MADRE: UPGRADING THE RE-ENTRY RISK COMPONENT OF ESA'S DRAMA SOFTWARE

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ABSTRACT

The understanding of spacecraft component demise during re-entry has been significantly enhanced by recent wind tunnel test campaigns, including those conducted on reaction wheels and sandwich panels. As a first step towards building a library of standard components, ESA requested the construction of models for a reaction wheel and a sandwich panel with CFRP facesheets for use in DRAMA.

Building these approved components requires that the material and aerothermodynamic models within DRAMA are sufficiently representative. By integrating algorithms from BRL's SAMj code, which has been shown to be capable of rebuilding wind tunnel test results, it is possible to improve the performance of DRAMA, such that it can reproduce the demise behaviour for these component models when simulated by SAMj.

While developing these models an auditable process was followed. This approach, along with the tools and techniques used, has been documented for use in developing additional DRAMA component models.

1 INTRODUCTION

As a piece of operational software, DRAMA is subject to lengthy and formal development cycles. The most recent of these concluded in 2018-2019. During this three year release cycle a number of advances in the state-of-the-art with regard to re-entry analysis have occurred. As a consequence, ESA has implemented a short, incremental development cycle focused on introducing the highest priority items into DRAMA. No new scientific ground has been covered within this activity, rather it is focused on adapting and integrating existing features and knowledge into the architecture of DRAMA-3 with the minimum of disruption.

As part of this work ESA requested the development of initial models for a spoked reaction wheel and structural sandwich panels with both aluminium and CFRP face sheets. The models should be grounded in the results of the latest destructive test campaigns and be representative of the demise phenomena, but remain both computationally tractable and easy to manipulate within the existing DRAMA interface.

As a result of constructing these exemplar models a process suitable for the construction of other re-usable DRAMA component models based on the results of on-ground test campaigns was to be developed.

Reaction wheels are complex assemblies of connected and nested sub-components, the details of which vary significantly between manufacturers and involve geometries that cannot be represented in DRAMA. Further, the testing of stainless steel structures has demonstrated that the DRAMA material models were conservative in terms of the melting point, but overly optimistic in terms of the emissivity.

Sandwich panels are significantly less complex assemblies, but are difficult to represent well with the simplified bulk material models generally used in destructive re-entry codes. They also exhibit complex fragmentation and demise phenomena, and the properties of such panels can be seen to vary based on the material and layup of the facesheet. Finally, the need to position and size sandwich panels within a larger vehicle model prevents the use of a connected multi-component model to represent the layup of the panel.

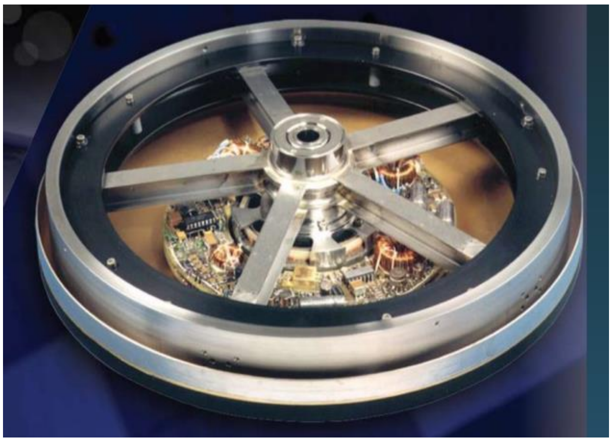

Figure 1. Rockwell Collins RSI 68 SS Reaction Wheel

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Ed. T. Flohrer, S. Lemmens & F. Schmitz, (http://conference.sdo.esoc.esa.int, May 2021)

2 DRAMA REACTION WHEEL COMPONENT

The baseline reaction wheel model used in this activity is derived from the geometry and properties of the Rockwell Collins RSI 68 SS. This is a spoked design with a 330mm diameter, 4.5kg steel flywheel, as shown in Figure 1. For the purposes of this activity, a simplified model has been constructed of 12 components, consisting of a two part cover and the internal geometry shown in Figure 2.

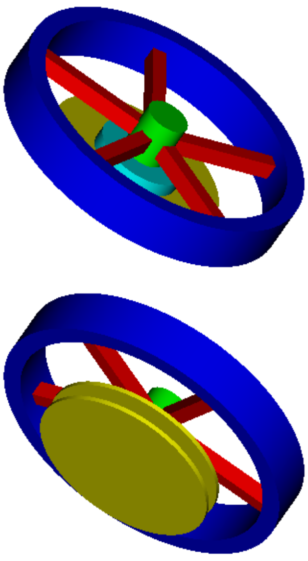

Figure 2. Spoked Reaction Wheel Model Geometry

The majority of the components were modelled as steel, with the exceptions being the GFRP PCB and aluminium covers and base. Where possible, the material models used were based on the properties found in the ESTIMATE database.

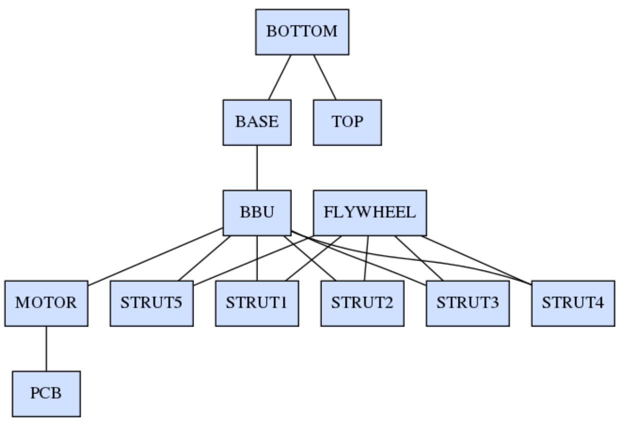

Figure 3. Baseline Reaction Wheel Connection Model

The model exclusively uses connected-to relationships, leading to the network shown in Figure 3, with all Spokes being connected to both the BBU and Flywheel. The majority of connections were configured to fail when 50%-90% of one of the connected components had demised. Remaining joints failed on complete demise of a component. It should be noted that this network of connections, ring primitive and partial demise criteria could not be used in DRAMA at the start of the activity.

A small campaign of 200 simulations was executed using SAMj in 6dof mode, controlled by the PADRE statistical framework to assess the performance of this model. The campaign was repeated from each of three release points (65km, 78km and 90km) on the DRAMA uncontrolled trajectory. This resulted in profiles of landed mass and fragment count, an example of which is shown in Figure 4.

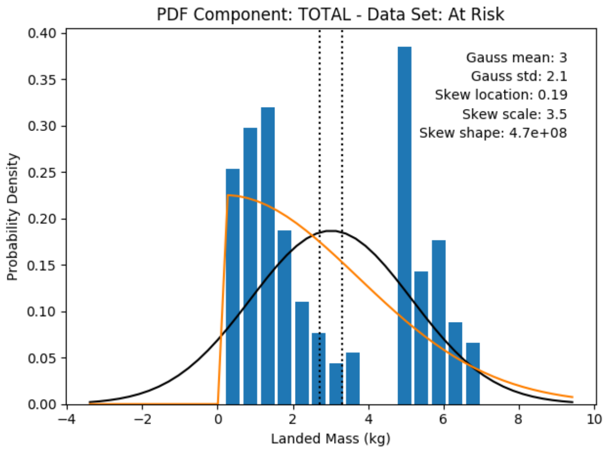

Figure 4. Baseline 6dof Landed Mass from 78km

Having established a baseline flight model, the second stage of development identified and evaluated simplifications that might enable construction of an equivalent, suitable for DRAMA. These steps highlighted modelling enhancements required in DRAMA. In total five stages of simplification were investigated:

1. Conversion of connection network to a strict tree and use of 3dof simulations.
2. Replacement of partial demise fragmentation with a complete demise criterion.
3. Substitution of ring primitives with cylinders.
4. Conversion of the fully connected-to model to a contained-in model with a single parent cover.
5. Consolidation of the base component into the cover.

The two most important simplifications were stages 1 and 4. The use of a strict tree model and 3dof simulations is a pre-requisite for any DRAMA model, and without the use of a single parent object the placement of the reaction wheel within a larger spacecraft using the DRAMA GUI would have been very complex and time-consuming.

The effect of each stage of simplification in terms of average impact mass and fragment count is summarised in Table 1.

Table 1. Evolution of Mean Landed Mass and Fragment Count Through Model Simplification

Model	Impact Mass (kg)			Fragment Count		
	65km	78km	90km	65km	78km	90km
Base	6.3	3.0	2.0	2.0	1.7	1.4
1	6.3	2.9	2.2	2.3	1.7	1.5
2	6.3	3.0	2.3	1.9	1.7	1.5
3	N/A	5.2	N/A	N/A	2.0	N/A
4	6.3	3.2	2.4	1.9	1.8	1.5
5	6.2	3.1	2.4	1.9	1.7	1.5

With the exception of replacing ring components with cylinders, which had a significant effect on inter-component shadowing, none of the simplifications had a large impact on the metrics that drive casualty risk. As a consequence, all other simplifications were adopted, leading to the final model shown in Figure 5.

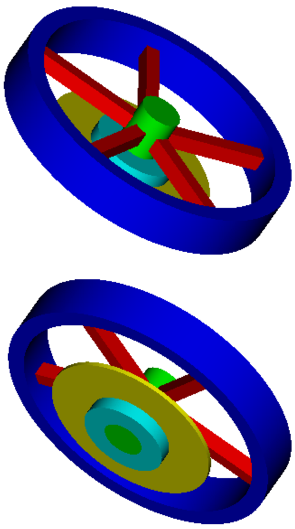

Figure 5. Final Spoked Reaction Wheel Model Geometry

All internal components, apart from the PCB, which is modelled in GFRP, are modelled in steel. All components fragment on total demise and are connected as shown in Figure 6.

In order for the model to be implemented in DRAMA a number of pre-requisite enhancements were made. These include the introduction of a ring geometric primitive, the addition of a catalycity model for metal objects and the upgrade of the box heating coefficient databases.

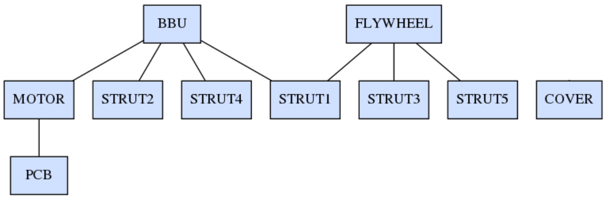

Figure 6. Proposed Reaction Wheel Connection Model

Having implemented the pre-requisites and model, a similar verification campaign was executed, comparing the performance of the model in DRAMA with SAMj. These tests found differences in the results predicted, most significantly at release altitudes around 78km as shown in Table 2. However, this was, in part, tracked to differences in the handling of geometry change as components demise in the two codes. Attempting to mimic the fixed shell geometry of DRAMA in SAMj led to the results in the final column of Table 2. These illustrate the sensitivity of results to small differences in modelling assumptions.

Table 2. Summary of Mean Aggregate Results Through Reaction Wheel Model Evolution With Shell Components

Variable	Release Alt	SAM 6dof	SAM 3dof	DRAMA 3dof	SAM Shell
Landed Mass (kg)	**90km**	2.0	2.4	2.8	2.7
	78km	3.0	3.1	3.6	4.4
	65km	6.3	6.2	6.2	6.2
Fragment Count	**90km**	1.4	1.5	1.3	1.4
	78km	1.7	1.7	1.4	1.8
	65km	2	1.9	1.9	2.0

Once it has been established that the proposed DRAMA model mimics the baseline SAMj model, the envelope of geometries within which the model can be used was investigated. This was done by scaling the geometry to flywheel diameters of 130mm and 400mm and repeating the back-to-back comparison with the equivalent model in SAMj. The results of these simulations are shown in Table 3.

Again, the DRAMA implementation of the reaction wheel model is seen to replicate the behaviour of the equivalent SAMj model well. Therefore, the model is recommended for use within DRAMA to represent spoked reaction wheels with steel flywheels of between 130mm and 400mm in diameter.

Table 3: Summary of Mean Aggregate Results Through Reaction Wheel Model Evolution with Shell Components

Metric	Rel Alt	400mm F'wheel		130mm F'wheel	
		SAMj	DRAMA	SAMj	DRAMA
Landed Mass (kg)	90km	4.3	4.0	0.31	0.39
	78km	6.1	5.0	0.55	0.62
	65km	7.8	7.8	2.3	2.3
Frag. Count	90km	1.5	1.4	0.62	0.42
	78km	1.9	1.5	0.9	0.61
	65km	2.0	1.9	1.1	1.0

3 DRAMA SANDWICH PANEL COMPONENT

The approach adopted for the construction of a DRAMA sandwich panel model focuses on the development of a number of proxy materials. Given that good practice favours multi-component connected or nested models over proxy materials this decision should be justified. In this case, a proxy material model has two significant advantages over a multi-part sandwich panel model comprising facesheets and honeycomb core. Firstly, at this point test results do not provide reliable fragmentation and demise criteria to make reasonable use of a multi-component model. Therefore, tuning a proxy model to the demonstrated behaviour is simpler as it has fewer input variables. Secondly, the DRAMA GUI does not support the scaling and placement of groups of components. As a consequence, use of a multi-component model would be significantly more time-intensive for multi-part models with components that must inherently be resized when placed in a vehicle model.

Having identified the use of a proxy material as a favoured approach, 18 test scenarios were selected. These covered the range of panel thicknesses and densities used within PADRE vehicle models (20mm light panels, 20mm heavy panels and 50mm panels), three face sheet types which have been used in tests (aluminium, 4ply CFRP and 8ply CFRP) and two trajectory types (a shallow 0^0 flight path angle at 120km and steep -2^0 flight path angle). The face sheet materials were 0.5mm, 0.3mm and 0.6mm thick in the case of aluminium, 4ply and 8ply CFRP respectively, with the thickness of the core adjusted accordingly.

SAMj 3dof simulations were run for each of these cases using a 1D representation of the panel placed on the outside of a sphere to correctly capture the effect of heating of one face of the panel. The output of the simulations were a set of baseline temperature profiles, such as the one shown in Figure 7.

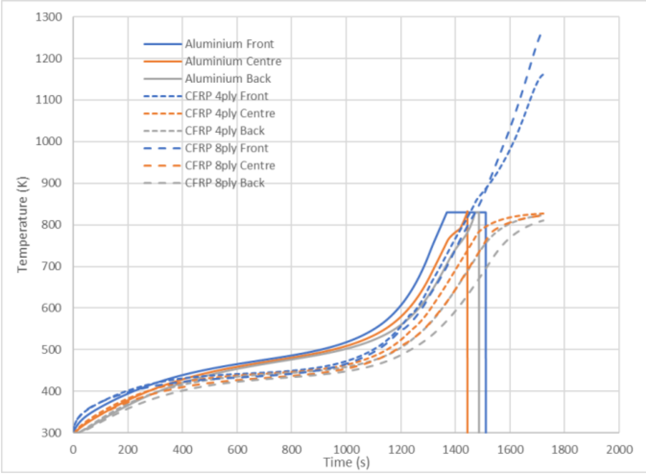

Figure 7. Temperature Profiles for 1D Model on Test Case 1 Shallow

The current modelling approach in DRAMA is to use the reduced density aluminium honeycomb sandwich model for all sandwich panels. As the CFRP facesheets are lighter than their aluminium counterparts, the panels with CFRP facesheets are lighter overall, resulting in earlier demise. This is not consistent with the demise behaviour observed in testing, where it is apparent that the CFRP facesheets survive longer and tend to provide more protection to the honeycomb core.

The SAMj 1D results were compared with those from the standard aluminium material within a bulk heating model, as would currently be applied by DRAMA. This showed that the bulk heating model is slightly conservative relative to the 1D model for the aluminium panel, and that this is consistent on the steep and shallow trajectories. The predicted behaviour of the CFRP panels demising slightly faster due to the lower mass of the facesheets was seen.

It is also worth noting that testing shows that the panels breakup well before they are completely demised. This suggests that the models may well be conservative, but there is currently insufficient data to develop a consolidated modelling approach which would provide a good representation of the point at which the panels can be considered to no longer pose a potential ground risk.

The construction of a proxy material model for sandwich panels with CFRP facesheets has initially been based on the simplified model which was developed within the ESA D4DBB activity [1]. The surface properties have been defined using the CFRP material, with an emissivity of 0.8. The specific heat capacity has been derived on a mass average basis for a 20mm thick panel with 4ply facesheets. Although this average would strictly be different for 8ply facesheets, and for different panel thicknesses, it is considered pragmatic to consider the same specific heat capacity for all panels. For conservatism, the core has been assumed to be without additional structure such that the specific heat capacity of CFRP has a significant impact. This removes the dependency of the model on the panel thickness, which would be complex to implement reliably.

With the intention being to retain a simple model for use in DRAMA, and with the demise processes not being well understood, a pragmatic definition of the onset of demise was sought. For an aluminium panel, this is clearly the onset of melt. For a CFRP facesheet model, an equivalent demise onset condition is required. The most appropriate condition which has been identified is the release of the facesheets from the honeycomb. Although this can be thought of as being driven by the failure of the adhesive between the facesheets and the honeycomb, a slightly more conservative approach where the back face temperature of the front facesheet exceeds the aluminium core melt temperature has been identified as a suitable proxy. Unfortunately, this temperature is not directly calculated in a simple bulk heating model. However, an investigation of the results produced by the 1D model has produced a suitable proxy.

Across the twelve test cases employing CFRP facesheets, the surface temperature at which the rear of the facesheet reaches melt temperature has been identified. These figures, relative to the aluminium melt temperature are given in Table 4. There is a relatively large variation in the surface temperature at the point where the front of the honeycomb reaches melt. The main drivers of this are the thickness of the facesheet (4ply or 8ply) and the nature of the trajectory. As the main interest is in shallow trajectories, these data are given more weight in the selection of the values to use in the models. The differences in the response from the CFRP thickness also provides a methodology to distinguish the reduced demisability of the thicker facesheets within a simplified modelling approach.

Table 4: Surface Temperature Level Above Aluminium Melt at Core Melt Onset

Case	**Shallow 4ply**	**Shallow 8ply**	**Steep 4ply**	**Steep 8ply**
Test Case 1	+30K	+70K	+100K	+210K
Test Case 2	+15K	+40K	+60K	+150K
Test Case 3	+30K	+70K	+100K	+210K

From this, demise temperatures were selected based on engineering judgement, and it is proposed to model the demise onset temperature as:

- Aluminium melt temperature +40K in the 4ply facesheet model
- Aluminium melt temperature +80K in the 8ply facesheet model

Once the demise onset criterion has been established, the demise energy is needed, which is represented by the latent heat of fusion in the bulk heating models. As the honeycomb core and included structures such as inserts, brackets and cleats are predominantly aluminium, use of the aluminium latent heat of fusion is proposed.

The overall model is summarised for the two facesheet thicknesses in Table 5.

Table 5: CFRP Panel Proxy Model Summary

Case	**4ply Panel**	**8ply Panel**
Emissivity	0.85	0.85
Density	450kg/m^3	450kg/m^3
Demise Onset Temperature	890K	930K
Latent Heat	400,000J/kg	400,000J/kg

Verification of the proxy model can only be done in terms of assessing the behaviour of the model against the 1D and bulk model performance, and relative to the expectation that the CFRP facesheets should decrease the demisability of the panels. Although, this is understood qualitatively, sufficient data does not exist to quantify the effect, and there is a clearly pragmatic aspect to determining whether the model is acceptable for use in DRAMA. The results of these tests suggest that the model behaves as intended, and although not a fully physical model, it has sufficient physical parameters to catch the different behaviour of the demising panels across a range of panel masses and thicknesses. The demise altitudes obtained across the test cases are summarised in Table 6.

Table 6: Demise Altitudes (km) in Test Cases

	Test Case 1		**Test Case 2**		**Test Case 3**	
FPA	**0^0**	**-2^0**	**0^0**	**-2^0**	**0^0**	**-2^0**
Aluminium	89.1	73.0	94.6	80.1	87.8	71.5
4ply CFRP	85.3	72.6	90.6	81.3	82.6	69.0
8ply CFRP	82.6	70.2	87.7	78.2	79.9	66.5

The material models to be implemented in DRAMA have been reviewed and updated. As well as the changes for the aluminium baseline model, the density of the panel material has been increased to 450kg/m^3 to avoid the potential issue of producing over-dense objects which is not allowed in the DRAMA GUI.

The performance of these models is shown in comparison to the current DRAMA material model in Figure 8. The effect of the increased specific heat capacity delays the heat-up of the panel in the final orbit, resulting in a significant difference in temperature at 110km altitude. After 110km, the heat-up of the panels is very similar, but the higher initial temperature results in the current aluminium panel model demising about 5km higher. The relative performance of the new panel models is equivalent to the behaviour observed in the SAMj simulations summarised in Figure 8.

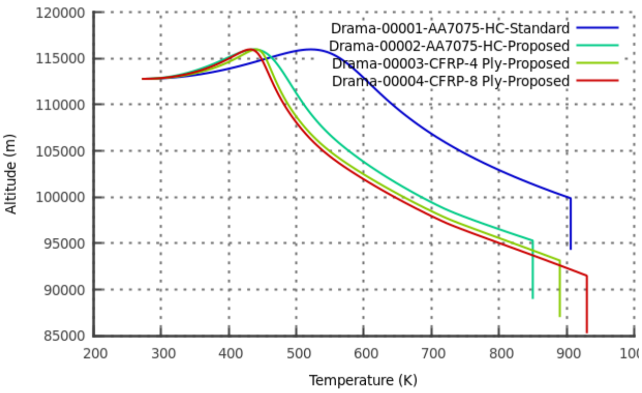

Figure 8. Performance of Panel Models in DRAMA

4 DRAMA COMPONENT DEVELOPMENT PROCESS

The lessons learned from implementing the reaction wheel and sandwich panel components were used to construct a set of guidelines for the implementation of similar approved DRAMA components. The primary goal of this procedure is to construct component models that are grounded in physics with an audit trail from experimental test results through to a final DRAMA model. The process is summarised in Figure 9.

Figure 9. DRAMA Component Development Process
Complex Flight Model

This description focuses on the development of the complex flight model through to a DRAMA implementation and has a degree of overlap with the ESA DIVE [2] guidelines.

4.1 Baseline Flight Model

The first step in the construction of the DRAMA model is the creation of a representation of the component in a design code, in this case SAMj. The construction of this model is likely to represent the weakest link in the audit trail from wind tunnel results to the final DRAMA representation. Experimental tests inherently focus on particular aspects of interest and are typically constrained to testing small samples or analogues of flight equipment under limited conditions. Extrapolating these results to a flight model applicable to all trajectory conditions and attitudes is difficult. When constructing a flight model the following guidelines should be followed:

- All sub-components that are likely to reach ground are included.
- All sub-components likely to generate significant shadow on their peers are included.
- Where possible, material models are grounded in experimental data.
- Where possible, nested models are preferred to proxy material analogues.
- A reasonable physical representation of the underlying component should be maintained for ease of use.
- The material selected to represent a sub-component should be the least demisable of its constituent parts. If this results in a very conservative model, the component should be further broken down into its constituent parts.
- The component mass, surface area and ballistic coefficient should be well represented.
- The evaluation of the flight model should be done using a Monte-Carlo of at least 100 runs using suitable uncertainties, preferably in 6dof.
- For components typically located within a vehicle, release altitudes of 65km, 78km and 90km should be assessed.

The output of this Monte-Carlo forms the baseline for the model. Key parameters are the mean number of fragments predicted to impact the ground and the mean landed mass.

4.2 Simplified Flight Model

Having established a baseline flight model this may then be simplified to reduce the computational cost or complexity in using it within the DRAMA UI. The primary means of simplifying the model are:

- Consolidate multiple parts into a single component.
- Replace connected-to relationships with contained-in relationships.
- Simplify the criteria used to trigger connected-to or contained-in fragmentation.
- Replace more complex geometries with simpler ones (e.g. sphere capped cylinder to cylinder).

In seeking to simplify the model the following guidelines should be observed:

- Parts predicted to reach the ground should not be consolidated.
- Parts that significantly shadow components that impact the ground should not be consolidated.
- The mass of a part being consolidated should be added to the recipient.
- The part being consolidated should not be modelled in a more resistant material than the recipient.
- Care should be taken not to alter the surface area or ballistic coefficient when consolidating components.
- Care should be taken not to change the shadowing of other components significantly.

As before, each version of the simplified model should be assessed in a stochastic manner using a Monte-Carlo of at least 100 simulations. The output simplifications, in terms of both mean fragment count and landed mass, should be compared against the baseline. As a guide, differences of less than 10% are good, less than 25% are acceptable.

4.3 DRAMA Component Model

Having implemented any enhancements required to DRAMA in support of the proposed model, the results of a 1000 simulation Monte-Carlo analysis should be compared with the proposed baseline. As with previous analyses the primary variables for assessment are the mean landed fragment count and impact mass. Although the models should be identical within the codes, it is recognised that other differences in the heating or aerodynamics may result in variations in results. Again, differences of less than 10% are deemed to be good, with variations of up to 25% being acceptable.

Once the baseline model has been validated, variations in geometry size and other parameters identified in the requirements should be tested to establish its validity envelope. When varying geometry care should be taken to maintain reasonable sub-component dimensions, for example it may not be appropriate to scale all dimensions or sub-components.

5 CONCLUSIONS

The activity successfully met the goals set out by ESA. Representative DRAMA models of a spoked reaction wheel and sandwich panels with aluminium and CFRP facesheets have been constructed. These have been demonstrated to replicate the behaviour of more complex SAMj flight models, which in-turn were based on the output of wind tunnel campaigns.

Through the development of these models a process has been established with guidelines for the construction of other DRAMA approved components.

6 REFERENCES

1. Fittock, M., Beck, J., Flinton, A., Gibbings, A., Guelhan, A., Liedtke, V., . . . Soares, T. (2018). Methodology and results of high enthalpy wind tunnel and static demisability tests for existing spacecraft structural joining technologies. *International Astronautical Congress (IAC). Bremen*

2. ESA, "DIVE – Guidelines for testing and analysing the demise of man-made space objects during re-entry", ESA-TECSYE-TN-018311, 2019.