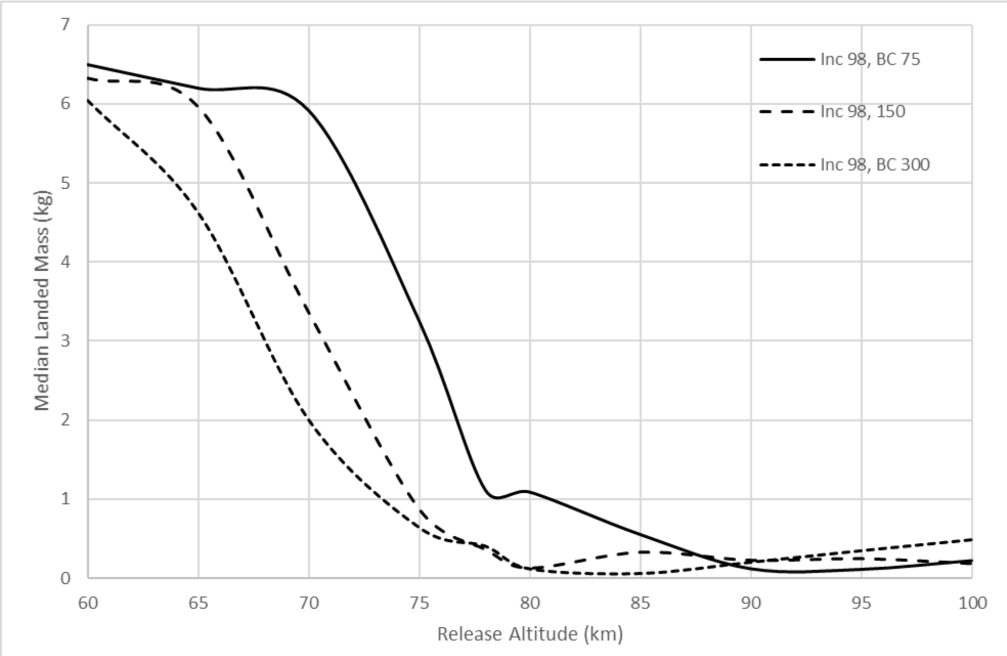


Figure 7-27: Median Landed Mass as a Function of Release Altitude for a Range of Parent Ballistic Coefficients

Varying the inclination of the orbit at a constant ballistic coefficient of spacecraft shows a reduced impact in the demise region, but a larger effect for objects released earlier, as shown in Figure 7-28. The increased relative velocity at high altitude has a significantly greater impact for objects released early, than differences in the ballistic coefficient of the parent object.

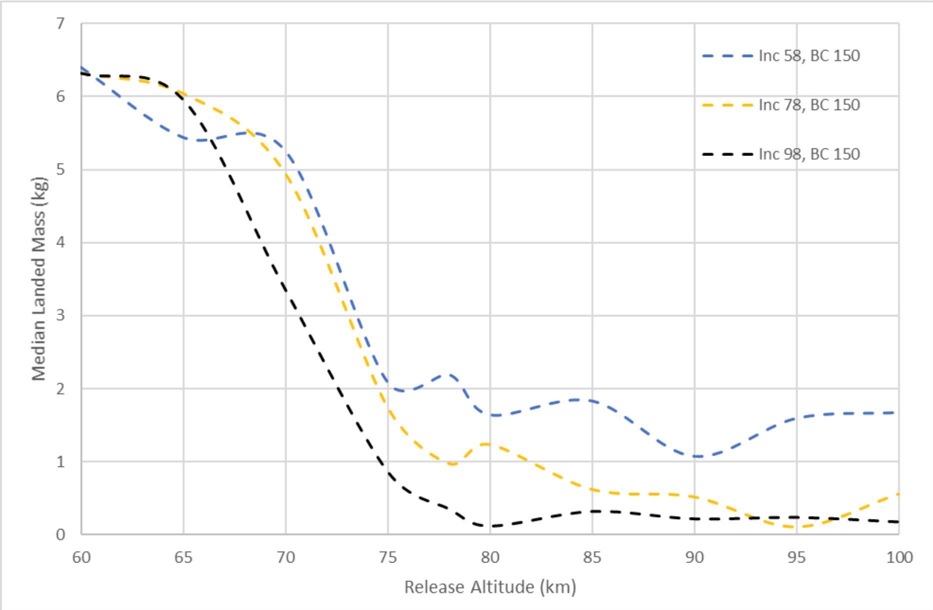


Figure 7-28: Median Landed Mass as a Function of Release Altitude for a Range of Orbit Inclinations

These trends, i.e. increasing demise at high release altitude with orbit inclination, and I increasing demise at 65-85km altitude release with spacecraft ballistic coefficient are consistent across the cases. It is also evident that the cases are not fully converged, as shown by the variation in the results as the release altitude increases above 80km.

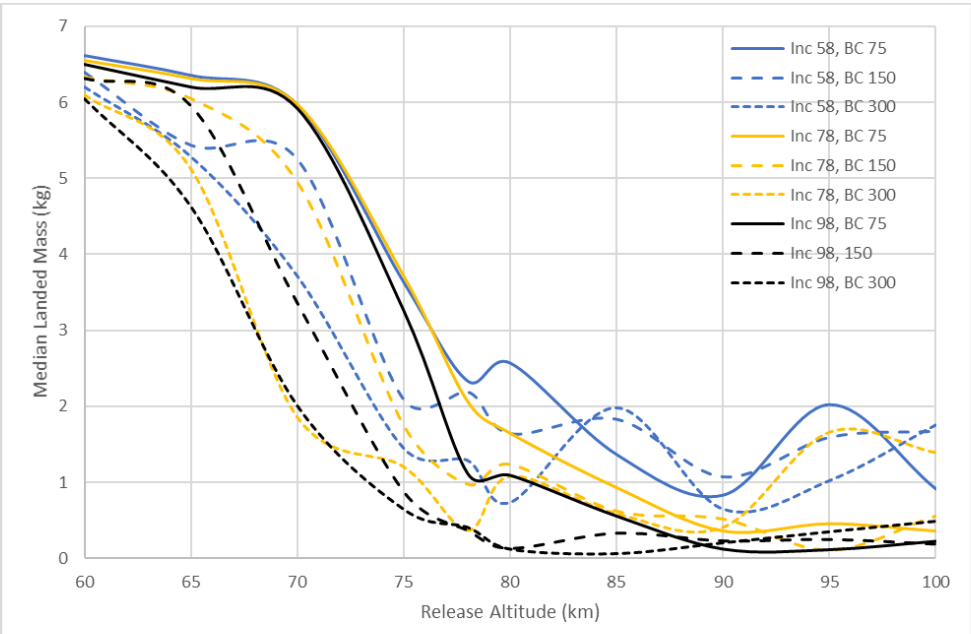


Figure 7-29: Median Landed Mass as a Function of Release Altitude for a Range of Orbit Inclinations and Parent Ballistic Coefficients

A similar assessment can be made for the number of fragments landed, as shown in Figure 7-30. It is worth noting that the mean is presented here – in general, the median number of landed fragments is lower than the mean, but the mean was considered more informative in this instance. The trends seen in the demise with variations in the orbit inclination and parent spacecraft ballistic coefficient can be seen to agree with those seen in the mass plot.

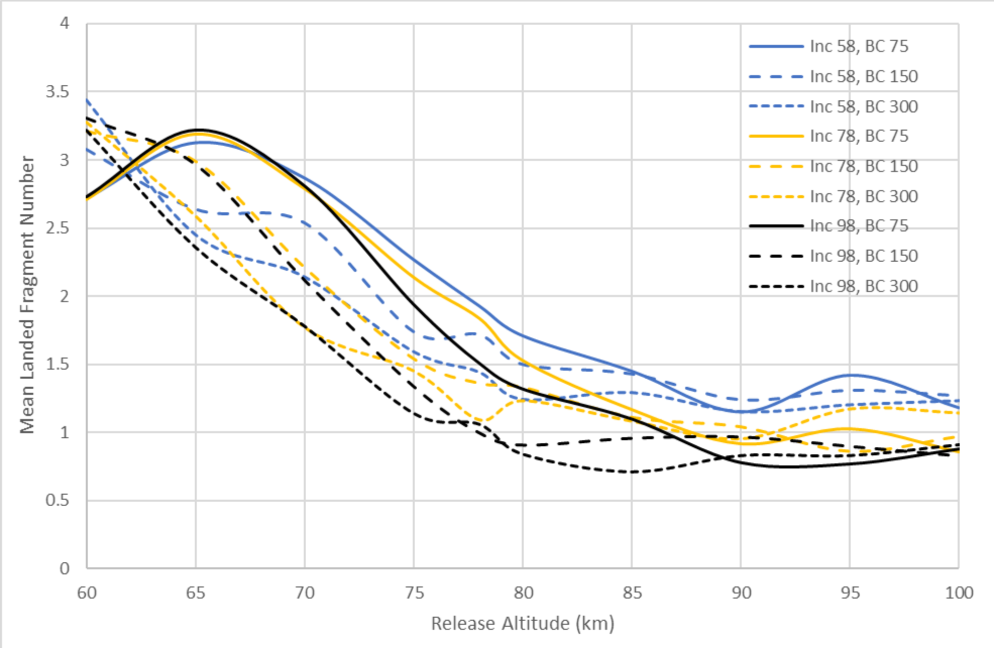


Figure 7-30: Mean Number of Landed Fragments as a Function of Release Altitude for a Range of Orbit Inclinations and Parent Ballistic Coefficients

From this it is clear that with the large uncertainties applied, there is not a clear “no risk” altitude. Indeed, the expected number of objects landed is around 1 for altitudes above 85km, and increases for lower altitudes. It is noticeable that the cases with smaller ballistic coefficient spacecraft start to land a higher fraction of more intact objects below 65km, resulting in a reduction of the fragment number. This effect is expected to be observed at lower altitudes for the higher ballistic coefficient spacecraft.

It is interesting to note that the number of landed objects exceeds the two standard objects (flywheel and ball bearing unit) as the release altitude drops below about 75km. The other object most frequently landed separate from these two components is the electronics card. Again, this component is modelled using the recommendations from test data. Some aluminium parts are also observed to reach the ground at the lowest release altitudes.

Using the nominal case (98^{o} inclination and 150kg/m^2 ballistic coefficient), the expected number of landed objects containing the ball bearing unit, the flywheel or both can be extracted, as illustrated in Figure 7-31. This suggests that almost all the objects reaching the ground when released above 80km are based on these two parts. Interestingly, the high altitude demise probability of the ball bearing unit is about 75%, whereas it is only about 35% for the flywheel, which makes the flywheel the most critical part in the SAM analysis. At the nominal case, the fragmentation of the ball bearing unit and flywheel is seen in the vast majority of runs, with both objects expected to land once released below 65-70km. Other objects begin to reach ground fall as the release altitude drops below 75km.

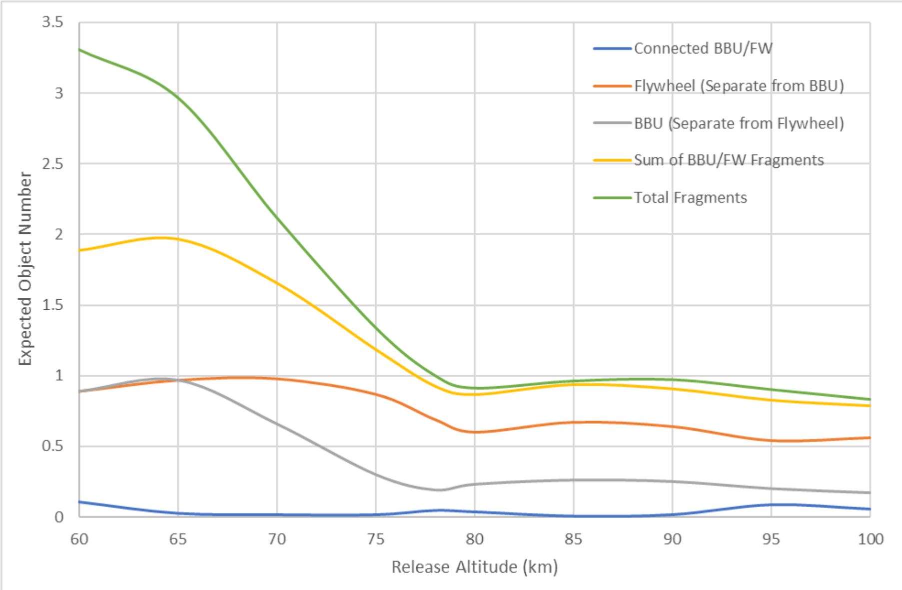


Figure 7-31: Expected Number of Objects as a Function of Release Altitude for a Range of Sub-Component Combinations

It is worth noting that a number of runs are observed in which complete demise of the reaction wheel is predicted, down to relatively low release altitudes. In the nominal case, the probability of complete demise is shown in Figure 7-32.

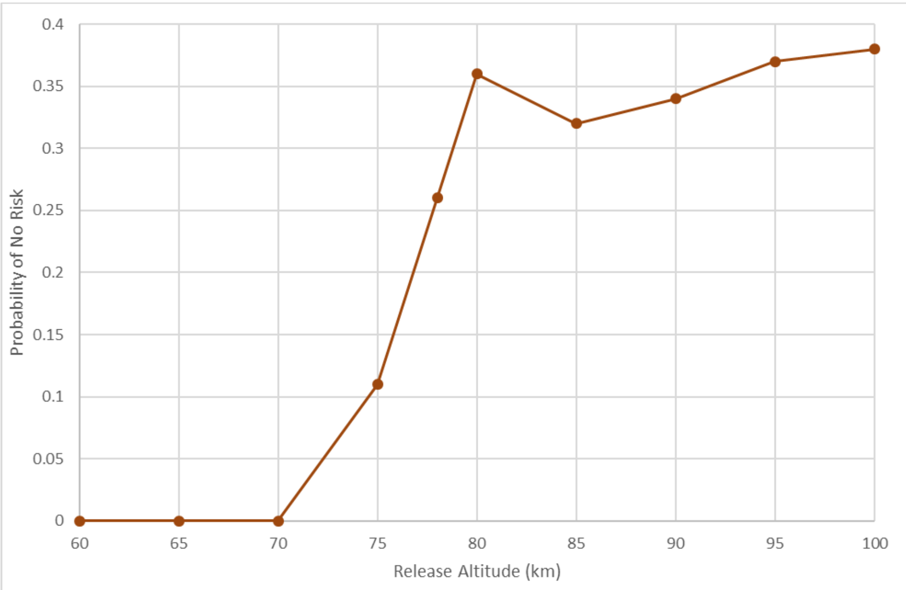


Figure 7-32: Probability of Complete Reaction Wheel Demise as a Function of Release Altitude

This suggests that for release altitudes above 80km, there is approximately a one-third chance that there will be no on-ground risk, but this falls to zero below 70km. This "no risk" probability at high altitude varies from about 20% (lower inclination) to 35% (higher inclination) with a smaller influence of the parent spacecraft ballistic coefficient. It is interesting to note that there are cases in which the casualty risk is zero for a release altitude of 75km.

Overall, the SAM analysis suggests the following:

- Use of DRAMA for the construction of all reference trajectories.
- There is no clear “no risk” altitude for the reaction wheel with the uncertainty model used.
- Objects released above 85km demise more at higher orbit inclinations.
- Objects released between 65km and 85km demise more when released from higher ballistic coefficient parent spacecraft.
- The flywheel is the most critical object, with a probability of demise under 0.5 in all cases and all release altitudes. [Aside: this is a much higher demise probability than obtained without the emissivity variation in previous SAM work].
- The ball bearing unit is less critical than the flywheel with a demise probability of 0.75 at higher altitudes.
- Lower release altitudes can result in a larger compound part reaching the ground as a single fragment. However, sufficiently low releases start to show aluminium and electronics parts also reaching the ground.

It should be noted that relative to SCARAB:

- The masses and sizes of the parts have been estimated. It is expected that the differences in the modelling will be significantly greater than differences resulting from errors in the equipment construction.
- The multi-component heating is performed at a local scale which is expected to result in earlier fragmentation and a greater degree of fragmentation.
- The separated object heating (to approximate primitives) is generally lower using the SAM correlations, so the separated items are less demisable.
- The emissivities are higher in SAM, which is important for the reduction in demise of the flywheel.

7.11 ANNEX M – Equipment Test Procedure Examples

Example 1: Reaction Wheel

The content below refers to the case of an example test for the RW. The results of the simulations have been reported in ANNEX L.

The following D4D measures have been applied to the RW:

- Aluminium flywheel replaces the stainless steel spoked wheel to ensure flywheel demisability
- An aluminium interface is introduced between BBU and motor rotor ring (magnet ring) to create a fragmentation of both parts and thereby increasing the BBU exposure
- An aluminium threaded ring is introduced in the BBU in order to foster the fragmentation of the BBU, i.e. release of the central shaft

Baseline wheel – Sequence of events	D4D wheel – Sequence of events	Demise phenomenology – Events to be verified by test
Housing melting	Housing melting	• Separation between upper/lower half of the housing • Melt through of thin wall sections • Brazing failure between the two parts • Detachment of the more massive upper/lower housing sections • Effect of the central Titanium post on housing detachment
Electronic melting	Electronics melting	• Confirmation of artificial material properties or material demise model, respectively
Spokes melting		• Confirmation of spoke melt-through before central hub brazing connection failure
Flywheel melting	Flywheel melting	• Confirmation of fragmentation of flywheel • Confirmation of complete demise • Verification of the numerical finding that the risk of fragments surviving can actually be neglected
Motor ring melting	Motor ring melting	
	BBU/central shaft separation	
BBU surviving		

Table 7-7: sequence of events for the demise of a RW

Test objectives

The test objectives correspond to the events to be verified by test. Some events might have higher priorities than others, i.e. some events could be more crucial for the overall sequence of events.

- Housing melting
  - Separation between upper/lower half of the housing
  - Melt through of thin wall sections
  - Brazing failure between the two parts
  - Detachment of the more massive upper/lower housing sections
  - Effect of the central Titanium post on housing detachment
- Electronics melting
  - Confirmation of artificial material properties or material demise model, respectively
- Spokes melting
  - Confirmation of spoke melt-through before central hub brazing connection failure
- Flywheel melting[5]
  - Confirmation of complete demise; verification of the numerical finding that the risk of fragments surviving can actually be neglected
- Motor ring melting
  - Confirmation of magnet material melting (material properties related)
- BBU/central shaft separation
  - Confirmation of separation event, i.e. central shaft sliding out of the BBU upon aluminium threaded ring melting

Selection of test facility

The selected test facility shall be able to achieve the "test subject", i.e. the events to be verified by test. The most interesting test subjects identified above are all melting related, i.e. melting of aluminium and steel, respectively. This means that the test facility has to be capable of achieving melting conditions of these two materials. Two of the test subjects also required some mechanical load in order to drive the separation/detachment. Ground-level gravity could be used for this. If further analysis provide data that more force is expected to occur during re-entry, actuators or other means of force introduction into the sample should applied (e.g. extra weights pulling).

Test definition (example for BBU/central shaft separation):

[5] This is a particularly interesting case. The complete demise of the flywheel has been observed in SCARAB (but not in SAM) and it is dependent upon the breaking of the flywheel into (quite large) bits by melting. It is something that is also highly likely to be relevant for the SADM and needs to be assessed at test level for each specific case.

- Test predictions
  - To generate unbiased numerical predictions of the potential test results
- Test conditions[6]
  - 1.6 MW/m²
- Facility calibration test
  - Heat flux probe at sample position
  - Pitot probe at sample position
- Test equipment (sensors)
  - Thermocouples in various positions of the sample (e.g. inside the central shaft, the separation ring/oil chamber (between the two ball bearings), the threaded ring)
  - Pyrometers pointing at the bushing of the BBU
  - At least two HD video cameras; one pointing from the side, one pointing from the front
- Test set-up
  - Vertical mounting of the BBU (broadside to the flow); Aluminium threaded ring point downwards; Aluminium threaded ring at the central axis of the flow
- Define success criteria
  - Success if BBU is sliding from the central shaft upon melting of the threaded ring
  - Fail if BBU stays stuck to the central shaft after melting of the threaded ring
- Testing
  - Test until either BBU is falling from the central shaft (SUCCESS), OR significant melting is occurring on the outer bushing (FAIL)
- Test conclusions
  - Summarise/report test data
  - Correlate test data with test predictions (model correlations)
  - Critically review the test conditions and test setup (Were the achieved heat fluxes too high/low? Was the introduced force load too high/low?)

[6] In some cases it is helpful to demonstrate both the steady state condition requirements and the heat flux mapping, especially as the BBU will be run broadside, so the shape is different from the calibration probe. It is advised to use a step-by-step heat flux approach, where it would be possible to get steady state data.

Example 2: Joints Testing in Sandwich Structures

A test campaign has been performed to assess the high altitude initial fragmentation of spacecraft structures, with a particular focus on the separation of joints. In order to achieve this, a set of tests was performed on a set of current joining technologies.

Test Objectives:

- The key objective was to understand the failure of joining technologies at high altitude.
- It was to be determined whether the joint fails or the panel breaks to cause separation.
- Surface, spool and edge inserts were tested.

Test Facility Selection:

- As the heat fluxes are low and the altitude high, the primary facility selected was a static re-entry facility.
- Tests in a wind tunnel were also performed in order to assess the importance of the flowfield.

Test Sample Selection:

- Two types of test sample were chosen. A two panel set-up with cleat was selected in order to provide an understanding of the overall behavior of the joint/panel structure failure, and a one panel set-up was selected in order to characterize the failure of a specific joint type.
- The two panel set-up is an example of a section of the equipment of interest.
- Test objects in the static facility are graphite sprayed to ensure that the correct radiative heat flux is received.

Figure 7-33: sample of two panel set-up with cleat (top) and sample one panel set-up (bottom)

Test Procedure:

- Test Predictions
  - o Heat fluxes to the samples were determined by CFD, which was in good agreement with correlation on the primitive shapes (flat panel, wedge at angle of attack) used.
  - o The initial plan was to test the samples at constant heat flux at the lowest level reachable by the wind tunnel. However, simulations showed that the long soak at low heat fluxes led to a different temperature distribution in the sandwich panels than the constant flux tests.
  - o This led to the decision to run two separate heat flux profiles in the static chamber; one representative of the heat fluxes in re-entry from a decaying circular orbit, and one at constant flux to read across to the wind tunnel results.
- Test Conditions
  - o The static facility used a heat flux profile representative of a trajectory defined by the predictions.
  - o The static facility also used a constant heat flux at the lowest level achievable by the wind tunnel.
  - o The wind tunnel used the minimum achievable flux level.
- Facility Calibration:
  - o The heat fluxes produced by the radiative heater were checked, and the heat losses from outgassing were monitored by use of a graphite calibration block.
  - o The wind tunnel was calibrated using a measurement of the cold wall heat flux and stagnation pressure. The enthalpy was found by performing CFD on the calibration sample, with support from nozzle flow calculations.

- Test Measurements:
  - The samples are thermocoupled.
  - The tests are video recorded to capture significant fragmentation events.
- Test Set-up
  - A force is applied on the panel ends in the two-panel set-up representative of the forces expected at high altitudes.
  - A similar force is applied to the joint in the one-panel set-up.

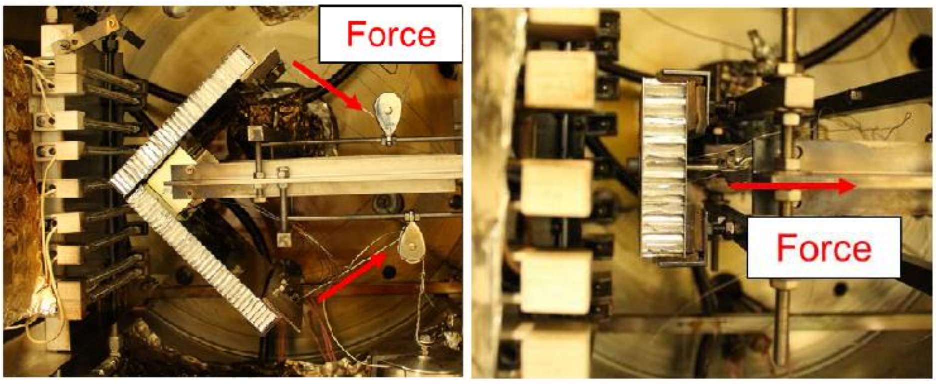


Figure 7-34: Force application set-up in the case of two-panel set-up (left) and one-panel set-up (right)

- Success Criteria:
  - Observation of a fragmentation event.
  - Correct application of heat fluxes and forces.
- Test Campaign:
  - Twenty static tests and ten wind tunnel tests were performed.
  - In general, the insert potting material failed when the trajectory flux was applied, and the panels failed when the constant flux was applied.
  - Panels were observed to melt quickly in the wind tunnel.
- Test Conclusions:
  - The potting material reacts endothermically and it is resistant to heating.
  - Once a critical temperature is exceeded, the potting material denatures and becomes very weak after some reaction time. This time is of the order of one minute, with significant uncertainty.

Depending on whether sufficient time/heat load for reaction has occurred, the insert is able to pull out of the joint before the panel breaks.

Example 3: Magnetorquer

The primary interest in the magnetorquer demise is the layer-by-layer failure process as this is the mechanism by which the item is expected to demise in re-entry. Therefore, the desired setup is with the layup in the flow direction and the axis of the magnetorquer normal to the flow. This results in the curved surface of the magnetorquer in the flow such that the flux on the side will be non-uniform. Standard scaling for cylindrical shape heat fluxes have been used in the past (see [RD9]) to estimate the heat flux to the curved surface in order to assess the required test conditions.

This suggests use of 100mm lengths of magnetorquer in the tests. As the diameter of the magnetorquer is 38mm, it is appropriate to use the 100mm nozzle exit in L2K (Plasma Wind Tunnel Facility at DLR). This means that the nominal fluxes will be set on the 50mm diameter flat-faced cylinder.

Nominal Flux 50mm Cylinder (kW/m^2)	Average Flux MTQ Side (kW/m^2)	Purpose
509	624	Removal of CFRP copper
542	665	Equilibrium
642	788	Equilibrium
749	919	Expected melt of Core
837	1037	Back-up in case of non-melt

Table 7-8: Test Conditions for Magnetorquer

The magnetorquer is held by the core using a U-shaped clamp, shown in Figure 9, with ceramic screws in order to minimize the heat losses. There is a space between the holder and the sample, again to minimize heat losses, but the possibility that melting material may fill that gap and create a thermal connection remains, increasing the heat loss.

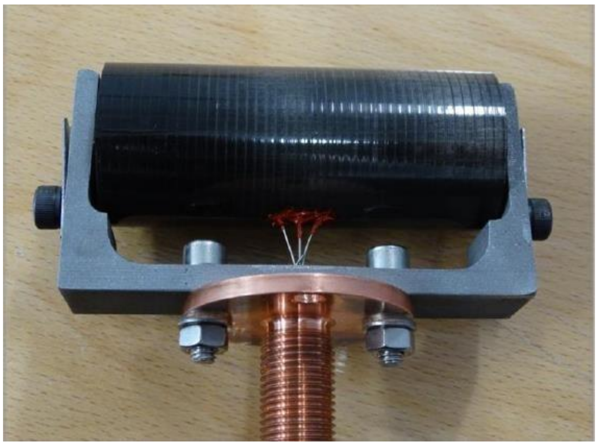


Figure 7-35: Magnetorquer Test Mounting

Also, visible below are the thermocouple connections. The thermocouples are located in the core, the copper coils, and the potting material.

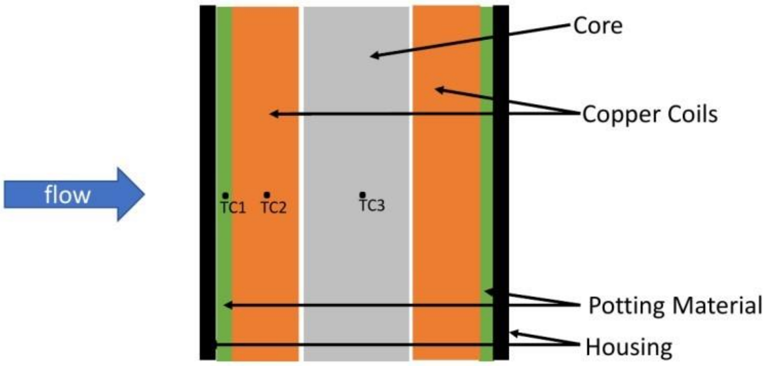


Figure 7-36: Magnetorquer Thermocouple Layout

The procedure for the magnetorquer test is as follows:
Test definition:

- Test predictions
  - Layer by layer demise process
- Test conditions (Average Flux MTQ side) with step-by-step heat flux approach:
  - 624 KW/m² (removal of CFRP copper)
  - 665 KW/m² (equilibrium)
  - 788 KW/m² (equilibrium)
  - 919 KW/m² (expected melt of core)
  - 1037 KW/m² (back-up in case of non-melt)
- Facility calibration test
  - 50mm diameter flat-faced cylinder
- Test equipment (sensors)
  - Thermocouples in various positions of the sample (located in the core, the copper coils, and the potting material)
  - An Infrared camera and at least two HD video cameras; one pointing from the side, one pointing from the front: Thermo-camera
- Test set-up
  - Mount the magnetorquer such that it has its axis normal to the flow, and the heat flux impinges on the cylindrical face
- Define success criteria
  - Success if MTQ demise layer by layer at the predicted conditions
  - Fail if MTQ stays stuck or unexpected demise behaviour is shown
- Testing
  - Test until demise of the core (SUCCESS) or if MTQ shows unexpected demise behaviour (FAIL)
- Test conclusions (see [RD8]):
  - The CFRP burnt through at the 542kW/m2 condition significantly more quickly than expected.

- The copper coils do not behave as solid copper due to the insulation between them causing a very low net conductivity. The failure is thus layer-by-layer. The copper also forms a conduction path to the sample holder resulting in significant heat losses.
- Equilibrium is reached with the copper removed at the 542kW/m2 condition, and a second equilibrium is reached at the 642kW/m2 condition.
- The core is observed to melt at the 749kW/m2 condition.

Example 4: Electronic Box and electronic cards

The requirement to cut the electronic box allows the size of the samples to be selected such that either the L2K or the L3K facility at DLR could be used. Sizing for the L3K facility would allow almost half the box to be used in a single test, which would provide the most representative test from a mechanical viewpoint. Some care is required when determining the size limit as a sample which is larger than the flow core is likely to provide significant blockage. This would also provide a large heat sink away from the parts being heated. Appropriate set-ups for this relatively large test object are similar to those for a smaller sample. The alternative philosophy is to attempt to produce representative samples for testing in L2K. There is sufficient material for a number of tests to be performed, and more flexibility, if less representativity, in the test objects which can be constructed.

Recalling that the major uncertainties from a destructive re-entry simulation viewpoint are the process of the fragmentation to card level, and the demise behaviour of the GFRP electronics cards themselves, there are a number of configurations which could be considered.

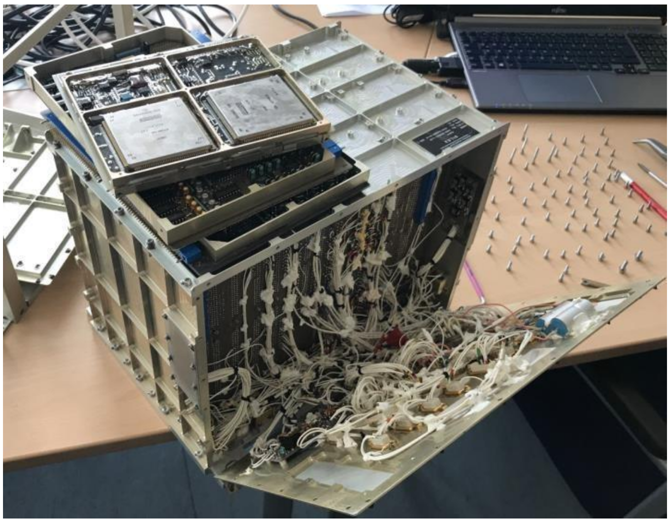


Figure 7-37: Electronics Box with Rear Housing Open Showing Backplane

Although it is expected that the aluminium housing will be removed reasonably easily, it would be expected to fail in large sections due to the tearing of the surface aluminium oxide layer. Generally, this has resulted in the aluminium being completely removed from the object, and the residue having no further part. This suggest that a test with the housing in place is useful, to confirm or deny this behaviour, but not necessarily essential. Indeed, the cutting of the housing in order to create a testable sample is the major representativeness issue.

There is another potential issue when considering inclusion of the aluminium housing within a test. There is a significant danger that mounting the electronics box sample by the aluminium housing may result in the failure of the housing and the slump of the whole setup under gravity at a relatively early point in the test. Although this will clearly demonstrate the weakness of the oxide-coated molten aluminium at relatively low temperatures, there is significantly more benefit to be gained from the mounting of the sample such that the cards stay approximately in place if the housing fails. This is likely to require a stronger connection that will result in greater heat losses from the sample to the support structure, but is necessary to ensure the test success.

To test this, the following configurations could be considered:

- A section of the electronics box with housing, backplane and card sections. This would give demise of the housing and separation of the internal parts.
- A section of the backplane attached to card sections. This would allow assessment of the process of the separation of the cards from the backplane.
- An individual electronics card. This would provide data on the failure of the GFRP material.

Although these configurations are desirable, it is not possible to construct a sample which is fully representative of a complete electronics box. One of the key difficulties when considering an item which needs to be cut is that the mechanical forces through the object will be different. However, it should be noted that this is already true by the simple fact that the test object is supported such that there is a (reasonably large) stress in the equipment from the gravitational force which would not be present in flight. Indeed, with the dynamic pressures being of the order of a few kilopascals, the gravitational effect is a similar order of magnitude, and so these tests will always be far from mechanically representative regardless of the precise set-up.

When considering the key fragmentation processes, the connections of the cards to the housing, to each other, and to a lesser extent the joints between the housing panels are expected to be of interest. The housing panels are connected by screws which are anticipated to fail when the screws are pulled from the panel. This is expected to occur when the aluminium oxide layer contains enough molten aluminium such that the force on the joint is sufficient to deform the material and tear. The failure of the connection to the cards is anticipated to be more complex. The cards are joined to the backplane by a set of pins, which enter into a socket which is soldered to the backplane. The solder would be expected to melt at a relatively low temperature ($<400^{o}$C), which suggests that the socket could easily be removed from the backplane were a force applied in the appropriate direction. However, the cards are also fed into the backplane along aluminium runners which are integrated within the housing. As this track is quite stiff, it would be expected that the failure of the solder would not be sufficient for release of the cards, and that this would be controlled by the failure of the housing. Some care is required in the set up as the pins may remain sitting in the backplane from either the aerodynamic or gravitational forces, giving the impression that the joint is intact.

Therefore, the set-up is required to allow movement with gravity of the cards once the housing has failed in order to confirm that they will be released. It will be interesting to observe whether the sockets are released with the cards to confirm the expected behaviour. Given this, the simplest set-up which can be envisaged is an ‘open’ configuration, where a 100mm cubic corner section is cut from the box, with all the relevant cards and connections to the housing corner. This section needs to be selected such that the backplane is included, and the rails in the housing also connect to the cards. Clearly, the cards themselves cannot be complete. Instead, they will also need to be cut, such that they fit within the housing section.

The left hand diagram of the following figure shows this set up in a ‘plan’ view with the top housing section removed for clarity. The cards are connected to the top housing section along the rails, and are connected to the backplane via the pin connectors.

In order to allow the movement of the cards relative to the backplane when connection with the pins is lost, this configuration is rotated by 45º, such that the view with the flow coming from the observer is as in the right hand diagram of the following figure. Here, the card configuration behind the aluminium housing panel is shown. This is described as Orientation 1.

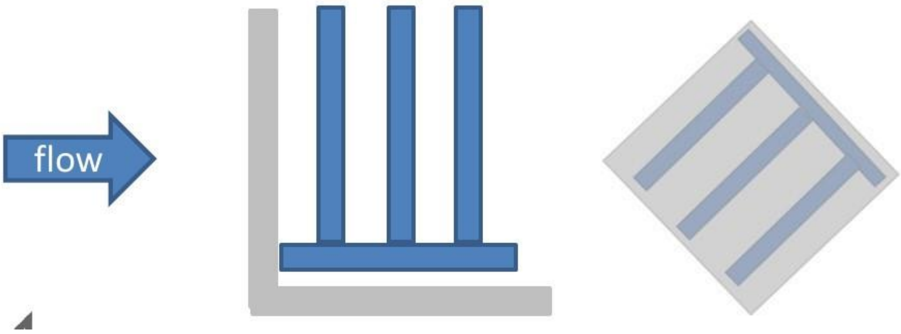


Figure 7-38: ‘Open’ Electronic Box Configuration Orientation 1; flow from left (right) and flow from observer (right)

Other configurations can be considered for this test. Indeed, a number of tests examining different configurations could be considered. From a viewpoint of understanding the processes at play, it is simplest to capture the incoming heat flux where the sample is normal to the flow as in the suggestion above. This provides a fairly straightforward flux profile on the housing and the cards whilst they are intact. An end on flow to the cards will then provide a significantly higher flux to the card edges to assess the possibility of demise and glass ‘melt’.

The first alternative orientation (Orientation 2) is shown in the following figure, which is obtained by rotating the setup of the previous orientation 1 by 90 degrees such that the flow comes from the right. This provides a more complex distribution of the heat flux over the test object, with the highest flux at the corner due to the higher velocity gradients, but also provides similar flux profiles over the GFRP cards.

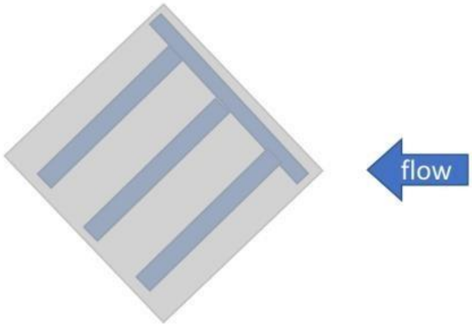


Figure 7-39: 'Open' Box Set-up Orientation 2

This orientation is most likely to provide more useful data directly on the cards themselves. It is also likely to be more representative of the flux distribution on the box itself as the corners will receive significantly higher fluxes than the face centers at any orientation more than a few degrees away from normal flow. The final orientation for consideration (Orientation 3) is half-way between these two, where the corner of the housing is directly into the flow. This is probably the most realistic from an incoming flux perspective, but the most difficult to assess numerically as the heat flux distribution is the most complex.

The 'open' box configuration has a further advantage in that the HD cameras will be able to monitor the aluminium housing and the cards behaviour simultaneously as the camera at the rear of the sample will view the open housing, particularly if the Orientation 3 is selected. As the aluminium housing is expected to demise first, the sample is to be mounted by the GFRP cards.

In order to increase the mechanical representativeness of the test object, it has been proposed to 'close' the sample by placing sections of aluminium housing to rebuild a cuboid. These would be attached using the same screws used on the standard housing connections. This has the advantage of providing a complete aluminium housing such that there are no free edges, but does not provide a second representative connection for the electronics cards as the cards are necessarily cut such that the lower runners are not in place. Disadvantages of this setup are the extra complexity in the manufacture of the sample, as extra housing parts have to be cut and grafted on the model using screw holes. Closing the housing also makes mounting the sample by anything other than the external structure more difficult. As already noted, this undesirable as it the high demisability of aluminium makes it likely that the test would be lost at the point that the aluminium housing fails, providing no insight into the behaviour of the electronics cards.

There are two potential issues here; the aluminium could become hot and melt, at which point the gravitational force may be sufficient to cause the sample to tear the oxide layer from the support. Alternatively, the back face could remain cold due to heat losses to the support structure which would provide a thermally unrepresentative test. Either of these issues are sufficient to select mounting via the cards themselves. Finally, the opportunity of viewing the cards from the start of the test with the rearmost HD camera will be lost if a closed box is used.

The set-up for a larger sample if the L3K wind tunnel is used is similar to the 'closed' box setup, even though there is unlikely to be sufficient material to close the open end. This will be the most representative sample, and less of a cut-and-shut component, but has the disadvantage of requiring the more powerful facility with the associated increase in cost.

On balance, the advantages of the ‘open’ box set-up are significantly preferable, particularly recalling the priority of the understanding of the connections to the electronics cards and the behaviour of the cards themselves. Therefore, the ‘open’ configuration is recommended. Further, the demise behaviour of the electronics cards is best assessed using a layout where the cards present a reasonable area to the flow as the fluxes will be more representative of typical values. With the cards parallel to the flow, the fluxes on the edges will be high. This can provide closer to a one-dimensional conduction layout, which is easier to simulate, but the high fluxes on the edges will not be maintained in any tumbling motion, and is therefore less representative of what might be expected in flight. This suggests use of either Orientation 2 or Orientation 3.

Given that the demise behaviour of the electronics cards is of interest, there is benefit in testing the backplane/cards set-up without the housing in place. This allows assessment of the separation of the cards from the backplane and the demise behaviour of the backplane itself. Again, Orientation 2 or Orientation 3 would be the most suitable.

It would also be possible to test an individual electronics card. In this case, as it is closer to a pure material test, the most appropriate orientation is with the card normal to the flow axis. The flux gradients on most of the card are relatively mild, so this will give a clear material response to a particular flux input.

From this discussion (see [RD8]), there are a range of possible tests for the electronics box, in either ‘open’ or ‘closed’ configuration.

- Option 1 Test 1: test of (close to) half the electronics box in L3K
- Option 1 Test 2: repeat of Test 1 with the other half of the box
- Option 2 Test 1: test of a section of the box inclusive of housing, backplane and cards
- Option 2 Test 2: test of a section of the backplane attached to cards
- Option 2 Test 3: test of an individual card or cards
- Option 2 Test 4: repeat of Test 1, with further option for changing the angle of attack

Given the greater flexibility in the L2K tests, and the realistic option of having more than one test using different configurations, or a repeatability test, leads to a preference for the testing of the electronics box to be performed in L2K. This does, however, require greater care in the test set-up.

As the electronics box has a similar aluminium housing the 100kW/m^2 condition is appropriate. For the individual cards, the behaviour of the GFRP material is not well known, and so the fluxes are stepped up from 100kW/m^2 to the point where demise is observed.
All three tests were performed successfully.

The mounting of the electronics boxes is a non-trivial problem. The initial concept was to cut the boxes and cards as shown in the following figure. However, it became clear that the cards could not be cut at any point due to the existence of an alumina substrate which caused cracking.

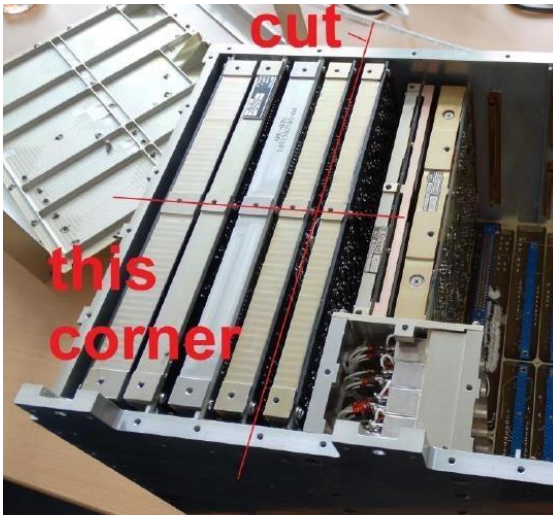


Figure 7-40: Electronics Box Potential Cut Method

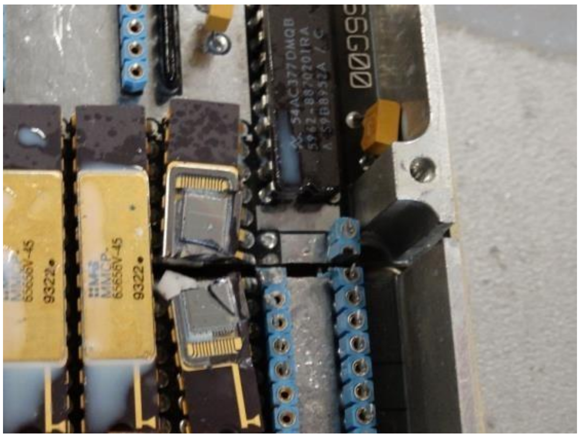


Figure 7-41: Cracked Items on Cards in Cut Attempt

Due to this cracking, reliable cutting of the cards can only be achieved lengthways, resulting in the need to consider a larger sample. The achievable cuts result in a sample with the geometry shown in the following figure. The sample is larger than planned, but the experience of the D4DBB activity (see [RD4]) suggests that this geometry can be run in the L2K facility. This results in the lower aluminium housing (blue in figure) being still present, so the housing is on four sides of the open sample.

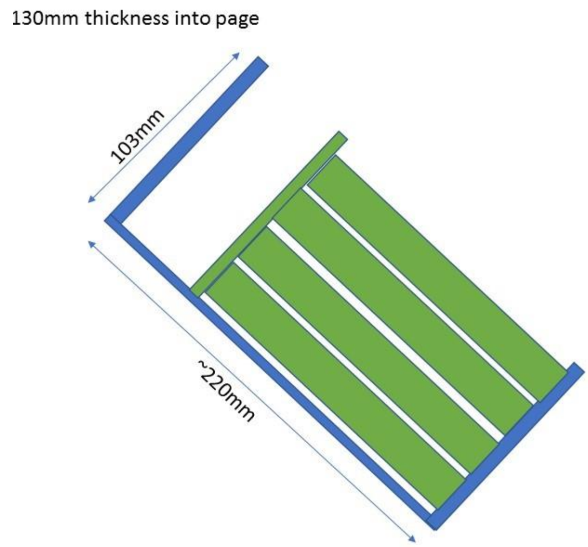


Figure 7-42: Achievable Geometry for Electronics Box

The mounting is schematically shown in the following figure. The backplane GFRP card will be held by a stainless steel bracket, which will be minimised in contact area to minimise the heat losses. However, there will be some heat losses from the sample. Insulation of the bracket such that a heat soak to the bracket can be allowed for can be achieved using ceramic paper.

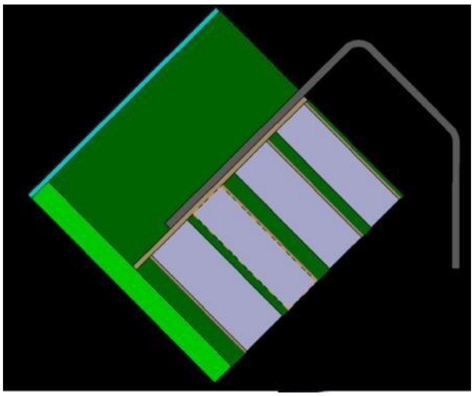


Figure 7-43: Electronic Box Mounting

The procedure for the electronics box tests is as follows:
Test definition:

- Test predictions
  - Demise of the electronic box housing and process of the fragmentation to card level
  - Demise of the GFRP electronic cards (in separate tests)
- Test conditions with step-by-step heat flux approach:
  - Insert sample into flow at 100kW/m2 flow condition.
  - In case that a steady state for 30s is reached, increase flux to 200kW/m2 condition.

- In case that a steady state for 30s is reached, increase flux to 300kW/m2 condition
- Facility calibration test
  - 50mm diameter flat-faced cylinder
- Test equipment (sensors)
  - Thermocouples in various positions of the sample
  - An Infrared camera and at least two HD video cameras; one pointing from the side, one pointing from the front: Thermo-camera
- Test set-up
  - The backplane will be held by a stainless steel bracket, which will be minimised in contact area to minimise the heat losses.
- Define success criteria
  - Success if the Electronic Box housing demise and there is the separation of the electronic cards
  - Fail if Electronic box stays stuck or unexpected demise behaviour is shown
- Testing
  - Test until demise housing and separation of the cards (SUCCESS) or if the sample shows unexpected demise behaviour (FAIL)
- Test conclusions (see [RD8]):
  - The aluminium housing fails due to tearing of the oxide layer consistently with previous observations.
  - There is significant charring of the exposed electronics, but no clear demise
  - Detachment of the front card is observed, but sufficient housing remains that the cards stay in place.
  - The four electronics cards lose connection to the backplane and a complete separation is observed.

As the separation of the cards from the backplane is complete, the modelling of electronics boxes as a housing with internal cards, such that the cards are released separately on the failure of the housing is supported by this test. Given this outcome, the tests on individual cards become more important as this is key to ensuring the demise of electronics components. Therefore, two samples of GFRP electronic cards have also been tested in two separate tests, with orientation normal to the flow.

The observations from the two tests on the electronics cards were remarkably similar, which has suggested that a single model could be used in simplified codes to represent a generic GFRP electronics card.
The observations are given below (see [RD8]):

- At 100kW/m^2, there is charring of the GFRP card, and the aluminium frame is removed.
- Some of the steel parts are observed to inflate, and some parts are removed from the card.

- An equilibrium is reached, and the flux is increased to 200kW/m^2. At this condition, the card bends and the glass material can be seen to reach a lower viscosity, but there is no major flow.
- A second equilibrium is reached, and the flux is increased to 300kW/m^2. Here there is clear flow of the glass material, the components are removed and the card effectively demises.

The failure of the cards is achieved at significantly higher temperatures than are used in current models. The first equilibrium surface temperature (100kW/m$^{2)}$ is at approximately 830^{0}C, and the second (200kW/m^2) is at approximately 1060^{0}C. The removal of large amounts of material is observed at 1200^{0}C, which is recommended as a proxy melt temperature for simplified models.

This is substantially higher than has been used previously. The emissivity measurements suggest a value of 0.9 should be used.

	Recommendation
Density (kg/m^3)	2200
Specific Heat Capacity (J/kgK)	1047
Emissivity	0.9
'Melt' Temperature (^{0}C)	1200
Conductivity (W/mK)	0.4
'Latent heat' (J/kg)	800000

Figure 7-44: Recommended Simple GFRP Model