OBJECTIVES AND ACHIEVEMENTS OF THE SPACE DABRIS MITIGATION PROJECT TEMIS-DEBRIS

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ABSTRACT

In January 2024, DLR launched the project TEMIS-DEBRIS (Technologies for Mitigation of Space Debris) with a focus on development of technologies for removal of spacecraft via uncontrolled re-entry at the end of their life, including the design of a sustainable satellite.

In the early phase of the project a system and mission study considering different types of satellites missions has been carried out. Two satellite missions were selected as reference cases representative for their respective categories.

To increase the demisability of the reference satellites and their critical components, multiple measures have to be combined. Therefore, concepts like demisable joints, modified matrices for fibre-reinforced composite structures and coatings that augment aerothermal heating are developed, investigated and qualified in the project.

1 INTRODUCTION

Sustainable space flight, reaching from the design and manufacturing of spacecraft and rockets, over space operations and to disposal of spacecraft at the end of their mission, belongs to the core interests of the German Aerospace Center (DLR e. V.). Complementary to this development, in January 2024 the TEMIS-DEBRIS (Technologies for Mitigation of Space Debris) project with a focus on development of technologies for removal of spacecraft with an uncontrolled re-entry after their life time and design of a sustainable satellite was launched. In the early phase of the project a system and mission study considering different types of satellites missions has been carried out. Two satellite missions were selected as reference cases representative for their respective categories: the small DLR satellite Eu:CROPIS and the larger ESA mission EarthCARE. Eu:CROPIS is a small greenhouse experiment with a mass of 230 kg in sun-synchronous orbit at 600 km and offers the advantage that DLR has insight into the complete data of the construction and mission and, apart from information concerning the few parts affected by ITAR, can also use and publish it freely. For ESA's EarthCARE mission, a 2200 kg Earth observation satellite in a 393 km low earth orbit, DLR does not have access to the design data. The satellite is roughly replicated based on publicly available data.

As the project applies a multidisciplinary approach, versions of the models are created with varying level of detail. A coarse model of the outer shell with the most relevant components only is used for the simulation of aerodynamics, thermo-mechanical coupling and multi-body flight dynamics. Concepts for increasing demisability of metallic structures by means of new coatings and modification of matrix properties of CFRP materials have been developed and first test campaigns have already been carried out.

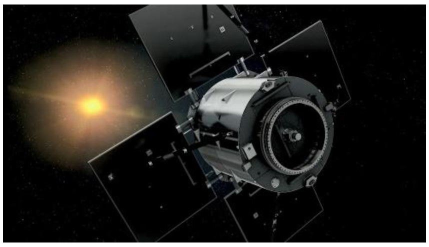
2 REFERENCE CONFIGURATIONS

One of the first tasks of TEMIS-DEBRIS was the creation of the baseline models of the reference satellite configurations. These need to represent the physical composition of the investigated satellites with positions, dimensions and masses of their subcomponents with sufficient detail, so that all models for the other tasks can be derived from these references.

AS mentioned above the two chosen configuration are ESA’s EarthCARE and DLR’s Eu:CROPIS missions. The former represents the class of large satellites, i.e. with a mass above 1000 kg, while the latter serves as a reference for mini satellites with a mass between 100 and 500 kg [1]. Rendered artistic images of both satellites are depicted in Figure 1.

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

a) EarthCARE [2] © ESA

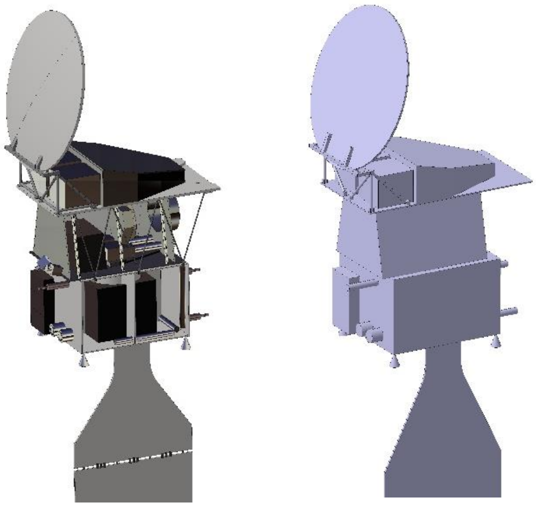


b) Eu:CROPIS [3] ©DLR

Figure 1. Artist's renderings of the reference configurations

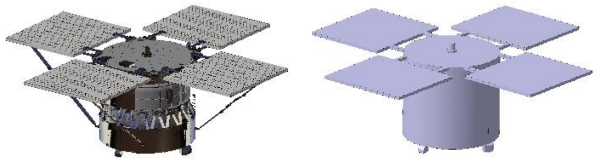
It has been decided that for each satellite, two baseline models would be created: a simple one and a detailed one. The simple baseline model focuses on the outer shell of the satellite and simplifies its geometry to the aerodynamically relevant elements. This model is used for generating the meshes for the CFD simulations of the satellite aerodynamics and aerothermodynamics. The detailed baseline model recreates both the outer shell and internal structure of the satellite down to small components. This is required for both the coupled CFD-thermomechanical simulations and the flight dynamics and aerothermodynamics during demise and simulations of multibody aerodynamic interactions. The representation of the reference satellites in ESA demise prediction software DRAMA is also derived directly from the detailed baseline.

The smaller satellite configuration, Eu:CROPIS, had been developed by DLR, so a CAD model with full details was available within DLR. Based on this model, a coarse one was straightforward to derive. However, the bigger configuration, EarthCARE, had been designed by ESA; therefore, both models had to be recreated based on the publicly available sources. This, in turn, translated to a lower detail level than in Eu:CROPIS, nevertheless deemed enough for the flight dynamics analyses. Both sets of models are depicted in Figs. 1 and 2. The recreated EarthCARE model has the total length of 17,6 m (with its solar array), and 1,6×3,0 m² envelope (largest plate); the model's total mass equals 2350 kg. Eu:CROPIS has the span of 2,9 m (with solar arrays), whereas its main, cylindrical part has the height of 1,1 m and diameter of 1,0 m; its mass equals 234 kg.



a) detailed b) simplified

Figure 2 Detailed and simplified models of EarthCARE



a) detailed b) simplified

Figure 3 Detailed and simplified models of Eu:CROPIS.

The models utilise a fixed set of reference materials, i.e. there is only one reference steel alloy, one reference CFRP, etc. Materials that are common in satellite design and which have been investigated in previous D4D projects were selected. This means that exhaustive laboratory data on the thermophysical properties of these material is available and their demise behaviour in the destructive simulations is already known. Regard that it is not our aim to exactly recreate the reference satellites. The main goal of the TEMIS-DEBRIS project is to improve the demisability of the actual satellites. These reference missions are only needed for demonstration of the Design for Demise (D4D) solutions, which are actually under development. Accordingly, the satellite geometries and materials can differ from the real satellites and are altered where required. For example, solutions for making CFRP more demisable cannot be demonstrated on metallic parts. Therefore, specific partially scientific solutions are developed and verified, even if it would not directly relevant for real flight missions.

3 D4D-TECHNOLOGIES UNDER DEVELOPMENT

Publicly funded design-for-demise projects and development efforts performed by space businesses typically aim at optimising or redesigning a single, specific component (e.g. a specific reaction wheel or tank). These projects consequently ignore generic D4D technologies that may allow improving many different components but require some investment in ground research first to make those solutions feasible. TEMIS-DEBRIS does not use this common approach: instead, the basic idea behind the project is to concentrate on investigating such generic solutions to overcome the high initial development efforts for a first implementation and thus make them usable for the demise community. By doing this, we provide these D4D technologies as a tool for other people to use on their specific components for demisability enhancement.

We therefore only investigate approaches for making spacecraft and parts more demisable, that can be applied more or less universally and thus have high application potential. These approaches don´t necessarily address component demisable, but may also optimise other aspects of the spacecraft and its decay to make a relevant contribution to the ground risk. Technologies applicable only to rarely used components or specific cases or that have to be taken into account at great expense when redesigning hardware are therefore not of interest in this context. Furthermore, the approaches shall have a low negative impact on the overall system (e.g. minimal increase in structural mass and no requirement for additional safety measures) and the integration cannot be a major effort or incur significant costs when being implemented.

The concepts investigated in the project for improving demisability utilise different mechanisms of action and address different parts of the satellites. They are briefly highlighted in the following.

3.1 Demisable materials

There are many materials commonly used in the space industry, that are not generally impossible to demise, but often make specific components non-demisable. Prominent examples are titanium alloys and stainless steel, which both can be sufficiently demisable if used for smaller parts, but become non-demisable if the parts made from these metals are heavy and/or have a low ballistic coefficient. Another prominent example is the fibre-reinforced plastic composites. These composites start demising at low heat fluxes and temperatures, but the demise process consumes high amounts of energy per mass, which often makes them practically non-demisable in the short hot phase of the entry flight. Addressing these materials with generic measures to improve the demisability is very promising, as it would allow shifting the threshold where these materials become a problem to larger or heavier parts or parts with a worse ballistic coefficient.

We investigate three approaches to achieve this. The first approach is optimising the surface properties: by application of coatings to the surface of the material, we achieve lower thermal emissivity, thus reducing the heat loss by thermal radiation. Furthermore, the coatings under development increase the catalytic efficiency of the surface, which helps the gas in the vicinity of the surface approaching the local thermal equilibrium. This reaction releases the chemical energy and boosts the incident heat flux. Both the reduced emissivity and the increased catalytic efficiency allow the material to receive a higher net heat flux, which accelerates the heating process and increases the temperature of thermal equilibrium. Regard, though, that the coatings may decay or get lost when the bulk material starts decaying. In this case, the coating mainly allows a component to start demising earlier, but will not necessarily help during the recession if lost completely. In case of materials, where the melting process removes the oxide skin and thus reduces the thermal emissivity, locally triggering the melting can be enough to make the complete part demise quickly. In such cases, the loss of the coating with beginning demise does not prevent the positive effect of the coating. This behaviour has been confirmed experimentally on different metals, but there are metals that do not show this phenomenology. Accordingly, metals in general and stainless steel in particular are the main target for enhancing demisability by the developed coatings. The solution can be sufficient to make components, that are on the edge of being demisable if untreated, just demisable enough to not pose a ground risk. The coatings are easy to apply, thin and light and should not interfere with the function if used on non-functional surfaces.

The second approach for material demisable improvement investigated in the project is the idea of in-situ-alloying: by adding an element or material that reacts with the base metal to form a eutectic with lower melting point, the base metals demisability can be enhanced significantly. The amount of heat lost by thermal radiation scales with the forth power of the temperature, so even small changes to the melting point can have a relevant impact on the critical heat load required for the demise. However, this approach does come with two major problems: diffusion is a rather slow process, which limits the applicability to rather thin-walled objects, and there must be a well-suited eutectic for the base metal. This eutectic needs to have with a significantly lower melting temperature than the base metal, a sufficiently high diffusion rate and the required mass fraction of the added alloying element must be low or the addition of the alloying partner will be prohibitively heavy. It goes without saying that this combination of properties is rather rare. Accordingly, thus far, the only promising application found for this approach is titanium and its alloys. Titanium alloys are often used for thin objects, such as thin-walled tanks, and often make these parts very hard to demise. Furthermore, there are attractive eutectics with titanium, some of which reduce the melting point to below 1000°C while requiring small amounts of the alloying partners and showing promising diffusion speeds. Demonstration of the in-situ-alloying has been conducted a several times, both on purpose and by accident, but a dedicated investigation of the effect, the best-suited alloying elements, the amount being needed for best operation, the influence on the development of the surface etc. are outstanding and will be investigated in detail in the project.

The third approach for enhancing the demisability by optimising the material, and not the part made thereof, is to make carbon fibre reinforced composites ablate faster. Composites with organic matrixes typically start demising at low heat fluxes and temperatures, but the extreme amount of heat absorbed during the process is a problem. In case of demise resistant carbon fibre composites, the main reasons is the material remaining solid after thermal decomposition of the matrix. This prevents the refractory fibre form being blown away, so the recession is limited by the slow oxidation of the carbon. In the entry flight environment with its low pressures, this process can be very slow. We therefore focus on improving the composites demisability by making the materials delaminate and disintegrate mechanically. There is experience on composite behaviour in experimental entry-flight simulations from several ESA and EU studies. The COMP2DEM project in particular was very successful in screening the impact of different composite properties on the material demisability [22]. Furthermore, the obvious solution – using a matrix with sufficiently low residue after thermal decomposition to release the dry fibres – has been demonstrated in that project. However, the limited budget did not allow to try all interesting parameters and concepts identified back then and there are still interesting ideas. Thus, the development of demisable composites in this project does not focus on a single concept but is a screening of different solutions. The selection of composite formulations to investigate experimentally has not been finalised yet and will be reported in future papers.

3.2 Demisable structures

Structures of particular interest for the design-for-demise are the ones that combine significant demise resistance, potential to improve their demisability and a widespread use in the space business. Two outstanding types of structures were found and will be investigated in the project: sandwich panels made with composite facesheets and larger silicon carbide structural parts.

Sandwich panel with composite facesheets are not non-demisable per se, but they tend to delay the demise process and an earlier demise, especially in case of the outer closure panels, is highly desirable. Aluminium facesheets are obviously an alternative to composite facesheets with excellent demisability, but the unique properties of composites, in particular the high stiffness achievable with high-modulus carbon fibres, are often demanded by the given application. As a potential solution to improve the demisability of carbon fibre composite whiteout omitting the material properties, hybrid composites combining carbon and flax fibres are investigated. The idea is to leave the composite structurally intact while introducing predetermined breaking points. The natural fibre flax is hoped to show good demisability and to weaken the composite during the thermal decaying. However, organic fibres that effectively become carbon fibres during their thermal decomposition were observed before, so the potential positive impact remains to be determined by experimental simulations.

Silicon carbide is often used for its outstanding thermal and mechanical properties: the material is dimensionally stable, has a thermal conductivity and stiffness and reacts chemically inert under most circumstances. This qualifies the ceramic for mainly for optical uses, e.g. for optical benches and mirrors, but there are parts made from this from this extraordinary material in many different forms, sizes, weights etc. The material is resistant in chemically and thermally aggressive environments, but it is brittle and mechanical fracturing by thermally induced stresses is common and design for mechanical fracturing in sufficiently small pieces may be a solution to this otherwise non-demisable material. There is little experimental data on material made by additive manufacturing and on light-weight sandwich structures, so an investigation by experimental entry-flight simulation will be conducted first. If the data suggest that a design for mechanical fracturing by thermal stresses is feasible, structures with enhanced mechanical demisability will be designed and tested to confirm the feasibility of this idea.

3.3 Demisable joints

An early opening of the outer shell of a satellite is often beneficial to demisability, as this allows the interior to be heated early. This way, the internal components are not released cold, which obviously helps with their demise. Ensuring that a satellite opens up early is thus often one of the measures taken to make the satellite meet the demisability requirements. This requires technologies for triggering the opening process early in the entry flight (i.e. at low temperatures), that must not pose a risk to the mechanical stability and functionality during start and orbital mission. Demisable joints are a solution to this. The positive impact on the demisability on system level can further be improved by not just opening the satellite, but by designing the process of fragmentation. Furthermore, it may be beneficial for some joint to stay intact for longer or up to higher temperatures, so demisable joints with tuneable triggering temperatures are a desirable solution.

There have been different ESA projects studying demisable joints [20, 21] and at least one project is currently ongoing. These studies included many different approaches to making joints demisable and some of the concepts have already been demonstrated to operate successfully in experimental simulations. However, there are many joints on a satellite that need to be detached to open up a satellite. Thus, a demisable joint solution can add only a small mass to the connection or the mass penalty will be prohibitive, it cannot be expensive, it should not require complex redesign of the joined parts and must be very reliable etc. In consequence, none of the solutions developed thus far made it beyond the conceptual phase, as they all had their own drawbacks.

We investigate three different concepts for creating demisable joints. One of them changes the inserts in sandwich panels, but keeps the fasteners [23, 24], the other two concepts do not require adaptation of the inserts or parts being attached and address the fastener itself to make it a drop-in replacement. We believe that this approach will make the threshold for using the demisable joints sufficiently low for them to actually be applied on real spacecraft.

3.4 Semi-passive separators

Besides using demisable joints, the opening of a satellite can also be achieved by brute force: we investigate whether cable cutters and shaped charges can be an attractive and cost-effective solution to improving demisability on both system and component level. Shaped charges would not be limited to removing the outer closure panels, but could also cut component like titanium tanks to make the demisable enough.

Unfortunately, the semi-passive separators have their own very specific problems. Any solution for improving the demisability must be feasible for the complete system or it cannot be used. However, these solutions use explosives, so a deeper system study is required to capture aspects that don´t need to be regarded for the other D4D concept. For example, the safety during handling on the ground and the potentially reduces satellite reliability (e.g. ignition of the separator by micro-meteoroid impact) need to be considered. Thus, the semi-passive separators will go through both experimental investigation and a thorough system study.

3.5 Component-specific approaches

Finally, we address two types of components. While this opposes the general idea presented in the beginning of this chapter, we believe that generic solution for the two types of components will be applicable for many implementations, so they are worth investigating.

The first component type under investigation is electronics. While electronics are obviously a very dissimilar component group, they are usually very similar regarding their demisability and potential for high ground risk. The problem with common electronics in the space business is, that they typically consist of an aluminium alloy housing and printed circuit boards made from glass fibre-reinforced epoxy matrix or GFRP. The housing melts easily during the entry flight, thus releasing the individual cards. And these GFRP cards have a very high demise resistance. The integrated circuit chips, resistors, capacitors etc. on the electronic cards can have a high demise resistance, but they have been found to usually be small enough to not pose a risk by themselves with some exceptions (e.g. larger transformers) [19]. Accordingly, the main problem with the electronic is the demise resistance of the GFRP. The behaviour of this composite is in many aspects comparable to that of CFRP, but there is one very important difference: the glass fibre is not refractory and does show melting or sintering, depending on the experienced fluxes and temperatures. Unfortunately, this means that a matrix that fully decomposes and releases the fibre was found to not make the composite delaminate, so there are different approaches needed to make GFRP demisable. We will investigate a substitute to the glass fibre that does not show the melting and sintering and we will apply the solutions found for CFRP on GFRP to try and make the material decompose mechanically.

The other component type addressed is batteries. Independent of the cell chemistry, batteries typically consist of individual cells contained in a stainless-steel shell, that are bundled by GFRP cards of PEEK pieces and contained in an aluminium housing. The housing obviously is not an issue in terms of demisability, but both the cells and the plastic or composite parts holding them together were found to be a problem [19]. Furthermore, the experimental data on demise behaviour is very poor and limited to Lithium-Ion-Cells. We will thus first investigate the demise behaviour of different cell chemistries and geometries. There is a new state-of-the-art in high-density battery packs in the car business, that is also very promising for future application in space: densely packed pouch-cells in an aluminium housing. This is very promising regarding the batteries demisability, so we will proceed with testing of such battery systems.

4 QUALIFICATION TESTS

The developed D4D technologies will go through destructive entry-flight simulations in the arc heated wind tunnels of DLR in Cologne. The developed technologies are meant to operate during different phases of the entry-flight and are used on different parts of the satellite. For example, the demisable joints are to be used on the outer structure and operate early during the flight, while they are exposed to low heat fluxes and temperatures. Other solutions, e.g. the in-situ-alloying of titanium parts, address components that are released later and experience higher loads. Accordingly, the dissimilar D4D concepts need to be exposed to different conditions. We therefore use the flexibility of the L2K to produce test conditions with low to medium heat fluxes and stagnation pressures and the L3K for those cases where high heat fluxes and pressures are required or the sample size demands a larger flow diameter. Figure 4 shows a functional sketch of the arc heated wind tunnel facilities. For additional information please refer to [16-18].

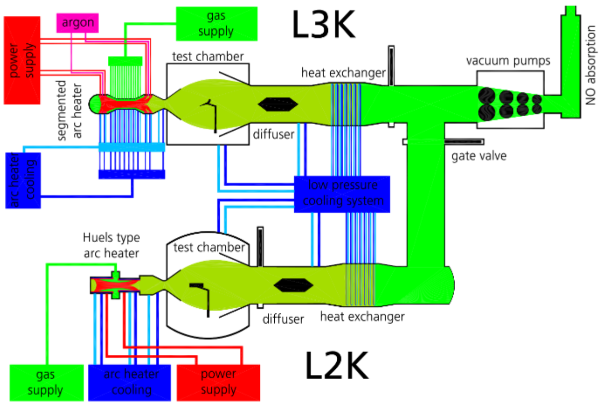


Figure 4. Sketch of the LBK facilities.

The experimental investigations focus on the operation of the concepts at realistic loads. It is not our goal to investigate or demonstrate the demisability of specific components or to bring a proof of demisability. We therefore use simple, stationary test setups with constant flow conditions.

For the D4D solutions that address the demisability of materials, this means that DLRs standard setup for material testing is used. This setup uses cylindrical samples oriented perpendicular to the flow to produce axially symmetrical conditions that can be reduced to a single dimension on the rotation axis. Figure 5 gives an idea of the material testing setup.

Figure 5. Stainless-steel sample tested in L2K

Other concepts either use the same simple standard, e.g. the ceramic sandwich panels were bolted to a material setup holder, or a similar static setup for positioning the sample in the flow. Figure 6 exemplarily shows the setup used for the testing of battery cells. In this case, a steel frame (grey) holds two bars made from insulative porous ceramics (white) into which the battery cells (green) are places. The setup ensures that little heat is lost by conduction to a colder holder, so the amount of heat released by a thermal runaway in the cells can be quantified via the measured temperature curves.

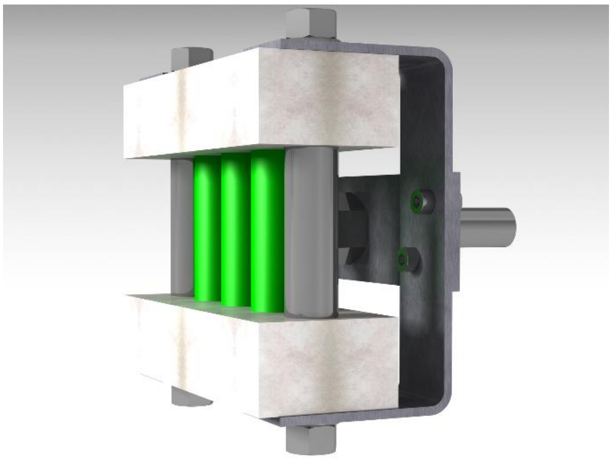


Figure 6. Rendering of the battery cell setup.

The instrumentation during the destructive simulation includes HD cameras, infrared cameras, pyrometers and thermocouple sensors. The HD cameras provide a visual footage and an overview of the demise process, which is of highest interest for interpretation of the phenomena occurring during the demise. The infrared cameras together with the pyrometers provide the temperature distribution on the surface of the sample and an estimation of the thermal emissivity. They are complemented by thermocouples attached to the rear of the sample or integrated into the sample, depending on the specific needs. The thermocouples provide insight into the internal temperatures and act as a reference for the temperatures measured remotely.

The tested samples go through dedicated post-test investigations. For example, the oxides formed on the surface of the samples with D4D coatings are investigated after the wind tunnel test and the elemental distribution is measured give insight into the diffusion processes. The post-test investigations are diverse and very specific to the technology tested, so they are not provided in detail here.

5 COUPLED AEROTHERMAL AND THERMO-MECHANICAL SIMULATION

The prediction of the heat input by the aerothermal loads during re-entry, its transport into the interior and the resulting distribution of the temperature in the structural components are of great importance for the selection and evaluation of suitable methods for enhanced demisability. Simulation tools based on simplified models for structure and flow features are essential to estimate a satellite's behavior along a spread of possible reentry trajectories, simulate the breakup process and vary design and state parameters fast during the design phase or as basis for e.g. statistical variations. For a detailed view on the behavior of specific parts or the systematic affection of structural components, a more detailed investigation of the thermal behavior of a satellite is needed, that considers variations of the aerothermal heat loads that occur locally and over time along the reentry trajectory. In the TEMIS-Debris project the temperature distribution in the satellite structure obtained from the simulations described below will be used to help design demisable joints [7], that will open parts of the outer structure at specific trajectory points to increase the thermal loads onto critical parts, such as inner electronics.

5.1 Subheadings

To simulate the transient interaction between the aerothermal loads and the heating of its structure, a coupled portioned method between a computational fluid dynamics (CFD) code and the structural analysis (CSM) software Ansys Mechanical is being used.

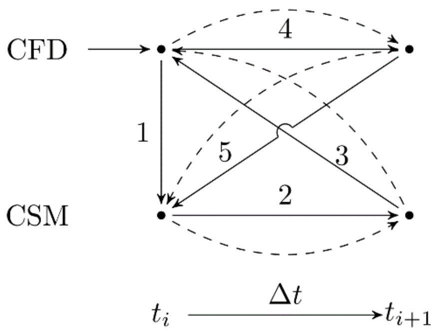


Figure 7. Schematic description of the coupling procedure

Fig. 7 shows a schematic overview of the partitioned solver coupling procedure that is applied to proceed from time step t_i to t_{i+1}. In a first step the flow solver computes the aerothermal loads which are interpolated onto the structural domain (1). The CSM solver uses these as Neumann boundary conditions and computes the structural temperatures (2, predictor step) which are interpolated to the fluid domain (3) and set as Dirichlet boundary conditions in the latter. The flow solver then proceeds to time step t_{i+1} (4) and returns the updated loads to the CSM domain at the preceding time step (5). Based on this updated information at least one corrector loop (dashed lines, analogue to 2, 3, 4) is calculated. The difference of the norm of the temperature vector of two consecutive inner loops is used as convergence criterion to ensure the partitioned simulations comply.

To enable the coupling procedure between the partitioned domains (here: CFD and CSM domain) the involved solvers have to exchange boundary condition and results data. The FlowSimulator is a modern framework that provides functionalities to efficiently exchange all data between the solvers (for more information and application examples see [8][9]) Instead of the classical approach to define interfaces between all solvers that require data exchange, each solver is integrated into the FlowSimulator as a plugin including a control layer to control the simulation steps and data interfaces to access boundary condition and solution data. While the CFD solver TAU provides a native interface to be accessed via the FlowSimulator control layer and exchange data with the FlowSimulator DataManager (FSDM), a similar interface has been implemented to use Ansys as a FlowSimulator plugin. The interface provides boundary condition data and APDL scripts for control over the time stepping procedure that can be processed by Ansys during each solution step. For the import of the mesh and solution data the interface uses the pyansys module [10].

5.2 Flow Simulation

The described partitioned domain approach, especially in combination with application in the FlowSimulator environment, has the big advantage over monolithic or other coupling procedures, that all solvers involved can easily be exchanged by alternatives without affecting the functionalities of the respective other domain. For the current work this is especially useful for the calculation of the aerothermal loads, since the satellite passes a broad range of atmospheric density from the re-entry onset, defined at 120km altitude within the project, up to the expected breakup at approximately 80km. The DLR-TAU code will be used to simulate the flow in the lower altitude range. TAU is a finite volume Navier-Stokes solver that is capable to model chemical reactions between multiple species, thermochemical nonequilibrium [11] and a slip-flow boundary condition [12]. By application of these models it is possible to adequately simulate the aerothermal heating of re-entry vehicles as shown for other configurations [13]. However, for sufficiently high altitudes and therefore low densities, the mean free path is in the same order of magnitude as the characteristic length scales. For these high Knudsen-number regimes the continuum assumption for the fluid is no longer valid. Ertl et. al. have recently given a vivid comparison of simulations using the continuum (DLR-TAU) and particle based methods for a generic upper stage [14]. The Focker-Planck extension of the DSMC code SPARTA [15], described by the authors, is planned to be used for simulation of the aerothermal loads in the early re-entry phase. To enable the combination of the mentioned different modelling approaches and to account for the different orders of magnitude in the time scales of the flow and structure, the solvers are not coupled directly, but via a database approach. For distinct points along the trajectory the flow is being simulated with different isothermal wall boundary conditions using the solver and setup best suited for this trajectory point. By stepwise global (flight parameter along the trajectory) and local interpolation (temperature on the surface) the local heating rate is then calculated from the database and returned to the FEM model. This procedure has proven to work reliably [13], allows for the maximum flexibility in the choice of the solver and enhances the simulation performance significantly.

For creation of the database simulations of the flow around the Eu:CROPIS satellite are currently performed using the DLR-TAU code. At the time of publication of this work, they were not completed and will therefore be shown and discussed in a later publication. Fig. 8 shows a preliminary result of the flow obtained from a simulation using the DLR-TAU code. The iso-surfaces of the density gradient magnitude (grey) visualize the shock positions. Due to shock-shock and shock-boundary layer interactions the shock forms complex patterns that also lead to strong pressure-, and hence also heat flux, variations on the satellites surface.

5.3 Structure Simulations

The Eu:CROPIS satellite has been chosen as first simulation case due to its relevance as described in Section 2 and additionally because a detailed CAD model was available for internal use. Based on this model a thermal model of the complete satellite was generated in

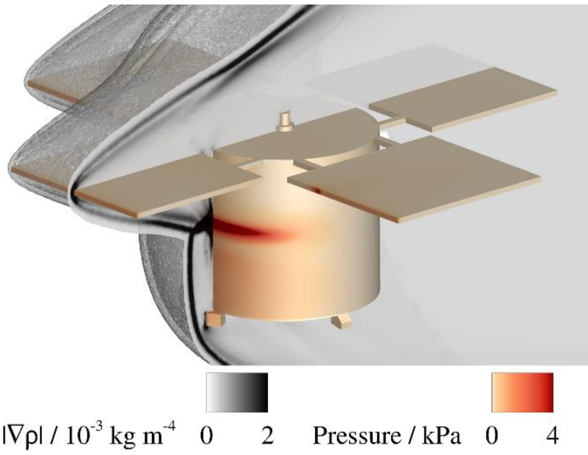


Figure 8. Shock structure and surface pressure obtained from a simulation of the flow around the Eu:CROPIS satellite

Ansys Mechanical. Fig. 9 shows an exemplary result of the heating simulation with the outer shell of the model partly cut open to display its inner structure. Aside from general simplifications, such as partly removed roundness, neglected screws, nuts and respective holes, the following major assumptions were made to simplify the model to an extent feasible for transient simulation.

1. The Eu:CROPIS payload was modelled as a homogeneous torus with mean values for heat capacity and thermal conductivity derived from integrated values of the subcomponents.
2. The CFRP pressure tank surrounding the Eu:CROPIS payload has been neglected. The structure is very thin and has an extremely low heat capacity. Apart from its expected low influence on the thermal inertia, this also implies that the radiation is transported towards the massive inner structure without an additional barrier.
3. Main body (as shown in Fig. 5) and solar panels are expected to be thermally decoupled. I.e. the solar panels are not modelled in this simulation stage. This assumption seems reasonable, since the solar panels are connected to the main body by thin CFRP structures that are expected to conduct no significant heat.

Aside from these simplifications and general assumptions, all structures and components have been resolved for the structural simulation. The resulting model contains 2.57 million second-order elements and takes into account surface-to-surface radiation between the largest internal surfaces.

To test the model, gain first simulation results and as a basis using the simplest aerothermal heat flow assumption, a uniform heat flux has been applied to the outer boundary surfaces that varies with the simulation time. Based on the orbit parameters of a typical re-entry trajectory, the resulting stagnation heat flux and the projected area theorem, the heat flux is in the order of 10 kWm^{-2} for a significant time of the early re-entry phase and then start to rapidly increase below an altitude of approx. 100 km. For this later phase, the influence of the flow pattern discussed in Section 5.2 is expected to dominate the structural heating transient.

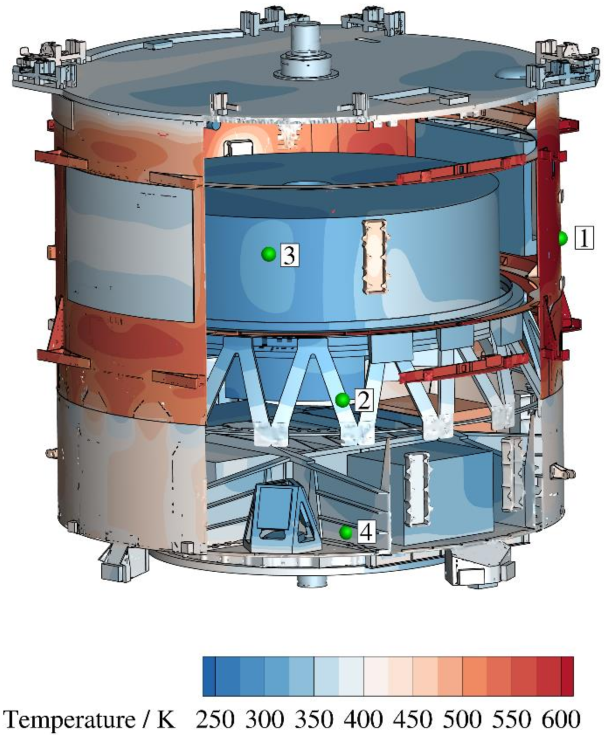


Figure 9. Result of the heating simulation of the Eu:CROPIS satellite

An exemplary temperature distribution obtained from the simulation is shown as colour on the surfaces in Fig. 5 for t=200s. As expected, the thermal conduction into the inner volume can be observed e.g. by locally alternating hot and cool spots on the outer shell where the ribs of the payload adapter cone are connected. Another general observation is the considerably lower temperature in the bus structure at the lower third of the model, due to the high volume and thermal inertia of the attached stiffener and electronic components. At the four positions marked with the green spheres in Fig. 9, the temperature has been read from the simulation domain. Fig. 10 shows these nodal temperatures over the simulation time.

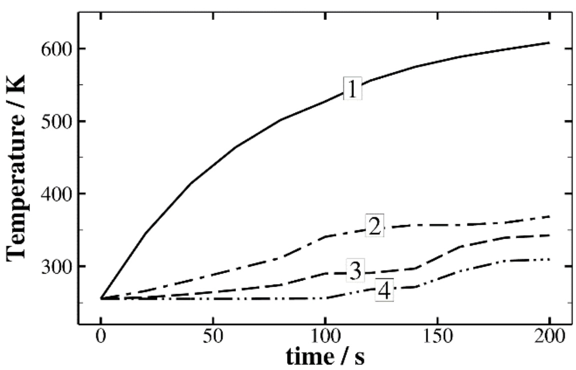


Figure 10. Temperature history of the marked nodes

Node 1 is located at the thin outer aluminium shell. This part of the structure has a comparatively low volume, is fully exposed to the external heating and all absorbed heat must either be conducted through the thin wall or emitted through radiation. As a result of these conditions the temperature rises rapidly and within the timeframe of the simulation this node is close to reaching its radiation equilibrium. Nodes 2 and 4 show a significantly slower rise in temperature since, due to their position, the main transport process at these positions is conduction through the surrounding solid parts. In contrast to that Node 3 is connected to the heated outer shell though a rather long path. As can be observed by the missing local influence of the adapter cone attachment points, the inner payload torus is mainly heated by radiative heat transport. However, the temperature history in Fig. 6 (Node 3) shows that in this region and for these large surfaces the radiative heat transfer is efficiently warming the inner structure to some extent.

6 FUTURE WORK

First concepts for increasing demisability have been developed and test models are in the manufacturing process. First qualification tests in the arc heated facility L2K show very promising results for the improvement of these concepts and delivery of validation data for numerical simulation of demise prediction.

A further activity started recently is the investigation of aerodynamic and flight dynamic interaction of fragments during atmospheric re-entry flight. Free flight tests in the hypersonic wind tunnel H2K and their numerical rebuilding are part of this activity.

Furthermore, the impact of demisable structures solutions on the overall satellite system will be analysed in a dedicated Concurrent Engineering Session.

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