SCARAB4 – EXTENSION OF THE HIGH-FIDELITY RE-ENTRY BREAK-UP SIMULATION SOFTWARE BASED ON NEW MEASUREMENT TYPES

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ABSTRACT

The high-fidelity re-entry break-up simulation software SCARAB (SpaceCraft Atmospheric Re-entry and Aerothermal Break-up) is currently being upgraded with new models for aerothermodynamics and material ablation. The capabilities of SCARAB are extended to improve the support of Design-for-Demise (D4D) methodology modelling and uncertainty quantification. A set of newly implemented features for the so-called measurement evaluation support (MES) provide the functionality to rebuild static flow conditions of wind tunnel experiments and Computational Fluid Dynamics (CFD) simulations and extend the SCARAB re-entry simulation with options for fixed attitude and reference trajectory input.

The new models implemented are validated with recent data from wind tunnel experiments, re-entry observations and CFD, using the new MES capabilities.

This paper provides an overview on the new SCARAB models and extended functionality.

1 INTRODUCTION

According to ESA regulations, compliance with the ESA Space Debris Mitigation Compliance Verification Guidelines has to be demonstrated. For a first assessment, ESA's DRAMA suite, including the so-called object-oriented re-entry code SESAM, has to be used to assess the casualty risk. In later stages, spacecraft oriented, i.e. high-fidelity, codes can be used for ground risk assessment [1].

SCARAB 3.1L [2], ESA's current high-fidelity re-entry break-up simulation code, has been released a decade ago and the development of the SCARAB core routines reaches back 25 years. Back then, the models and approximations implemented were limited by computational power, as well as the limited data available on heating and ablation of different materials used in spacecraft construction.

Recent experiments on different material samples in wind tunnel tests and other testing facilities provide significantly increased data of material behaviour, including ablation and oxidation, at high temperatures and under re-entry-like conditions. Newly developed, proof-of-concept models for re-entry simulations have been generated, e.g. for SAM [3] and through the support by computationally intensive methods, like CFD simulations, the development and validation of aerothermodynamic models in simplified (w.r.t. CFD) codes can be supported.

During the recent years, several limitations of the current generation of re-entry simulation codes have become apparent, especially w.r.t. the modelling of Design-for-Demise techniques, the simulation of very large structures, where shock-shock and shock-structure interactions play a role, or re-entries from highly eccentric orbit, where radiative shock heating can be significant.

DRAMA's re-entry and risk analysis modules have been upgraded in the past years [4], implementing up-to-date methods and more sophisticated ablation models, combined with the option for Monte-Carlo simulations enabling the variation of a large set of parameters. However, the use of a spacecraft-oriented code is still an important step in the process of ground risk compliance verification and object-oriented re-entry codes need to be validated against data and simulation results generated with higher-fidelity tools, i.e. spacecraft-oriented simulation codes or CFD data. CFD simulations are very complex and need significant computational power. Thus, they are not applicable for the simulation of heating and break-up for a whole spacecraft. Considering the recent advances w.r.t. re-entry related experiments, observations and models, an upgrade of the current

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spacecraft-oriented ESA code, i.e. SCARAB, is inevitable.

The objective of the activity is to upgrade and extend the current SCARAB (3.1L) to improve the calculation of the re-entry casualty risk, considering recent data and results obtained from CFD simulations, re-entry observations and experimental testing on materials and material response under re-entry conditions.

2 AERTHERMODYNAMICS MODEL

The heating mechanisms considered in the aerothermodynamics (ATD) model of SCARAB are

- Convective heating
- Radiative shock heating
- Shock-boundary impingement on large objects
- Internal radiative heat exchange
- Internal conduction between parts (not discussed here)

2.1 Convective shock heating

Convective heating is the standard heating mechanism considered in all re-entry codes. In SCARAB 3.1L a local flow inclination method was used in all flow regimes (free-molecular to continuum). With the new approach, a non-local method is used for the continuum regime, while keeping the appropriate local approach for the free-molecular regime. In the transitional regime still a bridging method is used, hence keeping the approach near-local in the free-molecular regime and non-local in the near-continuum regime.

The convective heating formulas are based on the boundary layer equations, which are considered as a compromise between a comprehensive, but not computationally affordable (e.g. Navier-Stokes) and a too simplistic approach like the pure local inclination method. Key parameters of the new method are the effective radius of curvature, which scales the order of magnitude of the heat flux, and the streamline length, which determines the local heat flux distribution. In SCARAB the surface of a modelled satellite is built of many small triangular panels. For each panel the streamline is traced upstream, based on the directions of the incoming free stream and the local surface direction (Figure 1), until a stagnation point is found. In this way the streamline length is determined. At the stagnation point the local radius of curvature is determined by the variation of the panel normal directions around this point. Special considerations are taken for the case that the geometry at the stagnation point is flat or concave.

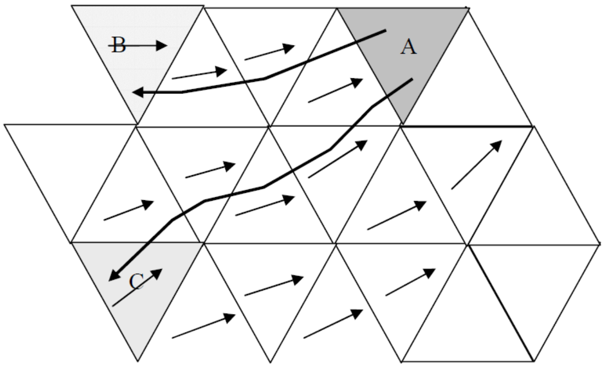


Figure 1: Streamline tracing by backward marching

2.2 Radiative shock heating

SCARAB was originally developed for the examination of re-entries from Earth orbit. It was later extended to Martian entries. It was not designed for super-orbital-velocity entries (above 8 km/s in Earth orbit), which may occur after a planetary mission nor for a return from a highly eccentric orbit. In such cases the thermal radiation of the shock in front of the entering spacecraft to the spacecraft can become significant and was therefore considered in the new version. The Brandis-Johnston model [5] is now implemented to compute the stagnation point and lateral heat flux distribution.

2.3 Shock boundary impingement on large objects

Re-entry codes are in general developed for relatively simple-shaped objects. Extended structures were considered in recent code updates e.g. of DRAMA and SAM in a heuristic manner. In SCARAB it is possible to construct and consider the interaction between the stagnation-region-induced shocks and the structure downstream with a local approach. The shock wave shape is computed by using the blast wave analogy. The computed shock wave intercepts the structure in certain regions, which can be localized by the software automatically. The missing information about the enhanced heating at intercept was derived from numerical experiments performed by IRS Stuttgart [6]. This database is undergoing upgrades, e.g. by evaluating the results of the R.Tech CFD SSI test case.

2.4 Internal radiative heat exchange

Besides of the external heating mechanisms there was one internal heating mechanism not considered so far in SCARAB yet, namely the heat re-radiation. While it was already coded in early times (i.e. 20 years ago) it was not actively used due to its demanding computation requirements. During the last 20 years the computing power has increased considerably, but according to test calculations, the inclusion of re-radiation does not appear out of reach, but is still demanding. The main effect of the re-radiation is that it cools the hot regions and warms the cold regions which in turn effectively delays the fragmentation process. This effect is going to be examined in test calculations.

2.5 CFD support for ATD model validation

To support the validation of the new SCARAB ATD model and supplement available CFD data (which is limited to simple shapes), a set of CFD computations has been performed by R.Tech, using the MISTRAL CFD flow solver. A total of four geometries have been simulated for different angles of attack, to provide averaged heat flux and pressure distributions. The geometries include a cylinder (Figure 2), a hollow half-sphere (Figure 3), a simplified satellite shape (Figure 4) and a shock-shock-interaction (SSI) case (Figure 5). The validation matrix w.r.t. specific phenomena simulated by the SCARAB ATD model is shown in Tab. 1.

	Cylinder	Hollow half-sphere	Satellite	SSI
Local heating effects, off-stagnation point & edge heating	X	X	X	X
Concave shapes		X		
Shock boundary impingement			X	X

Tab. 1: Validation matrix: SCARAB4 ATD model phenomena and CFD cases simulated by R.Tech

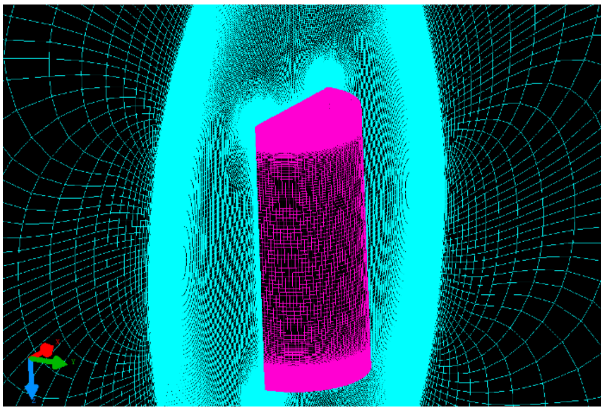


Figure 2: R.Tech CFD: Cylinder mesh

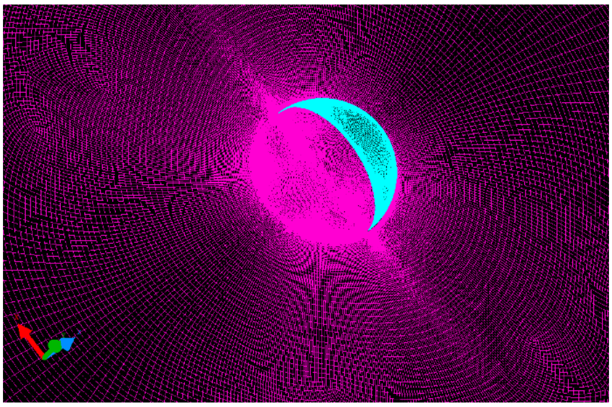


Figure 3: R.Tech CFD: Hollow half-sphere mesh

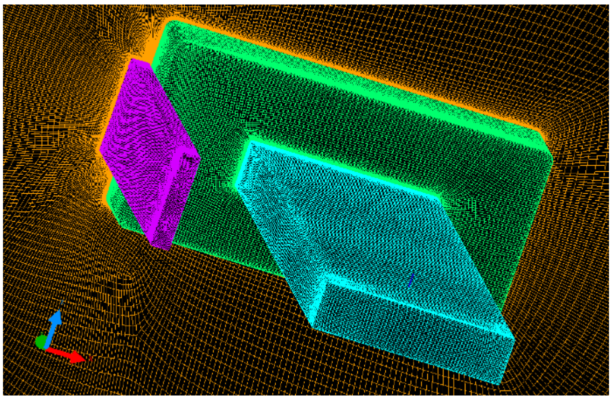


Figure 4: R.Tech CFD: Satellite mesh

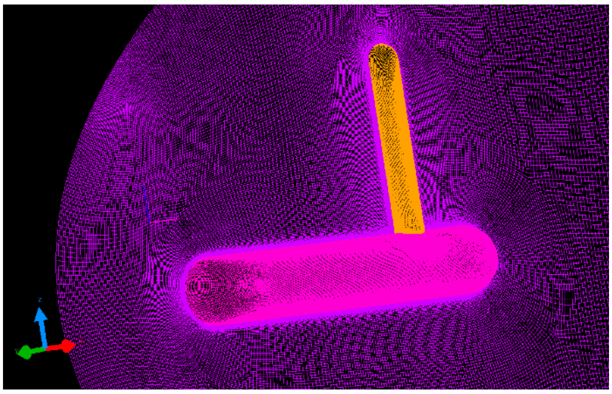


Figure 5: R.Tech CFD: SSI mesh

3 MATERIAL ABLATION MODEL

The Advanced Demise and Ablation Model (ADAM) [7] was motivated and described as a set of algorithms designed to assess the thermal and ablative response of different materials subjected to high-enthalpy air flows relevant to destructive atmospheric entries. ADAM is being developed specifically for integration with SCARAB, with the intent to improve the fidelity of the ground risk predictions. The proposed methodology adapts the existing finite difference scheme and overall architecture of the material ablation model of SCARAB and expands upon it, incorporating a larger number of distinct material types and accounting for a wider range of thermal response and ablation phenomena, which had been identified and characterised in the course of various past experimental activities, such as CHARDEM [8] and CoDM [9].

The scope of ADAM encompasses the following aspects relevant for ground risk prediction methodologies:

- Material property dataset requirements definition
- Thermal surface interface definition and handling for a given wall element, including conductive and radiative interfaces as well as aerothermodynamic interactions
- Thermal response assessment on the surface and within the volume of a given wall element
- Ablation response assessment for a given wall element
- Definition of demise criteria for a given wall element

The model in its current development state can simulate the behaviour of six more or less distinct material types, including metals, SiC-based ceramics, CFRP composites, and chemically resilient materials affected by melt but not oxidation such as oxide ceramics (“pure melters”). Trade-offs with regards to the complexity and accuracy of models describing the individual thermal response and ablation phenomena were made in order to limit computational costs while also attempting to fully exploit the available input from the aerodynamics interface of SCARAB.

The implementation in SCARAB covers five different material types and corresponding physical effects as listed in Tab. 2.

SCARAB material type	Examples	Effects
Pure melter	Glass, oxide ceramics	Catalysis, melting
Oxidising melter	Metals	Catalysis, melting, surface oxidation
Oxidising ceramic	SiC, C/SiC	Catalysis, surface oxidation
Ablator	CFRP	Surface oxidation/ combustion, pyrolysis
Combustor	Graphite	Combustion

Tab. 2: Material type and phenomena matrix of the SCARAB4 ADAM implementation

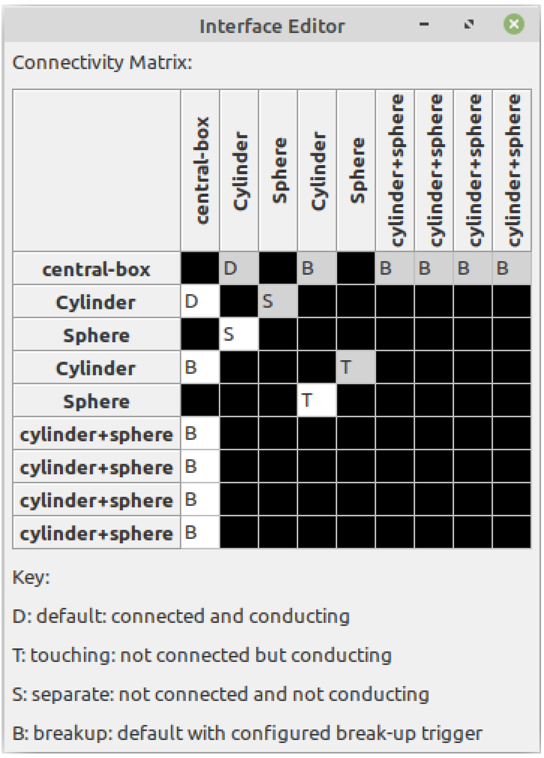
4 DESIGN FOR DEMISE METHODOLOGY MODELLING

A SCARAB geometry model is composed of numerous compounds which consist of simple geometric primitives, such as e.g. boxes, cylinders, spheres, tori or triangular or polygonal plates. In the past, these could be either physically connected or separated (via gaps) and during a re-entry simulation, break-up would happen, when melting occurs.

The SCARAB4 connectivity analysis checks for touching or overlapping model objects (compounds or primitives) and provides a lists of these interfaces (Figure 6). For each interface, the user can select between *connected* (physical connection and thermal conduction), *touching* (thermal conduction only) and *separate* (no connection or thermal conduction). *Connected* interfaces are similar to the old SCARAB model object connection, but can now be combined with one or more of the following break-up triggers

- Altitude
- Dynamic pressure
- Temperature
- Temperature for a specific duration

Any combination of these triggers is possible and the first condition matched during the simulation will result in the dissolution of the connection, i.e. switching the interface type from *connected* to *separate*.



Interface Editor

Connectivity Matrix:

	central-box	Cylinder	Sphere	Cylinder	Sphere	cylinder+sphere	cylinder+sphere	cylinder+sphere	cylinder+sphere
central-box	■	D	■	B	■	B	B	B	B
Cylinder	D	■	S	■	■	■	■	■	■
Sphere	■	S	■	■	■	■	■	■	■
Cylinder	B	■	■	■	T	■	■	■	■
Sphere	■	■	■	T	■	■	■	■	■
cylinder+sphere	B	■	■	■	■	■	■	■	■
cylinder+sphere	B	■	■	■	■	■	■	■	■
cylinder+sphere	B	■	■	■	■	■	■	■	■
cylinder+sphere	B	■	■	■	■	■	■	■	■

Key:

D: default: connected and conducting

T: touching: not connected but conducting

S: separate: not connected and not conducting

B: breakup: default with configured break-up trigger

Figure 6: SCARAB4 model interface editor

When a model object has no *connected* interface to another model object, it will separate, creating a break-up in the simulation. Thus, for model objects with multiple interfaces, all interfaces must fail to result in a break-up.

The definition of these interfaces allow for a more precise modelling of component connectivity, while the break-up triggers improve the modelling of D4D implementations, e.g. for early break-up.

A potential future extension of this approach could be to perform a combined thermo-mechanical analysis for these interfaces based on pre-defined connection types, like *bolted*, *glued* or *welded* with specific temperature dependent mechanical strength.

5 INTEROPERABILITY WITH DRAMA3

If DRAMA3 is installed in the machine, the SCARAB workflow can make use of DRAMA3 functionality, i.e. for orbit propagation and ground risk assessment.

5.1 Ground risk analysis

After a re-entry break-up simulation is finished, SCARAB automatically creates a ground fragment list in XML format compatible to the re-entry risk analysis module of DRAMA3, SERAM (Spacecraft Entry Risk Analysis Module).

The ground risk analysis can then be performed as part of the SCARAB simulation work flow, by calling SERAM. In addition, the user can export the fragment list for use in DRAMA3, e.g. to do a Monte-Carlo variation of the ground fragment data or the risk scenario using the corresponding DRAMA3 functionality.

5.2 Material data import

In SCARAB, material data and geometry model data are stored in a PostgreSQL database. The material editor of the SCARAB GUI has been extended with an interface to import material data from XML format, based on the format used by DRAMA3/ESTIMATE [10], to the SCARAB material database. To provide all material properties required by the SCARAB implementation of ADAM and the SCARAB structural analysis, the XML format was extended, based on the specific material type, with entries for

- Catalycity (virgin material and oxide)
- Combustion properties
- Material strength
- Oxide layer and oxide generation properties, including parameters for active and passive oxidation
- Thermal expansion

While DRAMA3 uses two distinct material types *CFRPMaterial* and *metalMaterial*, the XML import for SCARAB expects on of the following material types and the corresponding material properties:

- *ablator*
- *combustor*
- *oxidisingCeramic*
- *oxidisingMelter*
- *pureMelter*

5.3 Orbit propagation for escaping fragments

Highly eccentric re-entries can result in fragments escaping the atmosphere for another orbit revolution or even multiple ones, when the perigee is at high altitude inside the atmosphere [11].
As SCARAB performs a 6DoF propagation, simulating such additional orbit revolutions of possibly hundreds of fragments can have a significant impact on simulation run time. Thus, the standard approach used in SCARAB is to abort the propagation for an escaping fragment at a user defined altitude. In [11] DRAMA's orbit propagator OSCAR/FOCUS was used with a manual handover of data between the tools, to allow a full re-entry break-up simulation for every escaping fragment. In SCARAB4, OSCAR/FOCUS is called automatically by SCARAB when a fragment reaches the 'upper altitude limit'. The orbit state of the fragment is converted via CSTATE into a DRAMA3/OSCAR input file and OSCAR is executed. The target altitude for the OSCAR propagation is the re-entry interface, where the propagated state is passed back to SCARAB the re-entry simulation is continued for the fragment.

6 OTHER NEW OR EXTENDED FUNCTIONALITY

6.1 Cross-platform results visualisation

In recent years, a standalone visualisation tool, the so-called *SCViewer*, has been provided to HTG customers to inspect and visualise SCARAB simulation results.

This tool has been updated as well, now providing a single window overview (see appendix, Figure 8) on the simulation results on the

- Fragment tree (including all fragments generated during the SCARAB simulation)
- Ground track of the selected fragment
- Visualisation of the selected fragment with a timeline for the demise and tumbling state, as well as an optional a colour map overlay for
  - ➢ Heat flux
  - ➢ Pressure
  - ➢ Temperature
  - ➢ Wall thickness
- Ground fragment summary, including impact mass, velocity and position per fragment

The *SCViewe*r also provides the option to generate animations of a re-entry break-up simulation.

6.2 Mars environment

To comply with planetary protection regulations, it can be necessary to simulate the heating of a probe or orbiter during Mars entry. For such applications, SCARAB provides support for Mars environment models, i.e. the

MGS-85F2 gravity model and the MCD 4.3 and Mars-GRAM 2010 atmosphere models. The implementations were developed for *SCARAB Mars* [12], which was a separate, standalone tool, and has been merged into SCARAB4 to allow a more flexible selection of the planetary environment and easy future extension, e.g. with Venus environment models.

6.3 Uncertainty quantification

To enable uncertainty quantification, SCARAB4 provides the option for input parameter variation using a Monte-Carlo approach. It is possible to vary the

- Aerothermal heating (via global scaling factor)
- Break-up trigger conditions
- Initial orbit and attitude state
- Material properties

The material property variations include temperature independent properties, such as density or melting temperature, as well as temperature dependent ones, like emissivity, heat capacity or thermal conductivity.

In the case of a Monte-Carlo variation, the extended, automatic SCARAB simulation report provides a summary on the results of such simulation batches.

7 MEASUREMENT EVALUATION SUPPORT (MES)

To support the rebuild of Plasma Wind Tunnel (PWT) experiments and re-entry observations, as well as providing a sophisticated way to validate (new) models implemented in SCARAB, a set of specific features has been implemented.

The major component of the MES is the SCARAB Wind Tunnel Mode (WTM), which is based on an experimental, standalone tool used in the SCARAB simulations for CHARDEM [7]. The WTM (example shown in Figure 7) uses and supports all new SCARAB4 models and functionality. The first iteration supports static stream conditions, defined through

- Free stream density
- Free stream static temperature
- Free stream velocity
- Oxygen content

Re-entry break-up simulations provide the options to use a reference trajectory and/or fixed attitude of the so-called main fragment (*.1 fragments in the SCARAB fragment tree; usually the fragment with the highest mass). This allows to better rebuild re-entry observations where information on trajectory and/or attitude state is available.

For both run modes, re-entry and WTM simulations, sensor points can be defined to monitor temperature and pressure at specific points within the geometry model. Optionally, a sensor radius can be defined, where the values are averaged. The sensor point data allows to evaluate the conditions at points of interest within an object, e.g. to compare with thermocouple measurements of PWT tests.

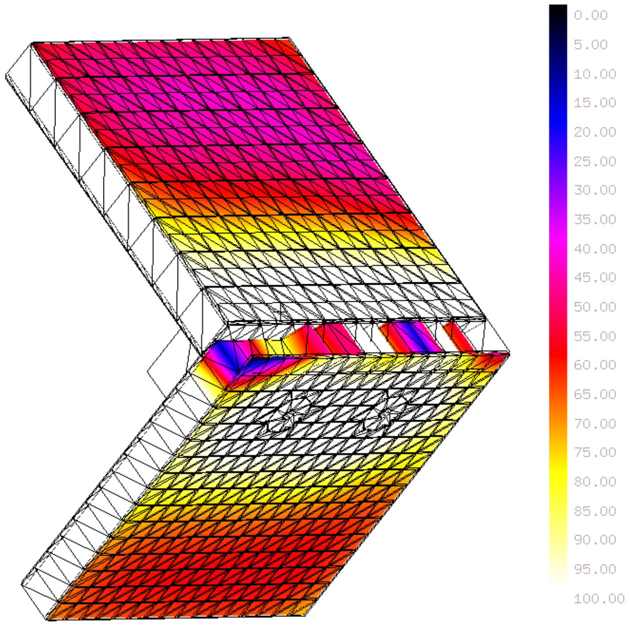


Figure 7: SCARAB4 Wind Tunnel Mode visualization example – Rebuild of D4D Breadboarding test 17 [13]

8 VALIDATION APPROACH

The new models implemented are validated with a two-fold approach using micro- and macro-measurement test cases to check the small scale behaviour, as well as the overall break-up and demise during atmospheric re-entry. For both types of validation cases, functionality of the MES is used.

8.1 Micro-measurement validation cases

To validate the new ATD and material ablation models implemented, CFD simulations and PWT experiments are rebuilt using the SCARAB4 WTM. These validation cases include

- Aerothermodynamics model validation with CFD comparisons
- Material ablation model validation with IRS PWT measurements
- Complex wind tunnel rebuilds for combined small scale ablation and break-up phenomena comparison

In addition to the new CFD simulations performed by R.Tech, CFD data from DLR [14] and ESA [15] is available for simple shapes, i.e. sphere, cube, cone, flat box/plate.

The implementation of ADAM is validated by rebuilding specific PWT experiments performed at IRS on a set of different materials, including A316, AA7075, CFRP, SSiC and PCW (insulator material), for both destructive and non-destructive tests.

After independent validation of both models, complex PWT test geometries are rebuild for three experiments, to make a transition from small scale heating and ablation simulation to demise and break-up of multi-material geometries:

- **D4D Breadboarding tests 17**, **18** and **21** (two aluminium honeycomb sandwich panels with aluminium or CFRP face sheets; connected by cleats and spool/surface inserts) [13]
- **SECRET BBU mock-up** (Test No. 8) [16]
- **SECRET battery mock-up** (Test No. 13) [16]

With these complex PWT rebuilds, the goal is to try to reproduce the demise observed in the experiment and the heating measured by the thermocouples throughout the samples. It has to be noted however, that these rebuilds are limited to thermal effects, since the application of forces and mechanical stresses is currently not included in the SCARAB WTM simulations.

8.2 Macro-measurement validation cases

As a final validation step, after the successful validation of the small scale behaviour, the general demise and break-up during atmospheric re-entry is validated and compared to observational data for the following cases

- **ATV-1**
  Re-run of previous SCARAB simulation [17] and comparison to observations and spectra recorded.

- **ATV-3 + REBR**
  Try to rebuild of specific events derived from Re-Entry Break-up Recorder (REBR) [18].

- **WT1190F** [19] and **Hayabusa** [20, 21]
  Validation of the radiative shock heating model and comparison to observation data.

- **PAM-D** (Delta-II third stage)
  Rebuild ground fragments found and validate temperature range during re-entry, e.g. via surface oxidation.

9 FIRST VALIDATION RESULTS

The validation of the models implemented is currently on-going. The aerothermodynamic model was compared with available CFD data from ESA, DLR, and R.Tech. The ESA and DLR data were computed with the DLR Tau code, the R.Tech data with the R.Tech Mistral code. The following figures show sample results for a sphere, a plate, a cone, a cylinder, and a hollow sphere.

Sphere

In Figure 9 (appendix) the heat flux on a 1m-diameter sphere is shown as function of the axial distance to the stagnation point. It is clearly visible that the new non-local approach used in SCARAB4 better fits the ESA CFD data than the local flow inclination method used in SCARAB 3.1L.

Plate

Figure 10 (appendix) shows the heat fluxes on a 1x1x0.05 m plate at different angles of attack, with 0 degrees indicating a perpendicular and 90 degrees a tangential incident. Next to the sphere, a flat plate is THE reference case for a boundary layer based approach. The agreement between ESA CFD and SCARAB4 is good, except for the tangential (90 degrees) case, where the heat flux behind the tip is overestimated in SCARAB4. This can be explained by an overexpansion around the corner of the small but finite plate front face at this condition, which is not considered in SCARAB4.

Cone

Figure 11 (appendix) shows the heat fluxes on a 1x1 m LxD cone at different angles of attack, with 0 degrees indicating the cone tip aligned to the flow. The agreement is again good, confirming that the boundary layer based approach is also applicable to axisymmetric geometries, which is mathematically justified by the Mangler transformation.

Cylinder

Figure 12 compares qualitatively the heat flux on a cylinder at 45 degrees angle of attack. It shows that the peak heating is qualitatively covered correctly by the new approach. This is confirmed by a comparison of the stagnation line heat fluxes shown in Figure 13. In SCARAB 3.1L the heat flux depends only on the local flow inclination and therefore shows no variation around the exposed tip.

Hollow half-sphere

Figure 14 compares qualitatively the heat flux onto and into a hollow sphere when exposed to the flow at zero (flow head-on to the concave side) and at 45 degrees angle of attack. The new ATD model considers the concave form of the geometry, resulting in a quite uniform heat flux distribution in the head-on case, in accordance with the CFD result. At angle of attack the flow structure inside the cavity is less pronounced in the new SCARAB than in the CFD results. This can be explained partially by the unsteady character of the flow (emerging in the time-dependent CFD simulation, the SCARAB approach is stationary) and, of course, by the approximations used in the simplified approach, which become especially critical when applied to of-design configurations.

10 SUMMARY

Based on recent data from wind tunnel tests, other experiments and Computational Fluid Dynamics (CFD), state-of-the-art models for material ablation and aerothermodynamics have been implemented into SCARAB. Developed by the Institute of Space Systems (IRS) of the University of Stuttgart, the new Advanced Demise and Ablation Model (ADAM) extends the capabilities of SCARAB to simulate the demise of five more or less distinct material types, including metals, insulators, ceramics, CFRP composites. The new aerothermodynamics model, developed by Hyperschall Technologie Göttingen GmbH, includes new features such as the calculation of local heating based on local radius of curvature, flow stream length and geometry conditions, shock impingement on large structures and radiative shock heating. The validation of this model is supported by CFD calculations performed by R.Tech Engineering.

SCARAB4 allows to define break-up triggers at the interface between geometric primitives or compounds, improving the capabilities of Design-for-Demise modelling and providing a more realistic modelling of joints between components. New interfaces to ESA's DRAMA software enable SCARAB to quickly propagate the orbit of escaping objects or fragments until the next re-entry and calculate the ground risk using the recently upgraded capabilities of DRAMA3. Similar to DRAMA3, SCARAB now allows uncertainty quantification using a Monte-Carlo like parameter variation on simulation input, including material properties.

The upgrade of SCARAB is accompanied by the development of a new feature set for Measurement Evaluation Support (MES), providing an additional run mode, the 'Wind Tunnel Mode', to enable the simulation of wind tunnel experiments, using pre-defined, static flow conditions and allowing the user to define sensors points inside the sample geometry to 'measure' the physical properties at these positions. This allows to validate the new models by re-building specific experiments. The MES also extends the capabilities of re-entry break-up simulations, allowing the user to perform simulations along a pre-defined trajectory, to rebuild re-entry events which can be compared to observations.

Using the MES functionality, the upgraded models are currently validated with a set of micro- and macro-measurements, including the rebuild of small scale behaviour, as well as the general break-up and demise process during atmospheric re-entry.

11 ACKNOWLEDGEMENT

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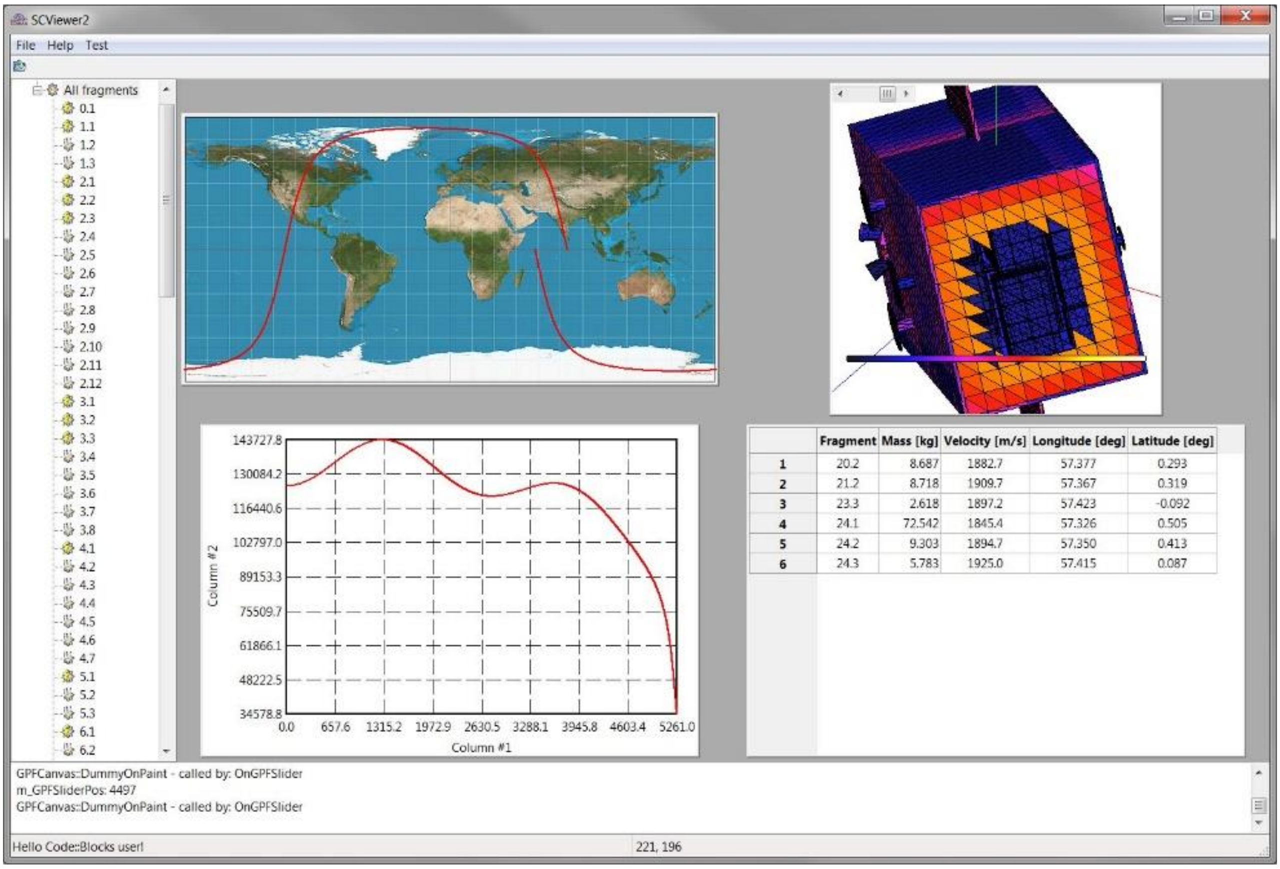
Appendix



	Fragment	Mass [kg]	Velocity [m/s]	Longitude [deg]	Latitude [deg]
1	20.2	8.687	1882.7	57.377	0.293
2	21.2	8.718	1909.7	57.367	0.319
3	23.3	2.618	1897.2	57.423	-0.092
4	24.1	72.542	1845.4	57.326	0.505
5	24.2	9.303	1894.7	57.350	0.413
6	24.3	5.783	1925.0	57.415	0.087

```
GPFCanvas::DummyOnPaint - called by: OnGPFSlider
m_GPFSliderPos: 4497
GPFCanvas::DummyOnPaint - called by: OnGPFSlider
```

```
Hello Code::Blocks user!                221, 196
```

Figure 8: SCViewer – SCARAB4 results visualisation mock-up with fragment list (left), ground track (top left), fragment visualization with colour map overlay (top right), variable x-y plot (bottom left) and ground fragment summary (bottom right)

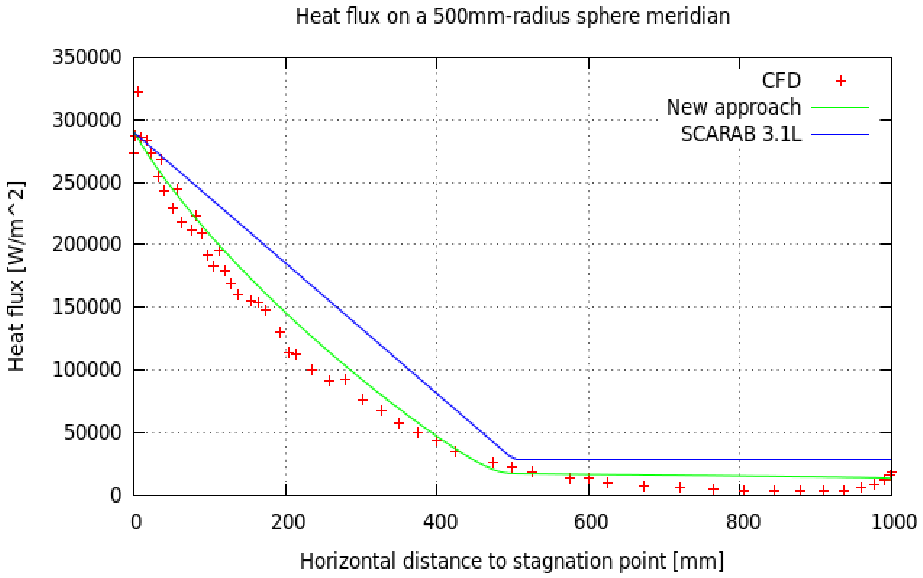


Figure 9: Heat flux comparison - Sphere: CFD, SCARAB3.1L and SCARAB4

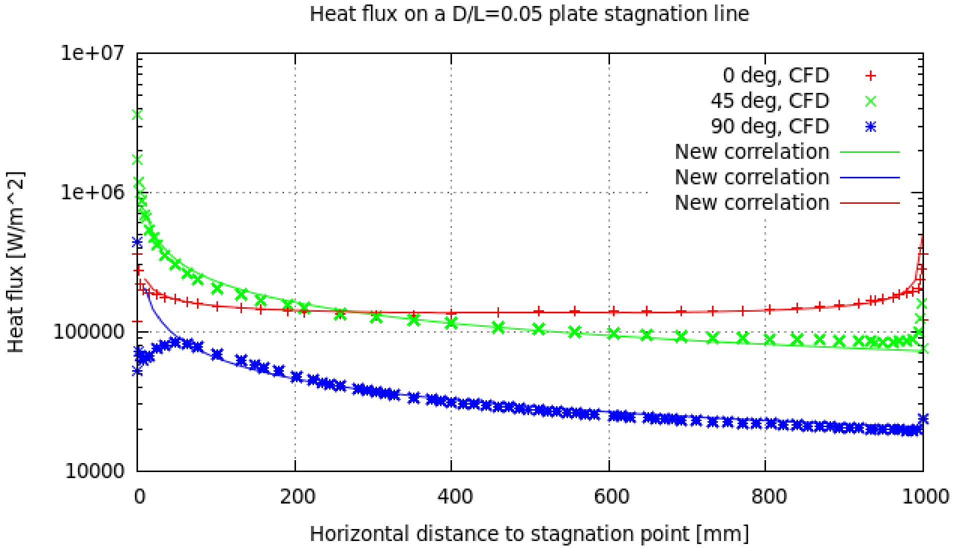


Figure 10: Heat flux comparison - Plate: CFD and SCARAB4

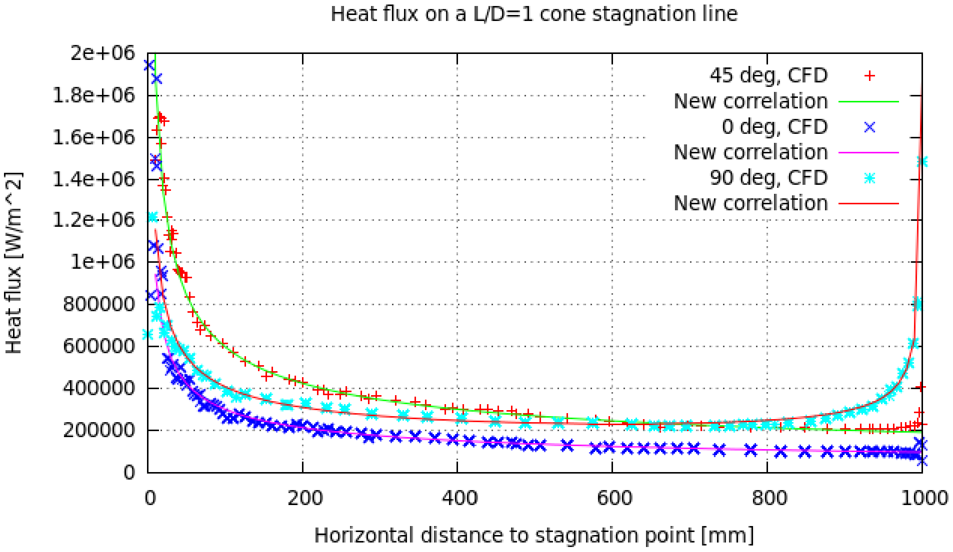


Figure 11: Heat flux comparison - Cone: CFD and SCARAB4

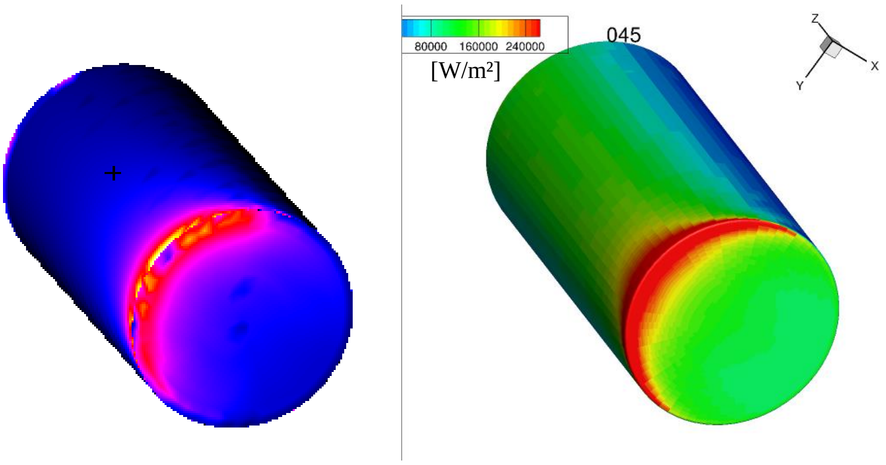


Figure 12: Cylinder at 45 deg angle of attack – Qualitative comparison for the heat flux computed with SCARAB4 (left) and CFD (right); Note: Colour scales do not match!

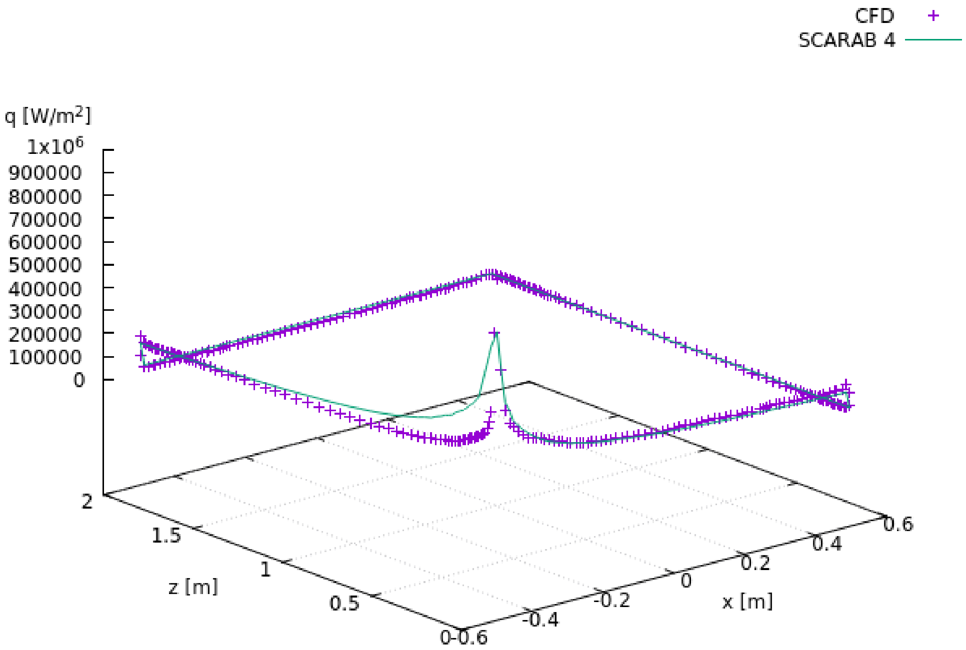


Figure 13: Cylinder at 45 deg angle of attack – Stagnation line heat fluxes for SCARAB4 and CFD

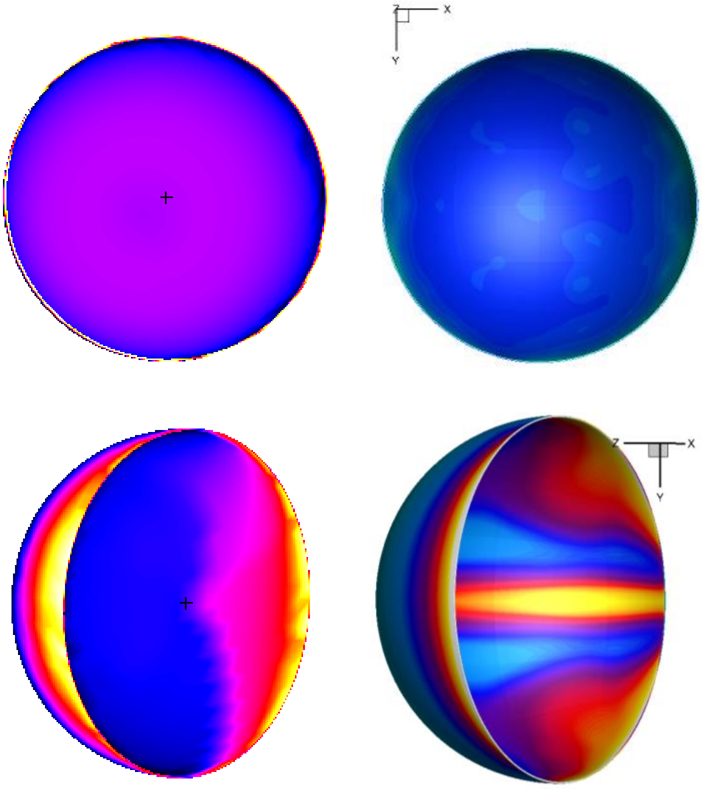


Figure 14: Hollow half-sphere – Qualitative comparison for the heat flux computed with SCARAB4 (left) and CFD (right); Note: Colour scales do not match!