Thermite-for-demise (T4D): thermite characteristics heuristic optimization on object- and spacecraft-oriented re-entry models

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Keywords: Atmospheric Re-Entry, Genetic Algorithm, Thermite, Spacecraft Demise

Abstract. The major hazard associated with uncontrolled atmospheric re-entry is the casualty risk on ground. An innovative concept to support spacecraft demise that is now under investigation is the use of exothermic reactions. Thermites are good candidates for this role, being capable of releasing a noticeable amount of heat upon ignition. An appropriate selection of the metal-metal oxide couple can grant a formulation that is compliant with the main space operation needs, e.g., that is relatively insensitive to external stimuli and non-toxic. To support the selection of the energetic material for the experimental tests in the ESA-founded project SPADEXO and to preliminarily size the charge to be placed on board, the object-oriented code TRANSIT has been developed. This software has been compared to ESA's spacecraft-oriented code SCARAB (developed by HTG), that is capable to predict spacecraft re-entry with the highest possible level of detail. Both the models were subjected to a genetic algorithm optimization process to identify the best thermite properties and the foreseen energetic material mass for simple geometries applications. In this paper, the SCARAB results obtained for one geometry will be presented and compared with the ones retrieved by TRANSIT.

Introduction

The threat posed by space debris to the access and use of space is becoming more and more urgent every year. Recently, both the European Space Agency (ESA) and the Inter-Agency Space Debris Coordination Committee (IADC) have published their reports on the status of the space environment [1,2]. Considering the protected Low Earth Orbits (LEO) region as defined by IADC [3], the space traffic is now 10 times the level observed in 2000. However, both the cited documents demonstrate that the adoption of the space debris mitigation measures is insufficient. The ESA report [1] reveals that the 93% of small satellites (<10 kg) are naturally compliant with the 25-year rule, but for larger payloads the compliant share is significantly lower. Only between the 40% and 70% of the total payload mass is estimated to reach its end-of-life (EOL) in an orbit compliant with the current mitigation rules. If naturally compliant objects are discarded, until 2017 only between 10% and 40% of spacecrafts respected the mitigation guidelines [2]. Even if the trend in the last years has been generally positive, it is evident that the compliance rate is significantly lower than the internationally declared objective (90% [1,3,4]). Therefore, post-mission disposal (PMD) is still a problematic topic and the adoption of the current, if not even more stringent, mitigation rules is of paramount importance to reach a sustainable exploitation of space.

However, the necessity of de-orbiting spacecrafts from LEO involves an implicit casualty risk on ground. The current international guidelines [3] impose a maximum threshold for this risk of 10^{-4}. A first strategy to meet this requirement is to perform a high-thrust manoeuvre to force the impact on an uninhabited area, with the subsequent impacts on costs (e.g., additional fuel) and design. A second option is to perform an uncontrolled re-entry, possibly after a low-thrust manoeuvre or the deployment of passive devices to limit the residence time in orbit coherently with the 25-years limit. In this case, the associated costs and impacts on the post-mission disposal reliability would be lower. The main limitation for the use of this second strategy is the casualty risk limit. Its value must be computed using re-entry software like ESA's Debris Risk Assessment and Mitigation Analysis (DRAMA) [5] or Spacecraft Atmospheric Re-entry and Aerothermal Breakup (SCARAB) [6]. The uncontrolled re-entry is allowed only if the casualty risk threshold is respected. As its value is strictly connected to the spacecraft mass and to the robustness of its components, a rather new field of research is now becoming more and more important. This approach, named Design-for-Demise (D4D), consists in the intentional design of the spacecraft to promote its demise during the atmospheric re-entry, to limit the number and the mass of the fragments reaching the ground. One of the D4D strategies involves the maximization of the available heat to aid the demise of the most robust equipment. The main proposed solutions to act in this sense are the modification of the ballistic coefficient of the spacecraft, the exploitation of particular shapes to increase the local heat fluxes, or the use of exothermic reactions to provide additional enthalpy. The latter approach is the focus of this paper.

The hereby named Thermite-for-Demise (T4D) technology consists in placing a pyrotechnic charge into the structural voids of some spacecraft components. The energetic material, once ignited, provides the additional enthalpy necessary to induce the demise of the equipment. Thermites are particularly interesting for this application, thanks to their high energetic density, high adiabatic flame temperature, tunability and intrinsic safety [7]. An appropriate selection of the starting metal-metal oxide couple allows to meet both performance and operational requirements [8]. Recent patents proposed the use of thermites to promote spacecraft demise [9,10], and wind tunnel tests proved the concept in relevant environment [11,12]. A systematic study on the topic is currently ongoing in the framework of ESA-TRP SPADEXO project [13].

One of the main aspects of this technique that needs to be defined are the minimum thermite mass to be used and the best ignition time. Even if these parameters are strictly connected to the particular application (e.g., re-entry path, equipment material and shape) a heuristic optimization is hereby proposed for a selected simple geometry. A genetic algorithm is used on both an object- and a spacecraft-oriented re-entry software to minimize the thermite mass. The impacts of the different level of detail of the numerical models will be assessed, as well as the ratio between the component and the thermite masses for the selected conditions.

Methodology

TRANSIT. The object-oriented re-entry software used for this analysis is the TRANsatmosferic SImulation Tool (TRANSIT), developed to support the research on the T4D technology. The objective of this Python novel numerical model is to provide simple and fast simulations for a preliminary assessment on the efficacy of a T4D strategy for a given application. The selected atmospheric model is the NRL-MSISE00 [14] and the non-spherical shape of the Earth is described through a fourth-degree zonal harmonic description. The dynamic model that represents the ballistic re-entry is lumped and considers three degrees of freedom [15]. The aerodynamic model can handle three different geometries (sphere, cylinder, and box). The correlations for the computation of the coefficients of drag are taken from [16]. Shape factors are used to relate the heat load on the three randomly tumbling geometries with the stagnation heat flux on a flat plate [17] (for free molecular regime) or on a sphere [18] (for continuum regime). The hot air after the shock is considered as a non-calorically perfect gas in chemical equilibrium [19]. The thermal model is lumped, and the surface is assumed to regress uniformly.

SCARAB. The spacecraft-oriented software used for this study is SCARAB. It was developed since 1995 under the lead of HTG in the frame of ESA/ESOC contracts. It has been used to model the re-entry of numerous European satellites and launcher stages, as well as for rebuilding test campaigns in hypersonic wind tunnels. It has been compared to other re-entry prediction tools and validated with in-flight measurements. The main characteristic that differentiates SCARAB with respect to the more common object-oriented codes is the panel-based description of the spacecraft. This discretization allows the use of the complete 6 degree-of-freedom equations for the trajectory computation and the more detailed description of the temperature field in the spacecraft and of its break-up process. This representation consents to abandon the common random tumbling assumption and to include conductive heat transfer in the space object. An arbitrarily complex geometry can be reconstructed and then studied.

Thermite model. The additional enthalpy provided by the thermite is modelled as an internal heat source, that is activated once the spacecraft reaches the ignition temperature. The effective heat transfer Q_{eff} from the thermite to its vessel is quantified as per Eq. 1, where η is the heat transfer efficiency (hereby considered equal to 0.6 [13]), m_{th} is the thermite mass on board, and Q_{react} is the theoretical reaction heat release (3958.20 kJ/kg).

$$Q_{eff} = \eta \cdot m_{th} Q_{react} \tag{1}$$

The additional enthalpy is released according to five different profiles (constant, gaussian, early triangular, late triangular, and centred triangular). The user can select the duration of the reaction. In SCARAB, the heat source is applied only on the internal panels of the geometry. The reaction is started once the mean temperature of the spacecraft (in TRANSIT) or the local temperature (in SCARAB) reaches the ignition threshold. The thermal inertia of the thermite charge is considered modifying the specific heat and the mass of the vessel.

Optimization approach. When it comes to determining the impact of a thermite charge on a re-entering spacecraft, the inherent complexity of the re-entry process must be considered. Trade-off effects can be difficult to estimate. For example, a higher thermite filling for a hollow object implies both a higher additional enthalpy release upon ignition and a higher thermal inertia for the system. A lower temperature of ignition could imply an early decrease in mass, with a change in the ballistic coefficient that can be beneficial or not. Moreover, an early ignition could anticipate so much the maximum temperature reached during the descent that could provoke a temperature increase not sufficient to reach the melting point of the spacecraft material. To consider the complexity of the process, the heuristic optimization adopted in this study involves the use of a genetic algorithm, based on the open-source Python package PyGAD [20]. An aluminium sphere, with radius of 0.5 m and thickness of 0.03 m, was selected for the optimization. The initial conditions and the boundaries of the optimization variables are respectively presented in Table 1 and Table 2. Table 3 shows the main genetic algorithm parameters for the optimization in TRANSIT and in SCARAB. Notice that the lower level of detail of the object-oriented code consented to perform an extensive number of simulations in a reasonable time, while the generation and population numbers for the SCARAB optimizations are more limited due to time constraints. The material properties used in both re-entry software were taken from ESA's ESTIMATE database [21]. No demise is predicted for the random tumbling cases without the additional enthalpy released by the thermite. In the SCARAB case in which the dynamic module was activated, the demise of around the 20% of the stating mass is registered for the case without thermite. The fitness function used for the optimization is shown in Eq. 2, where f is the fitness, m_f and m_{sp} are respectively the final and the initial mass of the spacecraft, and m_{th} is the thermite charge mass.

$$f = \frac{1}{m_f + \frac{m_{th}}{m_{sp}} + 0.0000001} \tag{2}$$

Table 1: Initial conditions of the test cases.

Variable	Value
Longitude [°]	0
Latitude [°]	0
Altitude [km]	120
Velocity [m/s]	7273
Flight path angle [°]	-2.612
Heading angle [°]	42.35
Temperature [K]	300

Table 2: Optimization variables and boundaries for the genetic algorithm. Notice that the melting temperature T_{melt} of the material of the test case is used as the upper boundary for the ignition temperature.

Optimization variables	Interval
Profile [-]	[1,5]
Burning time [s]	[1,100]
Thermite density [kg/m^3]	[781,1095]
Filling factor [-]	[0.1,1]
Ignition temperature [K]	[573, T_{melt}]

Table 3: Main genetic algorithm parameters used for the optimization processes in TRANSIT and in SCARAB.

Genetic algorithm parameters	Value, TRANSIT	Value, SCARAB
Number of generations	100	20
Population per generation	50	12
Number of parents mating	15	4

Results

Table 4 shows the results obtained for the genetic algorithm optimization in TRANSIT and SCARAB. Complete demise was reached in all cases, therefore the fitness function value is the

Materials Research Proceedings 37 (2023) 668-674 https://doi.org/10.21741/9781644902813-144

ratio between the starting spacecraft mass and the thermite charge one. It can be seen how its value is rather similar between all the simulations, around the 20-25% of the initial sphere mass. The optimization performed in TRANSIT appears as the worst case, implying the highest pyrotechnic charge mass. In the object-oriented code the best case is represented by a brief Gaussian heat release, while in the spacecraft-oriented one the best result is given by a centred triangle profile, for both the analysed conditions. In the one performed with SCARAB considering the dynamics of the sphere as computed by the dynamic module a rather long duration is preferred. This could be due to the lower impact of the burning time in SCARAB numerical model. Notice that these profiles inherently imply a delay between the ignition time and the maximum thermite heat release equal to the half of the burning time. Moreover, it must be considered that both the cases in random tumbling condition foresee a maximum temperature in case of failed ignition around 700 K. On the contrary, the third case already experiences partial demise without the thermite action. This behaviour explicates why a significant difference in the best ignition temperature can be observed between the random tumbling cases and the one in which the dynamic module of SCARAB is activated. Summarizing, all the optimized results show a release of additional enthalpy that is concentrated on the last phase of the re-entry, when the aerodynamic heat is more pronounced. This behaviour suggests that a late ignition is beneficial.

Table 4: Results of the genetic algorithm optimization for TRANSIT and SCARAB.

Variable	**Variable value, TRANSIT (random tumbling)**	**Variable value, SCARAB (random tumbling)**	**Variable value, SCARAB (dynamic module)**
Profile [-]	Gaussian	Centred Triangle	Centred Triangle
Burning time [s]	10.16	20.34	83.18
Thermite density [kg/m^3]	861.10	784.70	781.25
Filling factor [-]	0.16	0.14	0.16
Ignition temperature [K]	639.44	650.11	767.66
Fitness [-]	4.11	5.17	4.51

Conclusions

A genetic algorithm was applied on an object- and on a spacecraft-oriented code for a simple geometry, aiming at quantifying the best thermite properties for a T4D application, in terms of burning time, temperature of ignition and heat release profile. For the selected application, full demise was obtained in all cases. The methodology hereby presented could be applied to an arbitrary re-entry application. The TRANSIT result was more conservative than the ones achieved with SCARAB. It is suggested that this behaviour is due to the variation of shape that is considered in SCARAB once the geometry has started the demise process. This could imply that an object-oriented code could be a proper tool for a first sizing of the pyrotechnic charge, later to be verified and further optimized using a more detailed software. An extension of the presented study to other geometries and materials could strengthen this insight.

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