COMPARISON OF CNES, ESA, JAXA, AND NASA REENTRY ANALYSIS TOOLS – PHASE I: MODEL DESCRIPTIONS AND SURVIVABILITY OF INDIVIDUAL COMPONENTS

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ABSTRACT

Reentry analysis is essential to understanding the consequences of the post-mission disposal of a spacecraft via atmospheric reentry. Since disposal is a key factor in spacecraft development, CNES, ESA, JAXA, and NASA have developed tools to assess the survivability of objects during reentry. Criteria such as debris casualty area and impact kinetic energy are particularly important to understanding the risks posed to people on Earth. Therefore, space agencies have undertaken a series of comparison studies of their respective reentry codes for verification and improvements in accuracy.

CNES's PAMPERO and DEBRISK, ESA's Spacecraft Atmospheric Reentry and Aerothermal Breakup (SCARAB) and Debris Risk Assessment and Mitigation Analysis (DRAMA), NASA's Object Reentry Survival Analysis Tool (ORSAT), and JAXA's ORSAT-J reentry analysis tools serve as standard codes for reentry survivability assessment of satellites. These programs predict whether an object will demise during reentry and compute the debris casualty area of objects determined to survive, establishing the reentry risk posed to the Earth's population by surviving debris.

Two series of test cases have been studied for comparison, the first of which uses generic parts, defined to use simple shapes and various materials for a better comparison of the predictions of these codes. This study is an improvement on the others in this series because of increased consistency in modeling techniques and variables. The overall comparison demonstrated that the six codes arrive at similar results. Either most objects modeled resulted in close agreement between the six codes, or if the difference was significant, the variance could be explained as a case of semantics in the model definitions.

This paper presents the main results of PAMPERO, DEBRISK, SCARAB, DRAMA, ORSAT, and ORSAT-J for the simple shape case and discusses the sources of any discovered differences. Discussion of the results of previous comparisons is made for a summary of differences between the codes and lessons learned from this series of tests.

1 INTRODUCTION

The space agencies of France, Europe, Japan, and the United States have developed destructive reentry simulation capabilities not only to understand how spacecraft and rocket bodies fragment and demise in the atmosphere, but also to preserve public safety through the limitation of dangerous surviving debris impacts. Since 2000, there have been dozens of conference papers, presentations, and peer-reviewed journal articles detailing the results of various software tools for satellite reentry scenarios and offering some comparisons between these tools.[1,2]

It is of great importance that the tools that each agency uses for its risk assessments be properly verified, validated, and calibrated; through these interagency comparison studies, this record of fruitful cooperation and mitigation of reentry risk is continued.

2 REENTRY TOOL DESCRIPTIONS

2.1 CNES Tools

In response to the growing issue of space debris, France enacted the French Space Operation Act (LOS) in 2008, establishing a national framework for the authorization and supervision of space activities. CNES is responsible for ensuring the proper implementation of the law. To assess the debris survivability during a spacecraft atmospheric reentry, CNES developed its own object- and spacecraft-oriented tools, named DEBRISK and PAMPERO, respectively. Object-oriented tools are tools that convert spacecraft parts into simple models and

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perform survivability analysis of simple shapes. Spacecraft-oriented tools use 3D models of spacecraft and perform survivability analysis of complex shapes.

Since 2008, CNES has been developing its own certification tool, DEBRISK. In 2012, version 2 of the software was released to space operators, enabling them to independently perform atmospheric reentry analyses. A DEBRISK computation generates a list of potentially dangerous fragments by estimating their final mass, kinetic energy upon impact, and the casualty area for each.

Version 3 of DEBRISK was developed from 2015-2023 [3], which was made available on the *ConnectByCNES* site [4] in July 2023, with no distribution restrictions. DEBRISK V3 is based on six main areas of improvements in terms of physical modeling. New shapes (10 in total) are now available to users, enabling more realistic geometry modeling. The main fragmentation is automatically calculated, taking into account the thermal modeling of the vehicle before the primary break-up event. Aerodynamics and aerothermodynamics are no longer based on Klett and Cropp methodologies [5,6]; they are now derived from Computational Fluid Dynamics (CFD) for the continuous flow regime and Direct Simulation Monte Carlo (DSMC) for the rarefied flow regime. The low-speed regime has been enhanced for all available shapes and over an extended range of Reynolds numbers, based on an extensive bibliographic study. Accurate representation of this regime is essential for estimating ground kinetic energy. The oxidation phenomenon can have a considerable impact on the wall heat flux balance. The Cropp model has been replaced by a CNES-developed model based on experiments conducted by the PROMES laboratory in various solar furnaces. Furthermore, emissivity values, which can be significantly affected by oxidation, have been updated in the materials database. The materials database has been updated, and a collaborative effort with ESA has been undertaken to harmonize it with the ESTIMATE database. In addition to these physical improvements, DEBRISK V3 comes with a more comprehensive Best Practices Guide to help users fragment and simplify their satellite [7].

Version 4 has been under development since 2024, with objectives that continue those of version 3: improving the accuracy of the aerothermodynamics part for all flow regimes encountered during the atmospheric reentry phase (rarefied, continuum, and low speed), and developing a robust methodology to estimate the aerothermodynamics of multiple connected elementary fragments (a so-called “brother” relationship).

PAMPERO is a multidisciplinary tool based on a spacecraft-oriented approach, co-developed by CNES and R.Tech to model the complete atmospheric reentry of a spacecraft. This includes the complex processes of fragmentation and ablation along a six-degree-of-freedom (DOF) trajectory. This tool provides in-depth analysis of the fragmentation process and supports the sustainable use of space by evaluating new design solutions for vehicles and components.

Versions 1 and 2 of PAMPERO (developed from 2013-2019) served mainly research purposes. The accuracy of the various disciplines has been extensively assessed via comparison with experimental and numerical data coming from higher fidelity codes. Version 3 of PAMPERO, released in 2022, included a complete rewrite in C++, resulting in an optimized industrial tool extensively used in several studies, such as the AVUM reentry rebuilding [8], design for demise/containment studies [9], and support to the DRACO mission project (to be published). This version has been used to compute all the test cases. A new branch is currently in development called *Hifi* (for high-fidelity) [10,11]. Its long-term objective is to address the modeling gaps faced by all spacecraft-oriented tools, by coupling CFD and DSMC high-fidelity codes for aerothermodynamics predictions. This version is not yet applicable to complex industrial cases.

PAMPERO V3 addresses several key physical phenomena to simulate the complete atmospheric reentry of a spacecraft. The aerodynamics and aerothermodynamics modules are designed to compute the aerodynamic coefficients and thermal heat fluxes [12-14]. The thermal heat transfer module is based on a 3D implicit thermal solver, optimized for industrial structures, allowing to solve heat transfer problems up to five times faster than widely used software like OpenFoam [15] (comparison on a satellite using 16 cores in parallel). Continuous validations have been conducted against codes such as OpenFoam [15], ESATAN, CodeAster [16]), as well as experimental data [17, 18]. The analysis of the dynamic mechanical stress is taken into account, which results from aerodynamic and thermal loads [10]. The mechanical deformation and stress fields are calculated by resolving the dynamical equilibrium at each aerothermodynamics load. This is handled by coupling with Code Aster [16] and optimized using the MPI protocol. The destructive phenomena are assessed, including ablation and fragmentation.

New developments focus on improving the efficiency of coupling with the high-fidelity tool Aster for mechanical stress computations and enhancing the accuracy of fragmentation modeling. This progress enables more accurate and comprehensive assessments of spacecraft reentry scenarios. To address the lack of accuracy in modeling composite materials, PAMPERO V3 introduces models capable of handling materials undergoing pyrolysis and charring, such as carbon fiber reinforced polymer (CFRP) composites. These models are based on detailed local thermal and chemical equilibrium using the Mutation++ library. Dedicated equations are solved through the material to account for pyrolysis, carbonization, and gas propagation through the material and interactions with the reacting boundary layer [10,18-20]. A large effort has been devoted to automated continuous integration to verify the physical models implemented during each software development iteration. Tests cover various aspects, including geometry, aerothermodynamics, thermal solver, ablation, performance, and more.

2.2 ESA Tools

ESA's DRAMA suite [21] includes the Reentry Survival and Risk Analysis (SARA) module, which is divided into two core components: the Spacecraft Entry Survival Analysis Module (SESAM) and the Spacecraft Entry Risk Analysis Module (SERAM). SESAM simulates both controlled and uncontrolled spacecraft reentries into Earth's atmosphere, analyzing the likelihood of fragments surviving reentry, while SERAM uses SESAM data to estimate the potential casualty risk posed by surviving debris.

SARA's Monte Carlo feature enables a stochastic approach to simulations. The atmospheric model—based on US76, NRLMSISE00, and HWM14—encompasses year-round atmospheric variability, accounting for (predicted and historical) solar and magnetic activity. The gravity model includes J2, J3, J4, and J22 harmonics for accurate reentry calculations.

In DRAMA, spacecraft are modeled as assemblies of simple geometric shapes—such as cones, boxes, cylinders, spheres, and rings—connected by either "included in" or "connected to" relationships. In the "included in" relationship, one shape is fully enclosed within another and shielded from airflow (forming a parent/child hierarchy), whereas in the "connected to" relationship, two shapes are partially exposed and share conductive surfaces. It is a component-oriented model [1]. Pre-calculated aerothermal data, based on a database of coefficients derived from panel methods and validated with CFD data, are available for each shape. Fragmentation events are triggered when the "included in" or "connected to" relationships are broken, typically due to thermal degradation (demise), though additional user-defined criteria such as temperature, altitude, load factor, dynamic pressure, or heat flux can be set. During the reentry analysis of connected shapes, shadowing effects are taken into account to adjust the aerothermodynamic properties of each fragment. DRAMA's material database, derived from ESA-ESTIMATE [22], includes metals, composites and amalgamation materials for modeling multi-material objects such as battery and electronic cards.

The suite features two ablation models: a nodal approach for metallic materials and a layered approach for CFRP-like materials. In CFRP-like materials, the model accounts for pyrolysis (where the epoxy matrix decomposes under aerodynamic heat) and oxidation (where, following epoxy decomposition, "charred" carbon fibres are exposed and begin to burn, converting from solid carbon to gaseous carbon oxide) [23]. Additionally, the suite allows for object explosions to be modeled, following the NASA's EVOLVE 4.0 model [24], based on triggers such as temperature or altitude.

SCARAB (Spacecraft Atmospheric Re-Entry and Aerothermal Break-Up) [25] is an ESA software tool allowing the analysis of mechanical and thermal destruction of spacecraft during controlled or uncontrolled reentry. It is an integrated software package (flight dynamics, aerodynamics, aerothermodynamics, thermal, and structural analysis) used to perform reentry risk assessments (quantify, characterize, and monitor surviving fragments during reentry). The software has been validated with in-flight measurements and reentry observations, and it has been compared to other reentry prediction tools. It has been developed continually since 1995 and has evolved over time based on lessons learned from preceding software versions, upgrades, and specific requests on reentry analyses performed for numerous satellites, the Automated Transfer Vehicle (ATV), and the Ariane-5 launcher program.

SCARAB has recently been upgraded with new models for aerothermodynamics and material ablation [26]. The capabilities of SCARAB have been extended to improve the support of Design-for-Demise (D4D) methodology modeling 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 CFD simulations and extend the SCARAB reentry simulation with options for fixed attitude and reference trajectory input. The new models implemented have been validated with recent data from wind tunnel experiments, reentry observations, and CFD.

2.3 JAXA Tools

The Object Reentry Survivability Analysis Tool- Japan (ORSAT-J) is a tool developed by JAXA to assess the survivability and risk to the ground of objects reentering from low Earth orbit (LEO). This tool calculates the trajectory and aerodynamic heating of objects reentering the Earth's atmosphere from an altitude of about 120 km, to evaluate the survivability of the objects when they reach the ground. This tool is derived from NASA ORSAT version 4 and has since developed independently in Japan. ORSAT-J performs trajectory calculation and heating calculation (convective heating, oxidation reaction, radiative heating, and radiative cooling) with initial inputs of celestial body information (celestial shape/gravity model, atmospheric model), initial orbit conditions, and object shape (including material properties). These calculations use the traditional methodologies of Klett [5] and Cropp [6] as a baseline. The object to be analyzed needs to be replaced by a simple shape (sphere, cylinder, box, and flat plate). In ORSAT-J, the motion is a 3-DOF assuming random tumbling, and the object's attitude and rotational velocity are not taken into account in the calculation. The object temperature calculation method can be either the lumped mass method, in which the object temperature is uniform, or the one-dimensional heat conduction method from the surface in contact with the outside to the direction of the object's center.

2.4 NASA Tools

NASA's Object Reentry Survival Analysis Tool (ORSAT), version 7.0 was used to simulate the scenarios for this first phase of the reentry tool comparison study. ORSAT was first officially released for NASA use in 1994 as ORSAT v4.0; versions 5 and 6 were developed from 1998 to 2006 and ORSAT 6.1 was in operational use until 2017 with the release of ORSAT 6.2. Similar to the ORSAT-J tool that was based on ORSAT v4.0, NASA's ORSAT relies on the Cropp-Klett methodology, where heat fluxes and aerodynamic drag coefficients are computed for simple shapes such as spheres, cylinders, boxes, flat plates, discs, and other convex objects [2,27-28].

ORSAT 7.0 was developed from 2019 to 2022 with the goal of implementing a charring ablation model for CFRP and glass fiber reinforced polymers (GFRP), respectively. This new CFRP and GFRP model was built using data collected from several test series conducted at the University of Texas at Austin inductively coupled plasma facility, as well as post-plasma-exposure testing and characterization at the NASA Johnson Space Center [29-32].

In addition to reducing the conservatism associated with prior CFRP models, such as the transitional "two-material model" implemented for ORSAT 6.2.1 [33], ORSAT 7.0 now also includes for the first time a method to compute aeromechanical breakup for these composite components [31]. This feature is very important to be able to analyze large CFRP structures such as those found on the SpaceX Dragon Trunk, or various launch vehicle upper stages.

Previous releases of ORSAT 6 included a built-in parametric study mode, which allowed users to perform univariate sweeps of variables to understand the sensitivity of ORSAT results to certain inputs. For ORSAT 7.0, the Python code AutoORSAT was completed and put into operational status, allowing for GUI input into ORSAT, multivariable parametric studies, and massively parallel simulations on the NASA Orbital Debris Program Office compute cluster.[34]

One final line of effort for ORSAT 7.0 was a combination of numerical gas dynamic simulations and hypersonic wind tunnel testing. When modeling certain objects, the typical solid convex shape primitives do not match the actual gas flow around the outside of the object. Some objects are hollow, like piping or attachment rings. Depending on the ratios of length-to-outer-diameter, and inner-to-outer-diameter of these hollow objects, they generally have three kinds of behavior: first, where the flow passes through the object unimpeded. For these cases, ORSAT analysts typically "break" the object and model it with another shape – imagine a ring being broken into a single long rod. Second, if the object is long compared to its diameter (like a drinking straw), the flow through the object will be minimal, and the object can be simply treated as if it were solid. The third case is where the flow through the object is slightly impeded; for these objects, a special "hollow object model" was developed, which now includes heat transfer from flow to the internal walls of the object. This model was developed from computational gas dynamics simulations for continuum, transitional, and free molecular flow, and a brief test series was conducted at the University of Texas San Antonio's Mach 7 Ludwieg tube facility to validate the model for "low-speed" flow [35, 36].

3 Test Cases

Seven simple test cases were selected as a basis of comparison for the first phase of this four-agency comparison study. The seven components chosen for comparison were: two types of propellant tank, a combustion chamber analog, a battery box, a solar panel, and two large structures representative of spacecraft buses. The shapes, masses, dimensions, and materials for these components can be found in Tab. 1, with masses in kilograms and dimensions in meters. For the codes that use DOF models, the initial attitude motion was set to 10 degrees per second.

These seven components were simulated following three trajectories: first, a shallow reentry trajectory from an ISS-like LEO; second, a lunar-return-type trajectory;

Table 1. Summary of test case components.

Test Case No.	Analog	Shape	Material	Mass	Width/Diam.	Length	Height
1	Propellant Tank	Sphere	Ti6Al-4V	10	0.5		
2	Combustion Chamber	Cylinder	A316	10	0.1	1.7	
3	Battery Box	Box	Al7075	28	0.5	0.6	0.3
4	Solar Panel	Flat Plate	CFRP	10	1	2	0.03
5	Propellant Tank	Sphere	Ti6Al-4V	20	0.5		
6	Spacecraft Bus	Cylinder	Al7075	371	1	1	
7	Spacecraft Bus	Box	Al7075	472	1	1	1

and third, a steeper reentry from LEO. These 3 trajectories are summarized in Tab.2., where EI indicates the entry interface, typically 122 km altitude, and FPA is the flight path angle, the angle between the velocity vector to the local horizontal plane.

Table 2. Summary of three test case trajectories.

	Traj. 1	Traj. 2	Traj. 3
Apogee Alt. [km]	122	11000	210
Perigee Alt. [km]	-320	-25	-685
Speed at EI [km/s]	7.4	9.5	7.6
FPA at EI [deg]	-0.1	-7	-2.5
Inclination [deg]	52	98	45

Test cases 1-4 were simulated using trajectory 1, the shallow LEO reentry; test case 5 was simulated using the lunar return trajectory (trajectory 2), and test cases 6 and 7 used the steep LEO reentry (trajectory 3).

The lunar-return-type trajectory is a special test case for two reasons: first, the high speed causes a different kind of heating to be a contributor that otherwise is negligible for LEO reentries – namely, gas cap radiation, the heating associated with the extreme compression and radiation from the shock layer ahead of a reentering body. The second reason is that the high speed combined with a steeper flight path through the atmosphere causes a higher peak heating rate, but a lower total heat fluence; more debris is anticipated to survive from this kind of trajectory than a circular LEO reentry.

4 RESULTS

All seven components were simulated by six reentry codes (DEBRISK, PAMPERO, DRAMA, SCARAB, ORSAT-J, and ORSAT), and the outputs of the codes were compared in detail. The computed trajectories (altitude, downrange distance, and time) were noted to be very similar (see Fig. 1, where all the curves lie essentially atop one another).

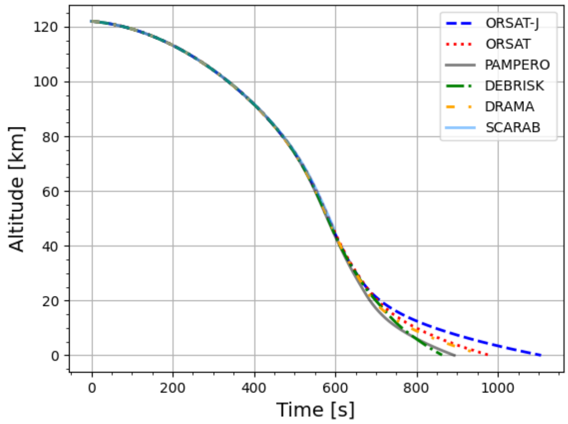

Figure 1. Comparison of altitude-vs-time curves for reentry tools for a generic test case.

The next items to be compared were the heating rates (total net heating, convection heating, oxidation heating, and re-radiation, *i.e.*, cooling). Even for simple shapes, like the spherical tanks, the different codes arrived at total net heating rates that differed by up to a factor of two, as in Fig. 2. Despite this large difference in the heating rates, however, the peak temperatures experienced by the objects did not generally differ by enough to change the character of the simulations. Fig. 3 shows an example of a test case where the temperature differences did not have a significant effect on the demise of the component; see Fig. 4 for a scenario (battery box) where the difference in the shape of the heating curves (higher heating rates at a higher altitude, earlier on in the reentry trajectory) can cause a difference in the demise result.

The qualitative survival/demise results for each component and each code are summarized in Tab. 3. Only one of the seven test cases showed significantly different demise results – test case 3 (the aluminum battery box). The two codes that predicted that the battery box would survive reentry also only predicted that less than 20% of the mass would survive, indicating that this object is of marginal demisability, an expected result for a nearly 30 kg block of aluminum.

Table 3. Comparison of Phase I reentry tool comparison study test case results

Test Case No.	CNES (DEBRISK)	CNES (PAMPERO)	ESA (DRAMA)	ESA (SCARAB)	JAXA (ORSAT-J)	NASA (ORSAT)
1 – Tank	Survived	Survived	Survived	Survived	Survived	Survived
2 – Propulsion	Survived	Survived	Survived	Survived	Survived	Survived
3 – Battery Box	Survived	Demised	Survived	Demised	Demised	Demised
4 – Solar Panel	Demised	Demised	Demised	Demised	Demised	Demised
5 – Lunar Tank	Survived	Survived	Survived	Survived	Survived	Survived
6 – Cylinder	Survived	Survived	Survived	Survived	Survived	Survived
7 – Box	Survived	Survived	Survived	Survived	Survived	Survived

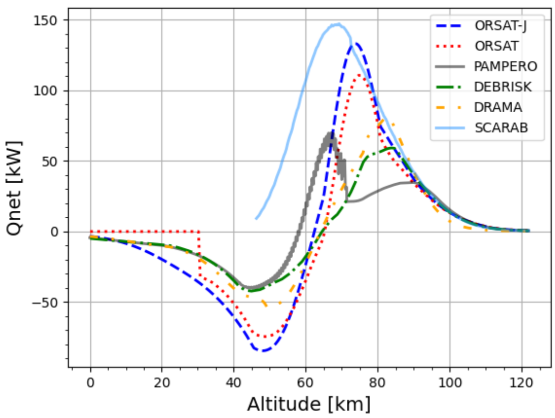

Figure 2. Comparison of total net heating rate for test case 1, the spherical titanium tank.

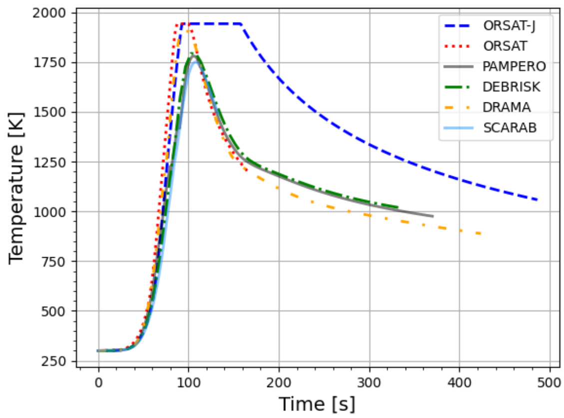

Figure 3. Comparison of surface temperatures along a trajectory for test case 5, the lunar-entry titanium tank.

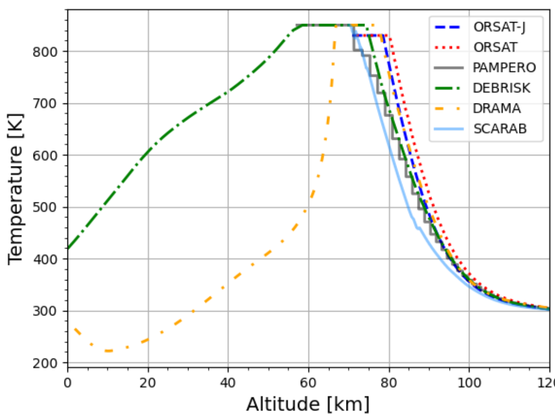

Figure 4. Comparison of surface temperatures along a trajectory for test case 3, the aluminum battery box.

5 CONCLUSION

With six of the seven test cases having the same categorical results across all six reentry codes being compared, and the last having some minor differences in the amount of surviving mass, a solid foundation of comparison has now been laid.

While some of the models, including oxidation heating, convection heating, and low-speed drag may need further investigations into the differences between codes, the overall results are not ultimately affected by these differences, at least for the selected seven test cases.

With these results, we are now confident in beginning the next phase of comparisons, which will comprise a full satellite test case with representative solar arrays, antennas, batteries, tanks, and other typical spacecraft components.

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