Development status and application of ArianeGroup Fragmentation/Survivability chain of tools

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ABSTRACT

The ArianeGroup Company is responsible, as prime, for the Ariane launchers family (Ariane 5 on going and Ariane 6 in development phase).

As part of the prime responsibility, it is mandatory to master the reentry of launchers debris on Earth, as required by international regulations and French LOS /FSOA (Loi sur les Opérations Spatiales / French Space Operation Act).

Following guidelines issued by UNCOPUOS concerning space debris mitigation, France has established a dedicated space law accordingly. Ariane 6 is the first launcher in development for which full compliance to French LOS must be demonstrated, including upper-stage deorbiting. To do so, the re-entry scenario of launcher upper-stages must be precisely predicted and mastered to avoid human casualty on ground.

Therefore it is needed to increase our knowledge of each domain of re-entry physics, to improve our models and to develop a mastered industrial methodology, including tools development, to reduce survivability model margin and improve the assessment of the launcher upper composite 'impact footprint size’

The objective of this article is to give a global overview of this activity carried out over the last years. A synthesis of the main outcomes will be presented, allowing its actual implementation to contribute to Ariane6 Safety File. The validation approach will also be outlined, including the possible need for a dedicated flight experimentation or an external observation, with a specific interest towards a better understanding of fragmentation phenomena.

1 INTRODUCTION

ArianeGroup as the industrial prime contractor of the next European launcher Ariane 6 has to demonstrate its full compliance with the French Space Operation Act (FSOA) requirements [1]. In particular, this Technical Regulation requires safe deorbiting of the launcher upper stage ULPM (Upper Liquid Propulsion Module). One essential aspect to be addressed in the safety file is therefore the consideration of the launcher fragmentation and survivability in far field, at fallback in ascent phase and at launcher re-entry [2].

It was hence decided a few years ago to develop an industrial methodology in order to gain the adequate mastery of the domain:

- Increase knowledge of each re-entry physics domain (hypersonic aerodynamic and aerothermal, flow surface interaction, thermochemical and mechanical material response under high temperature, tank thermodynamic)
- Reduce survivability model margin
- Improve the assessment of the launcher upper composite debris' impact footprint size
- Gather all the expertise needed in an in-house tool to cope at system level with launcher upper stage debris behavior

Corresponding studies have been undertaken in the framework of internal R&T, with a significant co-funding of CNES Research and Technology Launchers program for the major part [3]. The corresponding work plan was conducted over several years, which enabled the development of all necessary bricks: numerical tools, material characterization, uncertainty quantification [4].

2 OVERVIEW OF THE FRAGMENTATION AND SURVIVABILITY TOOL SUITE

2.1 Re-entry simulation framework

An end-to-end approach is required in order to consider the multiple physical phenomena occurring during the destructive reentry of a spacecraft (Fig. 1), with the final objective to evaluate the resulting casualty risk on ground:

- Determination of the upper stage trajectory from orbit till EIP (Entry Interface Point) (attitude, thermal,…)
- Simulation of Upper Stage Break-Up, resulting from combined thermal and mechanical loads
  - Then, application of the same methodology for 'complex children parts'
- Analysis of the survivability of each generated fragment
  - till complete demise or ground impact

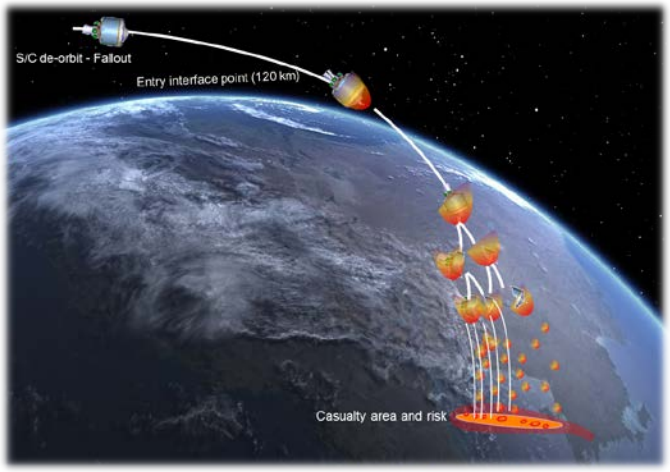


Fig. 1. Main phenomena during reentry

Over the past few years a comprehensive tool suite was developed within a co-funded R&T activity with CNES. In order to capture all abovementioned physical phenomena, it gathers the following elements (Fig. 2)

- a detailed digital mock-up of the spacecraft
- a combined 3D aerodynamic and aerothermodynamics code (ARPEGE®), coupled with a six degrees-of-freedom trajectory simulator (BL43)
- a commercial thermomechanical finite element software (SAMCEF®) and a thermodynamic code for the response of the propellant tanks (SITTARE®).
- engineering criteria to detect fragmentation, and build a resulting list of debris
- an object-oriented in-house code ADRYANS® [5], to analyse the survivability of all debris

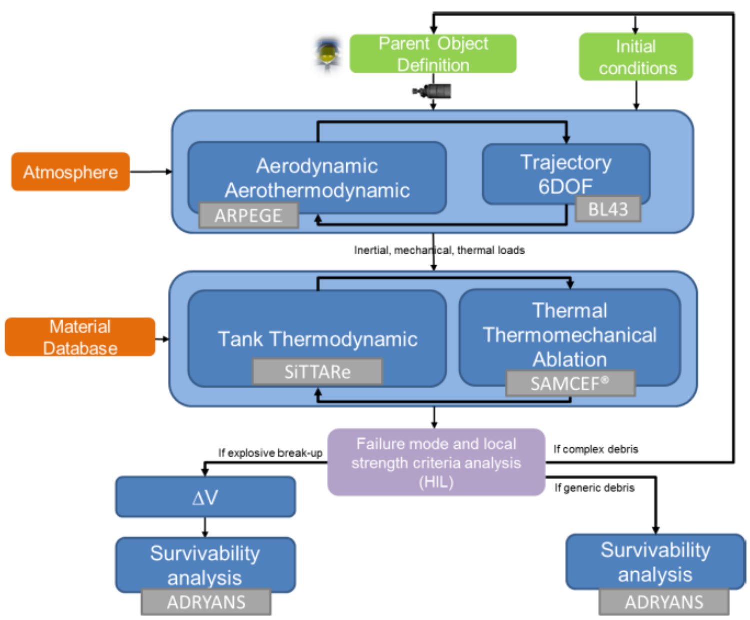


Fig. 2. Schematic Description of the fragmentation / survivability tool suite

2.2 3D aerodynamic and aerothermodynamics: ARPEGE®

ARPEGE, which stands for Aérothermodynamique de Rentrée pour PrédirE la fraGmentation d'Etages (reentry aerothermodynamics for upperstages fragmentation prediction) is an ArianeGroup code whose part of the development was conducted within co-funded R&T activity with CNES. It is applied on a complete stage, or on large fragments, and it main key features can be summarized as follows.

Inputs : – Geometry – Velocity / rotation – Position / attitude – Atmosphere model **Flow regime:** – From free molecular to continuum flow	**Outputs : Evolution vs time of multiple parameters:** – Pressure distribution – Aerodynamic coefficients – Shear stress coefficients – Convective and radiative heat flux

Its validation relies on a classical approach, considering multiple examples and test cases:

- Covering all flow regimes.
- Test cases extracted from :
  - Literature review: hypersonic on spheres, flat plates and half cone 15°
  - ArianeGroup's own database of wind tunnel tests:
  - ArianeGroup DSMC software: validation test cases
- Crosschecking with CFD results

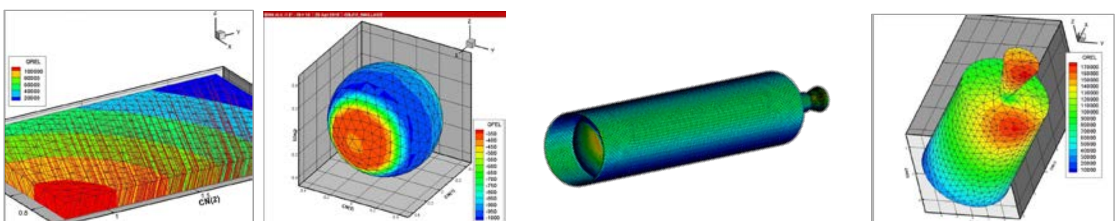


Fig. 3. A few results with ARPEGE®: from elementary validation to complete cases

2.3 Overview of the thermomechanical modelling and resulting fragmentation approach

In order to determine how the re-entering object will break-up, the second key step of the approach is the thermal and thermomechanical response, for which the industrial software SAMCEF® and its modules THERMAL – AMARYLLIS® and MECANO® have been used.

SAMCEF® is a commercial software that is technically supported by the University of Liège. These codes are dedicated to the simulation (in 1D, 2D, or 3D) of non-linear, transient thermal and mechanical responses of materials and structures. AMARYLLIS contrary to THERMAL, allows thermochemical degradation (pyrolysis) and ablation (by both chemical and mechanical) simulation. The THERMAL/AMARYLLIS® and MECANO® modules rely on the finite elements discretization technique.

A specific approach is also applied to consider pressurized vessels and residual propellants. Mechanical loads, pressure variations and phase change of propellants may indeed be a source of explosion and hence fragmentation of the stage. Low temperature and high thermal capacity of remaining propellant can act as a cooling fluid that delays thermomechanical degradation of the structure, or have a phase change that will induce a pressure burst that will cause the fragmentation of the stage.

Classical nodal convection approach is sufficient to get the right behaviour. As such, ArianeGroup has developed the SITTARe® tool and coupled it with SAMCEF® THERMAL to compute temperature and pressure variation in tanks (for both gaseous and liquid propellants) in the 3D thermal computation of the chain.

Based on above-mentioned simulations, one essential aspect is a proper break-up determination. This one relies on a few different engineering criteria encompassing the complete domain including possible unknowns and dispersions.

- The first degradation criterion for metallic parts and composite materials considers complete degradation of structure properties (melting of metals, degradation of sandwich composite skins and/or glue). It usually leads to the lowest fragmentation altitude.
- A second criterion has been considered based on a comparison between mechanical properties loss due to temperature and the global strain on the structures due to the trajectory (corresponding to 50% mechanical properties loss).
- A third criterion was considered based on dynamic pressure Pdyn-induced material stress that is computed and compared to the structure maximal allowable stress (temperature-dependent). It usually corresponds to highest fragmentation altitudes.

The debris survivability is then assessed taking into account these various altitudes of fragmentation. A list of debris is set up and the trajectories of released fragments are computed down to ground or complete demise.

2.4 Survivability and trajectory tool ADRYANS®

ADRYANS® which stands for Assessment of Debris Re-entry and ANalysis of Survivability is an object-oriented code that can evaluate the survivability of a piece of debris [5]. This ArianeGroup tool was co-developed with CNES within joint R&T framework. This survivability analysis tool is used after fragmentation, once multiple fragments are separated from the parent structure. It computes the 1-dimensional thermal, charring and ablative response of a simple metallic or composite shape (i.e. sphere, flat plate, etc.) (Fig. 4), coupled with on a 3 degree of freedom version of the in-house trajectory code BL43.

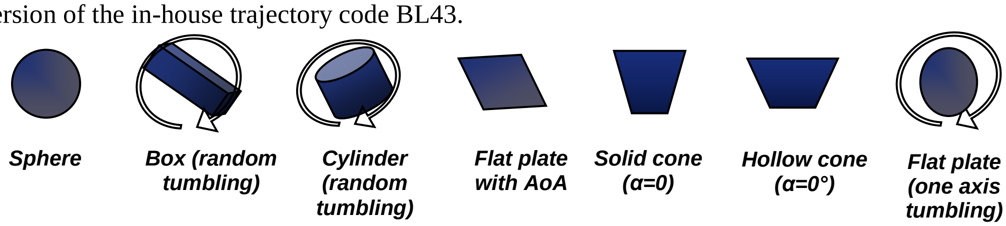


Fig. 4. A few typical shapes considered by ADRYANS®

Beyond the computation itself, material data are essential inputs for good quality results, and ADRYANS® database includes composite and metallic materials thermal models from specific experimental characterization campaigns.

3 MATERIAL DATABASE

In parallel with the development of the tool suite described above, the second major research axis consisted of a comprehensive characterisation of materials in order to better assess the behaviour of upper stages during re-entry.

As launcher parts are indeed not designed to survive an atmospheric re-entry, the temperatures and stresses on structures can become higher than the values they were designed to withstand during the ascent and in orbit life phases. As such, it is important to enhance the material database accordingly by performing adequate characterisation of metallic and composite materials. The corresponding series of tests were carried out over the past years as part of the ArianeGroup/ CNES R&T framework [3, 4, 6].

3.1 Characterization approach

An important initial step was the selection of the launchers materials to be experimentally characterized. It was based on the analysis of their mass distribution on the Ariane launcher family, both for metallic and composite materials. In addition, it was relevant to select at least one material for each major type, as summarized in Table 1.

Most of these materials have been used for long. Metallic materials families such as aluminium, titanium, steel, among other that are usual components of launchers as well as composite structures such as CFRP (Carbon Fiber Reinforced Polymer) products (tanks, parts, sandwiches). Other composite materials such as cryogenic TPS (Thermal Protection Systems) are used on cold tanks.

As such, they are pretty well known in their usual working domain, but there was little information in the literature about their behaviour at higher temperatures, when approaching their degradation limit under reentry conditions [3].

Table 1List of selected materials for characterization

Material family	Typical Use
Al 7075	Flange , tube, motor case …
Al 2219	Cryogenic tanks, dome, cylindre
Ti6Al4V	Spherical tanks, motor items
AISI 304L	Motor items, fluid circuits
INCO 718	Turbopomps, cardan

Material family	Typical Use
CFRP carbon skin	Carbon skin pre-selected for equipment bay of A6 Upper Stage
CFRP carbon skin	Carbon skin CFRP SYLDA A5
Wrapped carbon structure	Proposed baseline for A6 He Tanks Thick carbon structure compared to CFRP skins
Cold Thermal Protection	Cold (cryogenic) Thermal Protection Ariane5

A complete characterization test plan was thus undertaken, in order to address following aspects:

- Characterisation of the basic thermo-physical properties
- Characterisation of thermomechanical properties, up to temperatures as close as possible to degradation limit
- Characterisation of the materials thermo-ablative behaviour under a representative re-entry environment, by relying on ground tests involving plasma torch facilities. In particular, it is important to target a maximum representativity, because several phenomena are transient and can lead to different scenarios. For instance, oxidation of metals can create a protective layer, change the emissivity…which can result in significant discrepancies if not assessed properly.

As of today, this thermoablative characterization has been undertaken only partially, and needs to be pursued.

As a complementary thermomechanical characterization of joints could also be of high interest, the corresponding test rationale was established. This task might be undertaken if necessary to support further refinement of reentry predictions.

In addition, other characterization activities have been funded by CNES or ESA. Even though they are more focused on satellites materials, it is intended to take benefit -when relevant- from the publicly available data [7, 8] that are also gathered in material databases such as ESTIMATE (ESA) or MATREX (CNES).

3.2 Application to modelling

Characterisation effort described above enabled setting up a relevant material database.
However, it is also worth highlighting that all dispersions and uncertainties were also assessed, in order to include their influence in the evaluation of the casualty risk.

Complete materials models including ablation and pyrolysis phenomena can be derived from this database. However, 3D models can be very complex to handle with sophisticated material datasets. Simplified material thermal models were thus implemented as well with the objective to provide equivalent thermal response as with complex models on the thermal range considered as critical for the study. As such, the engineer task is simplified by limiting the simulation preparation cost. The second advantage is the reduction of the computation time.

4 VALIDATION: THE EPC TEST CASE

In order to apply the developed re-entry modelling tool and validate each brick, a test case already analysed in literature was relevant. As an observation campaign was organised for the Rosetta flight (V518, March 2, 2004), the corresponding EPC (Etage Principal à propulsion Cryotechnique which is Ariane 5 lower stage) was selected [9].

The complete tool suite was applied, including:

- Aeroshape modelling for aerothermal and aeromechanical loads computation with the ARPEGE tool
- Thermal and mechanical 3D FEM (Finite Element Method) model for thermomechanical computation with the SAMCEF® commercial software, enabling to establish fragmentation scenario
- Survivability analysis with ADRYANS® V5 tool [5], considering a relevant list of debris.
  - LOX and LH2 tank panels and domes
  - Electric pieces of equipment of the JAVE (Jupe AVant Equipée)
  - Pieces of equipment of the motorbay
  - Separated high pressure tanks for the Vulcain®2 engine: three spherical and one cylindrical tank
  - Vulcain®2 engine components: turbopumps, combustion chamber, nozzle. Due to their composition, these parts are assumed to survive until ground impact.

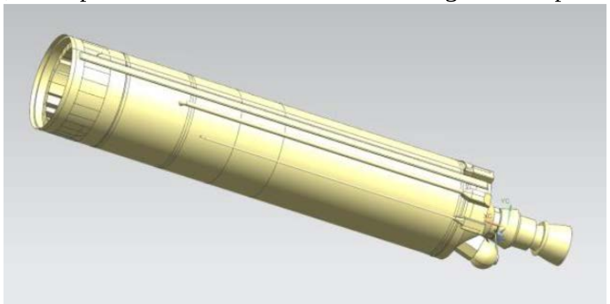


Fig. 5. Simplified geometry of the Ariane 5's EPC

Beyond satisfactory correlation towards observed fragmentations, this test case provided the first opportunity for a comprehensive trial of the tool suite, including overcoming of a few typical modelling issues:

- Improvement of materials models: metallic and composite materials models were created based on material characterization test campaigns performed between 2016 and 2019. They include behaviour at high temperature for both thermal and mechanical properties and include degradation models (pyrolysis and ablation for composite materials).
- Improvement of interfaces behavior, at high temperature and under re-entry induced mechanical stresses: analysis of both in-house and literature design and modelling methods was performed.
- Improvement of thermal exchanges: the work was performed on multiple heat fluxes sources; coupling with the thermodynamic tool SITTARE was validated.
- Optimisation of the modelling method for TPS and structure components.
- And more generally, all practical issues resulting from the huge size of the model, very difficult to mitigate while searching a maximum physical fidelity.

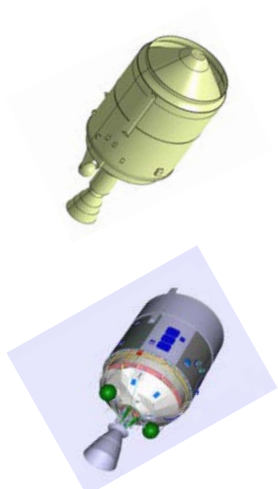
Further to the satisfactory results gained through this validation, the next step was the operational application for Ariane6 safety studies.

5 APPLICATION TO ARIANE6: ULPM FRAGMENTATION AND SURVIVABILITY AT RE-ENTRY

In order to comply with FSOA requirements [1], a safe deorbiting of the launcher upper stage ULPM is performed at end of mission. One essential aspect to be addressed in the safety file is therefore the consideration of the ULPM fragmentation and survivability in far field, during its re-entry [2].

5.1 Fragmentation scenario

Applying the developed methodology presented above, a realistic fragmentation scenario can be elaborated relying on thermal and thermomechanical analyses, enabling to assess on a given re-entry trajectory the altitudes of launcher elements fragmentation (Fig. 6).
Moreover, as the initial flight condition uncertainties and the breakup model parameters are likely the most important uncertainties, several trajectories at the boundary of the re-entry mission domain (direct re-entry as well as natural re-entry in case of failure leading to no de-orbiting) must be simulated.



ULPM CAD model

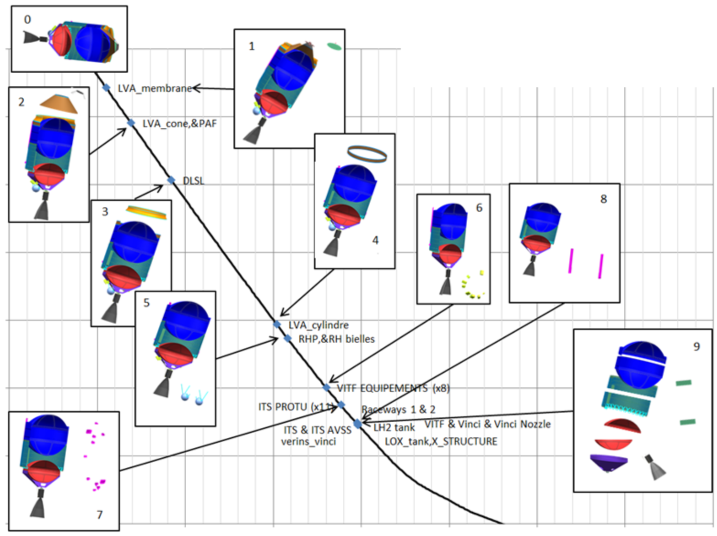


Fig. 6. Upper Stage fragmentation at re-entry

Launcher survivability is highly depending on the characteristics of the released fragments. The determination of the list of debris, based on engineering approach, is thus one of the major topics of the analysis. The main difficulty is to assess the launcher fragmentation when the melting temperature or the structural load limit is reached. It is therefore relevant to perform the analysis for two extreme cases (Fig. 7).

- For 'large debris' scenario, the upper stage is supposed to be broken into large structures. At the identified altitude of fragmentation, the removed part corresponds to a single large debris (such as an integer tank).
- The 'small debris' database is established by splitting the large debris into several smaller fragments. When reaching the altitude of fragmentation, each large part (identified as single debris previously) is decomposed into several fragments.

Large debris database is composed of about 10 fragments while small debris database comprises more than a hundred of different types of fragments.

Large debris: ~10 fragments

Small debris : > 100 fragments resulting from secondary fragmentations

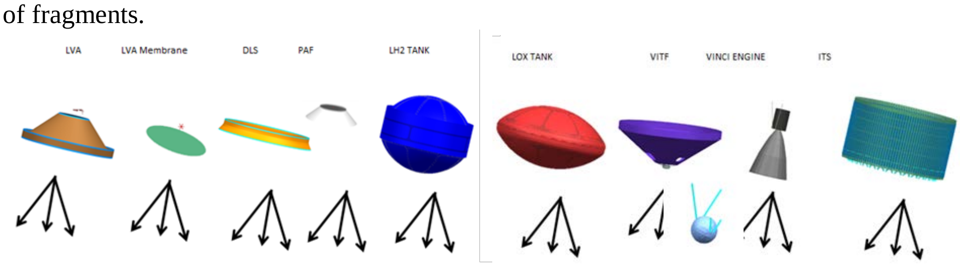


Fig. 7. Launcher fragmentation – Large and small debris lists

5.2 Survivability results

Depending on the fragmentation scenario, very different results may be obtained in term of survivability

- With 'large debris' approach, the large structures keep a high velocity and high heat fluxes along their trajectory. Thus the materials reach their degradation conditions and ablate all along the remaining re-entry trajectory leading to few surviving debris, corresponding to parts of the launcher made of Titanium or Inconel..
    - o The impact of conditions at re-entry is of second order. Only trajectory with a high slope at re-entry leads to more surviving debris. All fragments survive with almost their whole mass considering low altitude of fragmentation.
- For 'small debris' scenario, the structures will break into many pieces (with a lower ballistic coefficient). These small fragments slow down and lose momentum more rapidly than the big ones. It leads to keep the materials, even in Aluminium alloys, at a lower temperature. Hence the materials reach their degradation conditions later and do not entirely demise at re-entry.

The accuracy of launcher fragmentation at re-entry will therefore have a major impact on casualty risk assessment (resulting from whole casualty area). The 'small debris' scenario leads to the larger casualty area, while it is smaller with the 'large debris' scenario (Fig. 8).

It can also be highlighted that a precise knowledge of launcher materials and their characterization at re-entry is obviously another main contributor to survivability assessment [6, 9].

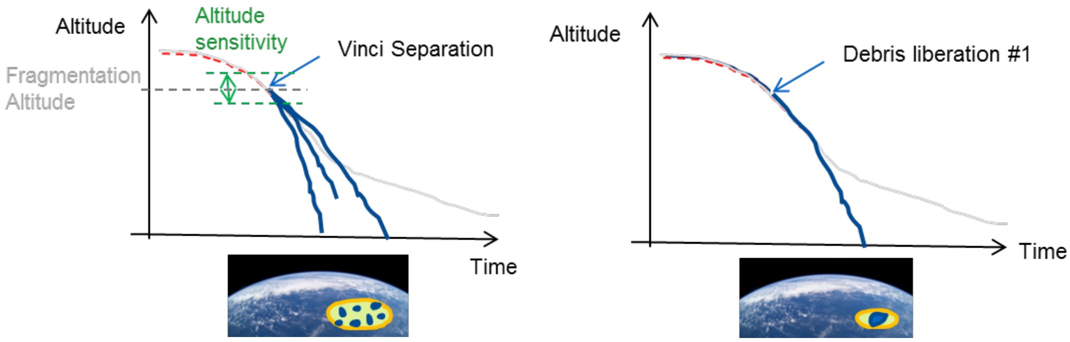


Fig. 8. Impact of debris database

Taken into account the large discrepancies in terms of surviving mass resulting from both fragmentation assumptions and also fragmentation altitudes, it is essential to select the best agreed launcher fragmentation database for casualty risk assessment. In addition to exchange with experts to assess through engineering approach, an adequate flight experiment and observation would be extremely useful to consolidate this topic.

6 Uncertainty quantification

Multiple complex physical phenomena occur during the entry phase of a launcher Upper Stage

– Hypersonic aerodynamics and aerothermodynamics
– Flow / Material interaction at the surface
– Thermochemical and mechanical response of materials at high temperature
– Tanks thermodynamics

The multiple interactions between those various phenomena make the complete analysis extremely complex, and it is hence widely acknowledged that uncertainties should be included in space object reentry predictions. This was therefore undertaken as joint effort between ArianeGroup and INRIA, as part of the tool suite enhancement process. In particular, this activity aims at an optimal management of the margins, as well as an identification of the phenomena with dominating influence over the risk.

However, uncertainty quantification analysis is usually extremely costly. Standard Monte Carlo methods require for instance hundreds of thousands of runs to get well-converged statistics. A more advanced approach was therefore developed [10]. A surrogate model is established for each module of the reentry simulator (Fig. 9), enabling a statistical approach to perform uncertainty analysis of the reentry of an upper stage. This analysis includes the uncertainties in the initial flight conditions, the material characteristics, the atmosphere model parameters, and the breakup model parameters. Moreover, a probabilistic breakup model is implemented. Instead of predicting a single deterministic breakup, this probabilistic breakup model derives a complete potential breakup distribution.

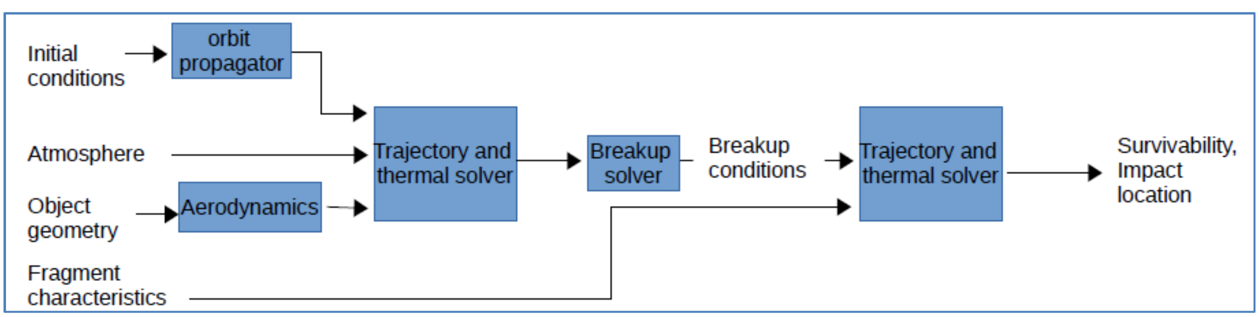


Fig. 9. Reentry simulator modules replaced by surrogate models

A sensitivity analysis based on the contribution to the variance of the flight conditions at breakup is also performed on a simplified upper stage model [11]. The initial flight condition uncertainties and the breakup model parameters are found to be the most important uncertainties (Fig. 10). Finally a robust estimation of the on-ground risk under uncertainty is proposed [12]. This uncertainty analysis is performed at limited computational cost thanks to the surrogate model construction approach.

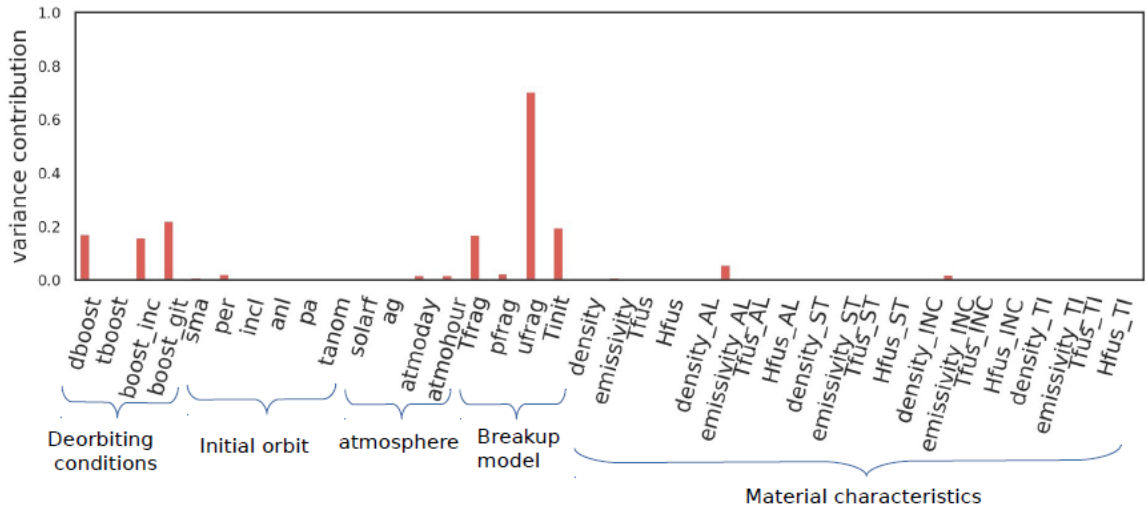


Fig. 10. Sensitivity analysis

7 Conclusion and Way Forward

This article summarizes the main activities performed in the framework of the shared CNES / ArianeGroup R&T activity. A comprehensive tool suite was developed in order to assess fragmentation and survivability during the destructive reentry of a spacecraft, with the final objective to evaluate the resulting casualty risk on ground:

This end to end approach also relies on a material database that required a significant characterization effort. Complementary work still needs to be continued to consolidate a few points, such as thermomechanical characterization of joints, or thermoablative behavior of materials.

A demonstration of the capability of the tool chain was achieved on the Ariane5 EPC test case, hence authorizing its operational application for Ariane6 safety studies. One essential outcome is that the fragmentation scenario is a major contributor for the determination of the casualty risk on ground.

The parallel development of an advanced methodology for uncertainty quantification was performed. Its application on a realistic upper stage model confirms the predominance of the fragmentation scenario to the final result.

In order to consolidate this aspect that relies to date on engineering expertise, an adequate flight experiment and observation would be extremely valuable.

8 ACKNOWLEDGEMENTS

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