SIMULATION OF THE ARIANE 5 EPC REENTRY WITH THE FRAGMENTATION TOOL SUITE

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ABSTRACT

European launchers and former French launcher programs are responsible of 7,2% of orbiting rocket bodies. With the French space act coming into effect, reentry of launcher bodies and satellites launched from the French territory must be compliant with both on-ground casualty risk assessments of 10^{-5} for controlled reentries 5.10^{-4} for uncontrolled reentries. Satellites operators and Launcher companies have also to carry on-orbit end-of-life disposal manoeuvers on LEO satellites in order to reenter in less than 25 years, the goal being to limit risks for exposed populations and to reduce the debris population density on key-orbits. In particular, Airbus Safran Launchers is now responsible for safety studies and risk mitigation regarding its new launcher Ariane 6.

A roadmap regarding space debris activities have been implemented over a 5-year-timeline on the context of R&T Programme of the French space agency CNES to develop the methodologies needed to assess fragmentation and survivability of launcher stages and other man-made objects. In the scope of Ariane 6 development, these tools are now being implemented and test cases are needed for validation purposes.

The focus of this paper aims at presenting the result of the EPC (Etage Principal à propulsion Cryotechnique which is Ariane 5 lower stage) test case. Inputs for the test case are composed of a 6Degree of Freedom (DoF) trajectory computation providing external aerothermal loads computed with an aerodynamic coefficient database. A SAMCEF® numerical Finite Element Method approach is used to model aerothermal and mechanical loads on the EPC. Structure parts and components characteristics are based on Ariane 5 design files; material properties are based on Airbus Safran Launchers SAS internal material properties catalog.

Presented results discuss impact of attitude of the lower stage based on the V 518 flight where the EPC reentry has been observed. This Ariane 5 flight took place on March 2, 2004, and the payload was the automated exploration spacecraft Rosetta. The result includes the estimation of the altitude of first fragmentation for the entire stage. After fragmentation, a survivability assessment is carried on the debris of the lower stage.

1 INTRODUCTION

1.1 Test case presentation

The chosen test case is the Ariane 5 G+ flight V 518 which took place on March 2, 2004. Its payload was composed of Rosetta and the lander Philae.

Figure 1: © ARIANESPACE/CNES : Rosetta during integration (left) – view of the launch (right)

1.1.1 The V518 observation campaign

This campaign was one amongst 3 where the EPC trajectory has been observed in the scope of the Ariane-5 EPC Re-entry Characterization Program of the French space agency CNES. These

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observations led to several studies [2,3,4] where numerical simulations results were compared to reentry data. The observation campaign was airborn with equipments implemented aboard the A300 ZERO G of Novespace. The payload consisted of:

- VHF radar to detect, acquire and track the EPC during its reentry as well as provide signature data of the different events occurring
- CCD camera to record the breakup process

Figure 2: A300 ZERO G equipped with VHF patch antennas

1.2 EPC description and simulation hypothesis

This specific flight was chosen due to its well documented re-entry initial conditions: EPC geometry, mass and inertia matrix, initial attitude, trajectory, all based on literature, CNES and Airbus Safran Launchers internal documentation as well as observation campaign reports.

The EPC is the main Cryotechnic stage of Ariane 5. It has a diameter of 5.4 m and a length of about 30 m. Its dry mass is approximatively 14 tons. Three parts compose the EPC:

- The front skirt (JAVE, Jupe Avant Equipée, will be called front part) is a heavy structure since it connects the EPC with the upper stage and the two EAP (solid boosters, Etage d'Accélération à Poudre).
- The LOX (Liquid Oxygen) tank is located above the LH2 (Liquid Hydrogen) tank with a common dome. The material is Light Aluminum alloy with a very small thickness.
  - FAV (Fond Avant). Upper spherical dome of the LOX tank
  - FAR (Fond Arrière). Lower spherical dome of the LH2 tank.
- The rear skirt (also called aft cone or aft section) is also a heavy structure interfacing the Vulcain engine with the tanks and also interfacing the EPC with the rear part of the two EAP.

1.2.1 EPC geometry

EPC geometry and composition has been modelled using EPC definition documents and CAD (Computer Aided Design) models.

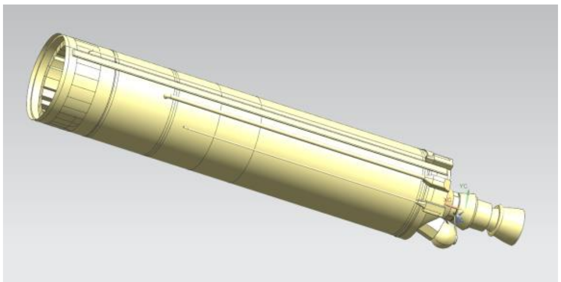

Figure 3: simplified geometry of the Ariane 5's EPC

In order to reduce computation efforts, only major structural metallic parts and thermal protections are modelled. Major protuberances and fluid lines are also represented since they impact the calculation of aerothermal fluxes and can become independent debris during re-entry.

A mean thickness is calculated for metallic panels which compose the LOX and LH2 ergol tanks and also fore- and aft-structures. The geometry of joints areas between panels is also modelled due to its different thickness impacting both thermal and mechanical behaviour of the tanks panels. The structural panels of the JAVE in the forefront section have a strong impact on mechanical behaviour of the stage in addition to carrying pieces of equipment. In fact, two specific areas are also where the EAP boosters are attached and their thrust redistributed through the EPC structure.

The Vulcain 2 engine is modelled using simplified shapes since dense pieces made of high temperature alloys such as steel, inconel and titanium are known to survive re-entry: The turbopumps, the nozzle and many parts of the motorcase will have little degradation until impact.

One of the pressure spheres is modelled for the computation of aerothermal fluxes since it causes a major disruption of fluxes in the aft of the EPC. All tanks will be considered to be independent debris for the survivability part of the study.

Since the stage was passivated and no explosive break-up observed for V518, ergols thermodynamic evolution in the tanks is not considered. According to CNES, residual ergols could trigger an explosive breakup [4].

1.2.2 EPC re-entry trajectory

The EPC reentry was observed using RADAR systems and optical cameras mounted on the Airbus A300 Zero-G of Novespace. They helped determine the start of the first major break-up event at 74-72 km altitude. Due to modelling uncertainties (atmospheric model, material thermal and mechanical model, structure simplification...) the simulation break-up altitude delta with regard to real fragmentation altitude is not to be considered as the only criteria of success for this test case.

A more detailed presentation of initial velocity slope and attitude hypotheses will be given in section 2.3.

1.3 Fragmentation and survivability tool suite presentation

Over the last 5 years, a co-funded R&T contract with the CNES French space agency has aimed at developing methods to assess upper stage reentry. Two major themes exist: materials characterization in order to better assess behaviour of materials composing upper stages during re-entry and the modelling of fragmentation and survivability. It will enhance the maturity of the inputs for the tool suite and help reduce uncertainties. The tool suite is composed of modules calculating aerodynamical data base, trajectory, aerothermal fluxes (ARPEGE), ergols thermodynamical behavior in tanks (SITTARE), thermal and thermomechanical responses (SAMCEF Thermal/Amaryllis and Mecano) and finally survivability of the created debris (ADRYANS).

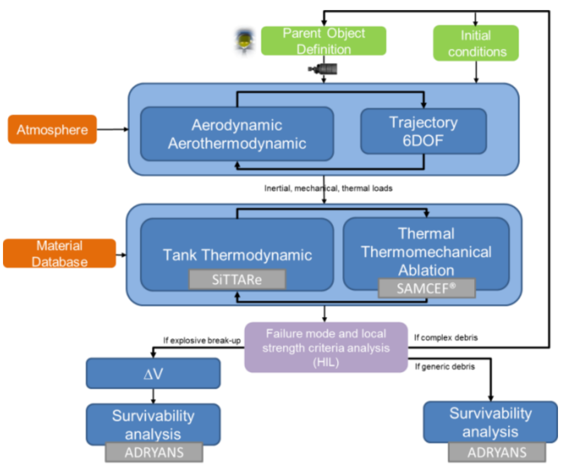

Figure 4: Description of the tool suite

Developments carried in 2015 and 2016 on thermo-dynamical and survivability modules allow for testing of the coupled tool suite in 2017. The EPC test case presented in this paper is not covering the the tank thermodynamic module. The next step is to integrate, test and validate the thermodynamic module within the tool suite before the end of the year.

2 TRAJECTORY SIMULATION AND AEROTHERMAL LOADS COMPUTATION

2.1 Aerodynamic and trajectory tools

Several tools have been developed to compute the aerodynamic behaviour and trajectory of re-entering objects. ARPEGE which stands for “Aérothermodynamique de Rentrée pour PrédirE la fraGmentation d’Etages » is a computer program designed to predict surface pressure, shear-stress, aerodynamic forces, coefficients and heat transfer distribution of an arbitrary shape at hypersonic speed (Mach > 5). It uses the local surface inclination methods and is able to compute from free molecular flow to continuous flow, with transition from laminar to turbulent regime based on Reynolds number. Aerothermodynamics is based on stagnation point heat fluxes with additional in house correlations.

BL43 is a 6 dof trajectory simulator used for re-entry analysis at Airbus Safran Launchers.

2.2 Aerodynamic database

Aerodynamic database was computed using ARPEGE in two domains: High altitude for free molecular interactions and in the continuum regime. A bridging function was used to link the two domains.

6 coefficients were computed:

- C_D, drag coefficient
- C_L, lift coefficient
- C_Y, side force coefficient
- C_l, rolling moment coefficient
- C_m, pitching moment coefficient
- C_n, yawing moment coefficient

Each coefficient is depending on Mach number, Angle of Attack (AoA) and the SideSlip Angle (SA).

2.3 6 degree of freedom trajectory

Initial conditions at 120 kilometers altitude were obtained from Airbus Safran launchers internal documentation. Relative velocity was set to 7790 m/s and the re-entry slope was set to -2.9°. Moments of inertia are summarized in the following table:

Table 1: Moment of inertia

Moment of inertia	Value (kg.m²)
Ixx	71810
Iyy	1884245
Izz	1884205

Aerodynamics reference surface is set to 23.3 m² and the aerodynamic length is 23.8 m. Due to tank passivation procedure a 80 °/sec rotational rate is set at the beginning of the re-entry. The goal is not to reproduce the exo-atmospheric trajectory based on the initial conditions at the jettisoning but to compute the aerothermal heat fluxes, shear stresses and pressure gradient on the EPC to perform a thermal and mechanical computation.

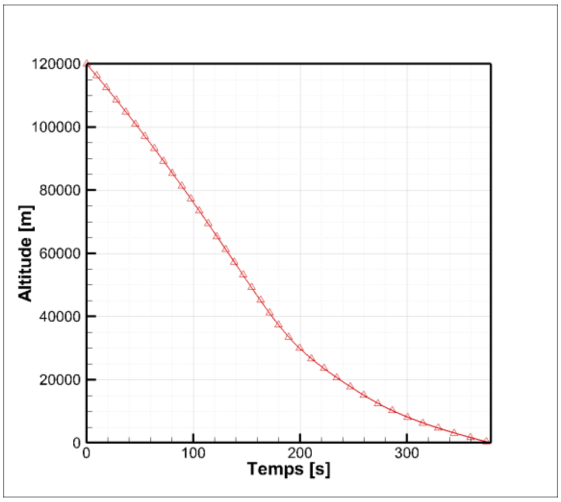

Figure 5: Altitude (m) wrt time (s) for the computed trajectory

2.4 Aerothermodynamic database

Following the 6 DoF trajectory computation, a mapping is necessary to link the aerothermal heat fluxes to the thermal meshing. A database is computed along the trajectory to be used as input for the thermal and mechanical simulation. The following figures highlight the athermanous enthalpy.

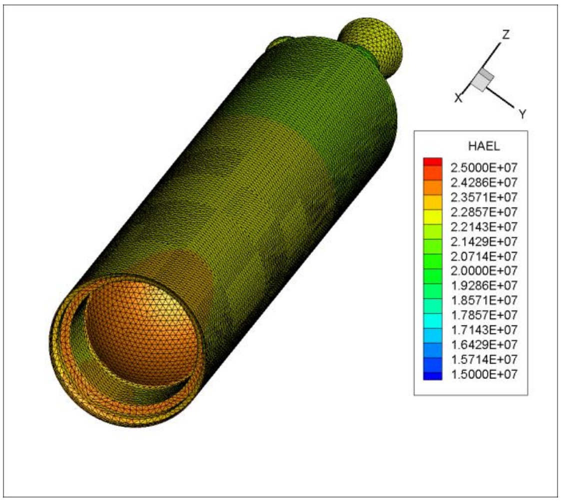

Figure 6 – Athermanous enthalpy (J/kg) on the EPC mesh with an AoA of 0°

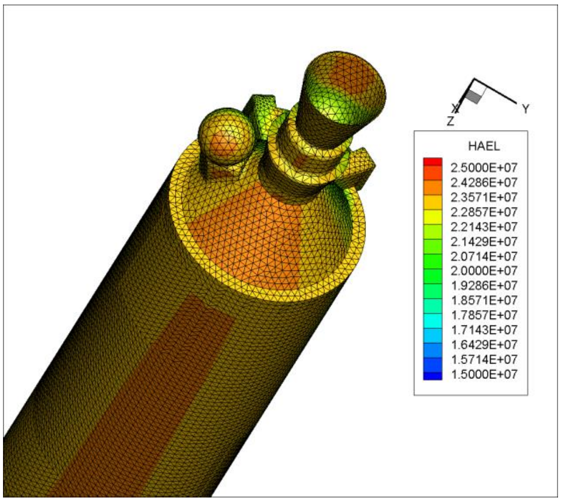

Figure 7 – Athermanous enthalpy (J/kg) on the EPC mesh with an AoA of 140°

Many variables are computed with ARPEGE and available for the mapping such as the local pressure, shear stress, radiation from the shock layer, etc.

3 SIMULATION RESULTS

3.1 Presentation of SAMCEF®

In order to calculate the thermal and the thermomechanical response of the EPC simulation model, the industrial software SAMCEF THERMAL – AMARYLLIS®[5],[6] and MECANO® have been used. They are modules of the numerical tool SAMCEF® developed and distributed by the company SIEMENS-SAMTECH® (Belgium), which is technically supported by the University of Liège. These codes are dedicated to the simulation (1D, 2D, 3D) of non-linear, transient thermal and mechanical responses of material. Regarding AMARYLLIS, thermochemical degradation (pyrolysis) and ablation (both chemical and mechanical) can be modelled which cannot be done in THERMAL. The use of THERMAL or AMARYLLIS is dependent on the type of material and whether it will suffer ablation/pyrolysis degradation. The THERMAL/AMARYLLIS and MECANO modules rely on the finite elements discretization technique.

3.2 Materials properties

Numerical models of materials are needed for both thermal and mechanical simulations. They consist of:

- The material density, conductivity, enthalpy
- A pyrolysis model, an ablation scheme (only for charring or ablative composite materials)

- The Young Modulus, Poisson's ratio, thermal expansion, and ultimate tensile strength of the material when under the hypothesis of plastic behaviour

Material models used in this test case are taken from Airbus Safran Launcher internal materials database and literature. Thermal, ablation, mechanical material behaviour and strength criteria are key input parameters in simulation tools: an update of the material models is expected in 2017 after high temperature characterization campaigns conducted in partnership with CNES. Measures on elementary thermal properties, thermo-optical behaviour, oxidation – Ablation and mechanical characterization are foreseen.

3.3 Mesh description

2D shell meshes are used to model the main structures of the EPC and the thermal protection parts. Meshes follow the EPC simplified forms and thicknesses. Meshes with smaller element sizes are employed to favour better computation of aerothermal fluxes onto the structure in specific areas. In general, element size is between ten and fifty centimetres.

Thermal exchange between meshes is guaranteed by either projecting the temperature field from one mesh onto another for conductive exchanges, or by having common nodes between adjacent meshes. When projecting the temperature fields, a conductive transmission coefficient is chosen with consideration to interfaces thermal conductivities.

3.4 Thermal computation results and analysis

In this first step, the thermal model of the EPC is loaded with boundary conditions corresponding to the aerothermal fluxes and pressure calculated by ARPEGE.

Thermal criteria were set for cold thermal protections which are not designed to resist high thermal fluxes. Thanks to ATG measures, a degradation model is set. When a given temperature threshold is reached, the material model density is lowered. It allows transmitting more energy to the structure parts that are less and less protected by the cold TPS during re-entry as its temperature rises.

On the following graphs, temperatures were probed on different places on the LH2, LOX, and fore section.

LOX tank being thicker than LH2, its temperature stays lower compared to LH2 global temperature: The break-up of this tank due to thermal degradation of the metal properties will occur later and lower than the LH2 tank. The 400 °C temperature criteria is reached at 122.5s in areas of LH2 tank and of the JAVE while only about 4s and 12s later respectively for the dome and the panels of the LOX tank, as it can be seen below on Fig. 8 and Fig. 9.

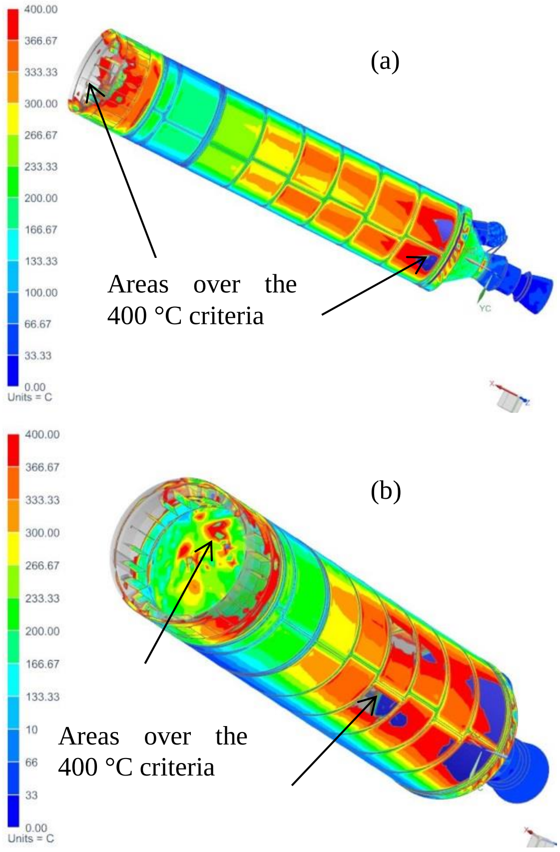

Figure 8: Temperature of structure parts at 122.5s (a) and 126s (b)

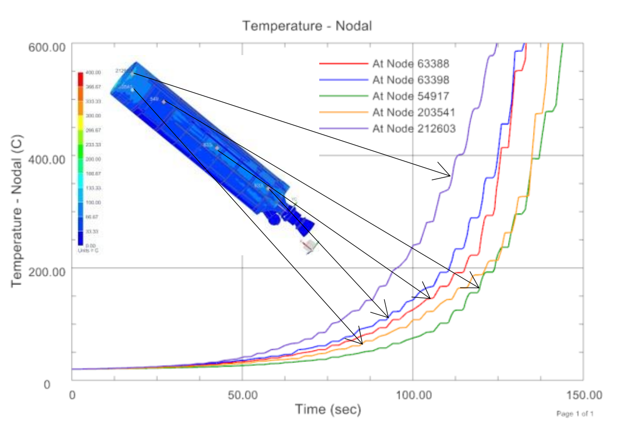

Figure 9: Evolution of the mean structure temperature (°C) wrt time (s)

Joints of the panels of the LOX and LH2 tanks act as heat-sinks as it can be seen below on Fig. 10 with temperature differences as high as 200°C on the LH2 tank.

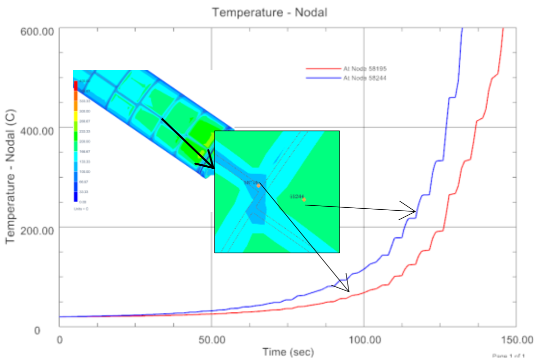

Figure 10: Focus on joints areas of the tanks panels at 110 s for visuals, wrt time (s) for the graph

In a pure thermal analysis, the most probable area of first fragmentation is the area where a temperature of about 400-500°C is reached. At this temperature, aluminium mechanical properties start to be strongly degraded until the melting temperature which is between 500-600°C. Our simulation shows that the area at the bottom of the LH2 tank near the aft cone of the EPC (BME: Bâti Moteur équipé, Motorbay structure) goes over this criteria at approximatively 122.5 seconds. This corresponds to an altitude of about 65 km, as seen in Fig. 8 (a).

In addition, the first two areas to reach 400°C are the JAVE structure and the area where feed lines are fixated on the aft section, respectively at about 110 and 111 seconds. This corresponds to an altitude of 71 kilometers approximatively.

3.5 Thermo-mechanical computation results and analysis

In this second step, the thermal evolution previously calculated is loaded on the mechanical model of the EPC in order to perform a thermo-mechanical analysis. Since mechanical properties of TPS are much lower than metallic parts, only major structural pieces are simulated: metallic domes and sections of the LH2 and LOX tanks. This will allow computing stress and strain with regard to time. This simulation goal is to identify where and when the major beak up event of the EPC occurs.

Measured values of resistances in the joint areas of the LOX and LH2 tanks show up discrepancies in mechanical strength for a similar temperature compared to initial material properties due to welding operations. An opening of the tank has more probability to occur on or near a joint since the mechanical strength is lower in these areas.

3.6 Conclusion on first fragmentation altitude

Decision on how complex should models be with regard to input uncertainties (atmosphere, trajectory, attitude, materials…) in this kind of computations is a mandatory step that every fragmentation study faces. As of now the question of augmenting the complexity of the EPC model is structured as follow: should the model integrate more sub-structures, more detailed pieces, enhance modelling of non-perfect interfaces for example, whereas uncertainties on fluxes and material models still exist? This topic will be discussed in 5.

4 SURVIVABILITY

4.1 Survivability and trajectory tool

ADRYANS which stands for Assessment of Debris ReentrY and ANalysis of Survivability is an object oriented code that can compute the 1-dimensional thermal and chemical ablation response of a simple metallic and composite shape (i.e. sphere, flat plate, etc.). This trajectory tool is used when the fragmentation has occurred and several objects are ejected from the parent structure. It is based on BL43 with a 3 degree of freedom approach.

4.2 Fragments general description

After the fragmentation simulation results, engineers have to determine the different fragments created during re-entry of the EPC. At this step, it is important to include pieces of equipment that were not part of the fragmentation study, since they did not impact fragmentation.

We consider for the survivability study the following fragments:

- LOX and LH2 tank panels and domes
- Electric pieces of equipment of the JAVE
- Pieces of equipment of the motorbay
- Separated high pressure tanks for the Vulcain engine: three spherical and one cylindrical tank
- Vulcain engine components: turbopumps, combustion chamber, nozzle. Due to their composition, these parts are assumed to survive until ground impact.

4.3 Modelling of the fragments

The following table summarizes the modelling of each fragment.

Table 2: ADRYANS modelling

Fragment	ADRYANS modelling
High pressure tanks for the Vulcain engine : 3 spherical tanks	**Debris 1**: 2 spheres of 0.41 m radius made of Titanium with Overwrapped Carbon fibres. **Debris 2:** 1 sphere of 1.3 m radius. Mainly made of Aluminum.

High pressure tanks for the Vulcain engine 1 cylindrical tank	**Debris 3:** Cylinder of 0.22 m of radius and 1.5 m in length. Made of Steel overwrapped with Carbon fibres.
Electric equipments	**Debris 4:** Box of 0.5m by 0.37m by 0.23 m
Engine's structural support	**Debris 5:** Cone of smaller radius 0.9 m, bigger radius 1.8m and total length 2.5 m. Mainly made of Aluminum alloy.
LOX and LH2 tank panels and domes	**Debris 6-10:** All fragments are modelled as flat plates with various thicknesses and sizes depending on the position.
FAV	**Debris 11:** half sphere modelled as sphere radius 2.7m
FAR	**Debris 12:** half sphere modelled as sphere radius 2.7m,
JAVE	**Debris 13:** Cylinder with 2.7m radius and length 3.3m. Mainly made of Aluminum alloy.

4.4 Survivability results

The chronology of the fragmentation determined by thermo-mechanical analysis provides the input for the survivability's study. Initial temperature is set to 400°C, trajectory conditions are based on the timing of the main trajectory (velocity, slope) and finally the shapes of the fragments with their masses will determine their trajectories.

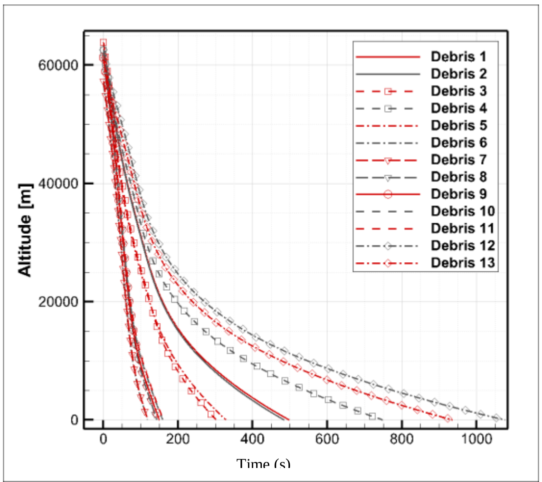

Figure 11: Trajectories of several debris wrt time (s)

With breakup altitude in the 68km-62km range the velocity has already started to decrease to about 6000 m/s. Some fragments have ballistic coefficients around 0.1 m²/kg when most of the others are around 0.01 - 0.03 m²/kg. The biggest ballistic coefficient will contribute to the longest trajectory.

Table 3: ADRYANS's results

Fragment	Results
Debris 1: 2 spheres of 0.41 m radius made of titanium with Overwrapped Carbon fibres.	Spheres are released around 68km. Ablation starts at 60km with maximum surface temperature around 1200K. Fiber glass substrate rises over 700K.
Debris 2: 1 sphere of 1.3 m radius. Mainly made of Aluminum.	Biggest sphere is released around 70km and slows down rapidly. Temperature rises up to 600K. Melting is not reached since the thickness of the tank is relatively high compare to other structures (around 4mm)
Debris 3: Cylinder of 0.22 m of radius and 1.5 m in length. Made of steel overwrapped with Carbon fibres.	Ablation starts at 59km and the maximum temperature is 1150K. The cylinder will reach the ground due to the thermal protection of the CFRP.
Debris 4: Box of 0.5m by 0.37m by 0.23 m	Ablation starts at 57km and stops rapidly. Most of the box will reach the ground.
Debris 5: Cone of smaller radius 0.9 m, bigger radius 1.8m and total length 2.5m. Mainly made of Aluminum alloy.	Melting start at 55km but the overall size and weight is significant therefore most of the structure will reach the ground.
Debris 6-10: All fragments are modelled as flat plates with various thicknesses and sizes depending on the position on the EPC.	Due to a late fragmentation of the main structure, the flat plates are released around 60km and below. Some flat plates reach their melting temperature but most of them will survive.
Debris 11: dome (half sphere) modelled as sphere radius 2.7m	Very large and light weight structure for the FAR. It reaches its melting temperature around 59km but cools down in re-entry.
Debris 12: half sphere modelled as sphere radius 2.7m,	Very large and light weight structure for the FAV. It reaches its melting temperature around 57km then it will partially survive
Debris 13: Cylinder with 2.7m radius and length 3.3m. Mainly made of Aluminum alloy.	If the structure is separated from the EPC and re-enters the atmosphere as a random tumbling cylinder then the structure will partially survive. Panels with less than 3.5 mm thickness will start to melt whereas panels with thickness of 5mm and more will survive.

5 COMPARISON WITH OBSERVED REENTRY AND FORMER STUDIES

Inputs for the test case were composed of a 6DoF trajectory computation providing external aerothermal loads computed with an aerodynamic coefficient database. A SAMCEF® numerical Finite Element Method approach has been used to model aerothermal and mechanical loads on the EPC. Structure parts and components characteristics are based on Ariane 5 design files; material properties are based on Airbus Safran Launchers SAS internal material properties catalog. The result includes the estimation of the altitude of first fragmentation for the entire stage above 65 km as presented in 3.6. Previous studies [2] correlated observed events as following: LH2 tank opening at 74 km, and of LOX tank at 67 km altitude. After fragmentation, a survivability assessment has been carried on the debris of the lower stage which forms were chosen based on Airbus Safran Launchers SAS expert's knowledge and previous CNES and Airbus Safran Launcher studies [3][4].

The first level of accuracy improvement for this test case results compared to real data can be described through the following points:

- Improvement of materials models: behaviour at high temperature for both thermal, mechanical properties and degradation models (pyrolysis and ablation for composite materials)
- Improvement of interfaces behaviour at high temperature and under re-entry induced mechanical stresses
- Improvement of thermal exchanges: for example, radiation in cavity could also be modelled for the aft section between the LH2 tank dome and the conic part of the launcher aft and in the two LOX and LH2 tanks (domes and panels).

The first three points are currently being considered through several R&T projects co-funded with CNES.

A last domain of improvement is the complexity of the model, especially in regard with thermal protections: in this test case, the repartition, nature and thickness of hot thermal protections was simplified with a consequence of local under or over protection of the structures. Since this is a test case, a certain level of simplicity was mandatory to conduct quick and efficient assessment of the tool capabilities.

This last point is currently under study, as the uncertainties on simulation inputs can be quite important in comparison to how precise a structural model can be: what value can be given to the results computed on an extremely detailed model submitted to inputs with large uncertainties? Answers from previous studies on EPC re-entries in 2001 [3] were for example to keep simplified models and perform Monte-Carlo analysis by dispersion of several parameters (atmosphere parameters for example).

Airbus Safran Launchers SAS has launched an uncertainties identification doctoral thesis with INRIA (French public research centre on digital sciences and technologies) to deepen our knowledge on the uncertainties of the tool suite and decide on the best level of complexity for our simulations as well as reduce the identified uncertainties whenever possible.

6 CONCLUSION

The tool suite is currently under construction: each tool that was developed and updated is in its validation phase. Developments on the ADRYANS® tool made in 2016/2017 included composite materials in the available models of materials behaviours in order to prepare for computations of upper stages re-entries. An evolution of the presented EPC test case including tanks thermodynamics will be run at the end of the year 2017. Further improvements with implementation of materials thermal and mechanical models issued from R&T characterization projects will be implemented in the next year and added to the final testing of the tool suite.

7 ACKNOWLEDGMENTS

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1 REFERENCES

1. C. Bonnal. (2016). Space surveillance and orbit population catalog: Origin, evolution and observation, STO-AVT262 *Space debris lecture series*, Von Karman Institute, Waterloo, Belgium
2. T. Lips, B. Fritsche, G. Koppenwallner, C. Leveau. (2008). Ariane-5 EPC re-entry - a comparison of observations and SCARAB

simulation results, Proceedings of the 2nd IAASS Conference "Space Safety in a Global World" 14-16 May 2007, Chicago, USA (ESA SP-645, July 2007)

3. J. Villa. CNES/DLA/SDT/SP (2001). Overview of Ariane stages reentry simulation method and flight experiments. Presentation to CoordinationGroup on Space Debris 8th meeting
4. CNES Direction des Lanceurs. (2016). Internal study on EPC fragmentation during reentry