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Thermite-for-Demise (T4D): Preliminary assessment on the effects of a thermite charge in arc-heated wind tunnel experiments

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Abstract

The use of thermite to aid spacecraft demise during atmospheric re-entry is investigated in the ESA-TRP SPADEXO project. The Thermite-for-Demise concept was tested in L2K arc-heated wind tunnel facility. In this paper, the design of the samples for the experimental campaign is presented. The SCARAB software was used to tune the heat load on the samples and to predict the test results. A new extension for the representation of exothermic reaction was implemented. A set of numerical and experimental data were compared, confirming good agreement in terms of thermal behaviour of the samples, extra heat provided, and ignition time.

1. Introduction

The number of objects in space, comprising debris and non-manoeuvrable satellites, is rapidly growing and already poses a threat to the safe access and use of specific orbits. The Council of European Union has recently acknowledged this problem and called for a reconsideration of the 25-years rule, towards a more stringent limit [1]. Actually, both the European Space Agency's (ESA) Annual Space Environment Report [2] and the Inter-Agency Space Debris Coordination Committee's (IADC) Report on the Status of the Space Debris Environment [3] reveal that the global space activity is not even compliant with the current mitigation rules. With the present level of adoption of the IADC mitigation guidelines, it is foreseen that the doubling of the space debris population may occur in the next 25 years. In addition, the increase of catastrophic collision events could lead to the multiplication of the space junk objects number by 10 times in the long term. It is evident that a widespread adoption of the IADC guidelines is of paramount importance especially for the Low Earth Orbits (LEO), where the space traffic is now 10 times the level observed in 2000. For this protected region the main mitigation measure is the atmospheric re-entry at the end-of-life (EOL). While the share of spacecrafts that is naturally compliant with the 25-years rule has significantly increased in the last years, the percentage of successful EOL manoeuvres for the non-naturally compliant ones is still low. If only the latter ones are considered, until 2017 only between the 10% and the 40% of spacecrafts respected the mitigation rules. In the last years this value increased to around 50%, but mainly due to the de-orbiting of one constellation and to the low number of satellites dismissed into non-compliant orbits. If these percentages are compared to the minimum compliance threshold required (90% [4][5]), it is evident that post-mission disposal (PMD) is still a problematic topic.

However, the reliability of PMD is not the only requirement that must be considered. A re-entering spacecraft inherently implies a risk for people and goods on ground, whose acceptability threshold is commonly defined in 1 in 10 000. A strategy to observe this necessity is to perform a high-thrust controlled re-entry targeting an uninhabited area. Unfortunately, this solution implicates a significant impact on mission budget and design complexity. A second possibility is to limit the fragments reaching the ground at the end of the re-entry process. This is the rationale behind the Design-for-Demise (D4D) approach. D4D is the intentional design of the spacecraft to promote its destruction during the atmospheric re-entry, to comply with the casualty risk limit and therefore to enlarge the share of spacecrafts for which an uncontrolled re-entry can be allowed. This would permit to spare a noticeable amount of fuel and to simplify the spacecraft design, with economical and reliability benefits.

Several studies have proposed and evaluated different D4D techniques [6][7][8]. Among the approaches that have been investigated there is the replacement of the most robust materials like titanium or steel, the weakening of structural joints to exploit the advantages of an early fragmentation, the use of porous materials or particular shapes to control the heat load distribution, and the utilization of nets or tethers to reduce the number of fragments. A relatively new strategy is the incorporation of an energetic material into the spacecraft voids to maximize the available heat [9][10][11]. Thermites are particularly interesting for this role, thanks to their high adiabatic flame temperature, high energetic density, and relative stability [12].

This last technology is the focus of this paper. This approach is hereby defined as Thermite-for-Demise (T4D). In the frame of the ESA-TRP SPADEXO project, led by Hypershall Technologie Göttingen GmbH (HTG) and involving Politecnico di Milano, DLR-Cologne, ReActive Powder Technologies, and Airbus Defence and Space, T4D is currently under study. Thermite charges have been tested in the DLR L2K arc-heated wind tunnel to verify the applicability and effectiveness of this technique. In the following sections, the preparatory studies to the experimental campaign will be detailed. Particular effort was dedicated to predicting the thermite ignition as well as its effect on the sample temperature, and to assuring the safety of the test facility. In Section 2 a background on D4D verification and thermites is presented. In Section 3, the geometry of the samples and the formulation used in the test campaign is reported. Section 4 describes the experimental set-up and the numerical model used to assess the measurability of the energetic charge effect. In Section 5, three test cases are chosen to validate the computational tool. Lastly, Section 6 presents the conclusions and the next steps of the project.

2. Background

2.1 D4D technology verification

The verification of a D4D strategy is a complex subject. The main problem is the difficulty of directly testing the equipment in re-entry conditions. A pioneering project in this sense is the ESA mission DRACO (Destructive Re-entry Assessment Container Object), to be launched in 2027 [13]. It will be the first destructive re-entry experiment aimed at measuring the break-up of a spacecraft in the space environment. Until now, observations of re-entry events have provided the research community only limited data, allowing at best the verification of general trends (e.g., the typical altitude of the main fragmentation event [14]). In this framework, the typical approach to assess the effectiveness of a D4D technology implies both ground testing and numerical analysis. To support this process, ESA has established guidelines and best practices for the verification of D4D at system, equipment, and material level [15].

Different types of ground facilities can be used for D4D verification, depending on the purposes of the study. Static tests typically involve the use of a vacuum chamber, in which the material or the equipment is heated up to temperatures relevant to the re-entry conditions, through a radiative heat source. Such experiments are useful to characterize material properties and the thermochemistry of the sample surface. In some cases, mechanical loads can be applied, but the interaction of the sample with the high velocity flow typical of re-entry environment cannot be studied. A second type of facilities that consents to reach hypersonic velocities are shock tubes. They permit to recreate aerodynamic conditions (Mach and Reynolds number) that are representative of the re-entry process. The test time is very short (few seconds at maximum), so it is not possible to reproduce the heat conditions of an atmospheric re-entry. Experiments in these facilities aim at studying the aerodynamics and shock interaction. A third type of premises used for D4D verification are the high-enthalpy hypersonic wind tunnels. A continuous high-enthalpy flow is created and reaches the sample, after passing through a nozzle. The method employed to create the flow categorizes the wind tunnels, as it defines the conditions that the facility can recreate and therefore its recommended use. Among the different types of high-enthalpy hypersonic wind tunnels, the arc-heated ones can produce particularly high heat loads, therefore these premises are better suited to study the late phase of a re-entry trajectory. Generally, the dimensions of the test chamber are limited, so it is possible to work either at equipment or material level. In Europe, the facility that can test the largest sample (< 2 m) in relevant conditions is CIRA's SCIROCCO [16], while the typical sample size for other premises is below 0.5 m. The main limitations of high-enthalpy hypersonic wind tunnels are the complexity of testing random tumbling objects and of reconstructing the dynamic heat load that a spacecraft experiences during the re-entry. Nevertheless, these experiments are precious to prove D4D concepts and validate their simulation.

The other tool used to verify D4D technologies is the numerical analysis. Various re-entry models have been proposed in the last decades, each one with its own peculiarities and level of detail. In Europe, the baseline is the Debris Risk Assessment and Mitigation Analysis (DRAMA) [17], the instrument provided by ESA to spacecraft builders to verify the compliance to the debris mitigation requirements. Other tools have been proposed over the years: noticeable examples in the European framework are the Spacecraft Atmospheric Re-entry and Aerothermal Breakup (SCARAB) [18], the Spacecraft Aerothermal Model (SAM) [19], and PAMPERO [20]. In particular, SCARAB is a comprehensive software package capable of simulating flight dynamics, aerodynamics, aerothermodynamics, as well as thermal and structural analysis. It was developed under the lead of HTG in the frame of ESA/ESOC contracts, since 1995. It has been compared to other re-entry prediction tools and validated with in-flight measurements and observation. It has been used to model the re-entry of numerous European satellites and launcher stages. Its principal commercial application is the assessment of re-entry casualty risk, nevertheless it has been successfully employed to rebuild ground test campaign in wind tunnels. SCARAB comprises a Wind Tunnel Mode (WTM) that is able to represent the typical conditions reached in a hypersonic wind tunnel. An example of this application is the CHARDEM (Characterisation of Demisable Materials) project [21], in which five materials commonly used in space industry have been completely characterised in DLR-Cologne's L2K and L3K facilities. These results were of paramount importance for the establishment of ESA's material database ESTIMATE [22]. Another project of relevance for the study presented in this paper is the ESA-founded ERASD test campaign [23]. In these experiments, performed in L2K wind tunnel, a realistic ball bearing unit (BBU) geometry was filled with thermite and then exposed to the high-enthalpy flow to prove the concept behind the T4D technology. The outcomes of this campaign were the starting point of the SPADEXO project.

2.1 Thermites

Thermites are the perfect candidates for an exothermic reaction-assisted spacecraft demise. This subset of energetic materials is characterized by a high adiabatic flame temperature, a high energetic density and intrinsic safety. These materials, usually in powder form, are formed by a mixture of a metal and of a metal oxide. If stimulated by an appropriate energy source, these formulations start a redox reaction that results in the oxidation of the starting metal and in the production of the pure metal of the starting oxide. The first patent regarding this type of reactions was presented by H. Goldschmidt in 1895. Since that moment, thermites found many industrial applications thanks to the noticeable heat that is generated during their reaction and to their tunability. Some examples are rail welding [24], cutting torches [25][26], green firecrackers [27], and incendiary grenades [28]. The selection of the metal - metal oxide couple assures a wide range of properties, especially in terms of heat generated, gas production and sensitivity [12][29]. Moreover, the formulation is not the sole degree of freedom when selecting thermite properties: granulometry, particle shape, oxidizer to fuel ratio, and compaction can strongly influence characteristics such as reaction rate and reactivity. Lastly, the material preparation method is an additional tuning leverage. Activation of the starting powder can grant exceptional features by altering the initial shape, surface finishing, composition, or structure. This family of processes can be divided in three categories: mechanical, chemical and mechanochemical activation. A comprehensive discussion of these methods can be found in [30][31]. In the SPADEXO project, mechanical activation through high-energy ball milling has been applied to a thermite formulation to increase its reactivity and guarantee reliable ignition even at relatively low temperatures. In this study, a conductive approach was chosen to transfer heat from the reacting thermite to the target. This T4D embodiment consists of placing the pyrotechnic charge in the structural voids of the equipment, letting the reaction start due to the heat up of its vessel thanks to the interaction of the spacecraft with the re-entry environment. The ideal characteristics of the formulation are a high energetic density to limit its impact on the equipment design, a high combustion temperature to be able to heat up to melting typical space structural materials, an insensitivity that grants no unintended ignition in the operative conditions of a spacecraft (e.g., ground storage, launch, in-orbit thermal cycles), and a tunable reactivity to select the desired temperature range for ignition. Thermites can fulfil all these requirements.

3. Materials tested

3.1 Equipment mock-ups

Three different geometries have been placed in the L2K wind tunnel and tested at various thermite filling factors. The outcomes of ERASD project [23], that involved experiments with realistic BBU-like samples, indicated that a simpler configuration is beneficial for retrieving the thermal behaviour of a T4D application. For this reason, in the SPADEXO test campaign simpler mock-ups were designed, avoiding details such as the ball bearings and the layered structure of the oil chamber. Three cylindrical geometries were derived from two applications: a ball bearing unit (BBU) and a solar array drive mechanism (SADM). Figure 1 and Figure 2 present two out of the three configurations that will be analysed in this paper. The third one, named thick-walled BBU, is similar to the one shown in Figure 1 but is characterized by thicker lateral wall. The BBU geometries had an external diameter of 50 mm, while the SADM one of 100 mm. All the samples were made of steel 316L. The samples were instrumented with a set of type K class 1 thermocouples, placed as reported in Figure 1 and Figure 2. In addition, two pyrometers (Maurer KTRD 1485 and QKTRD 1483) were used to acquire the front face temperature. Two IR thermocameras (Optris PI 1M and Infratec VarioCAM HD) registered further thermal data. Finally, videos of the tests were recorded from different perspectives.

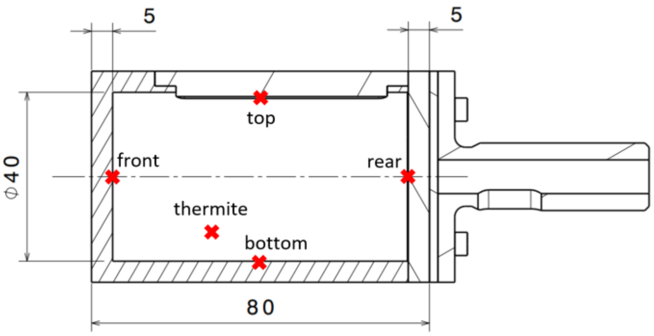

Figure 1: Thin-walled BBU geometry. The red crosses indicate the position of the thermocouples

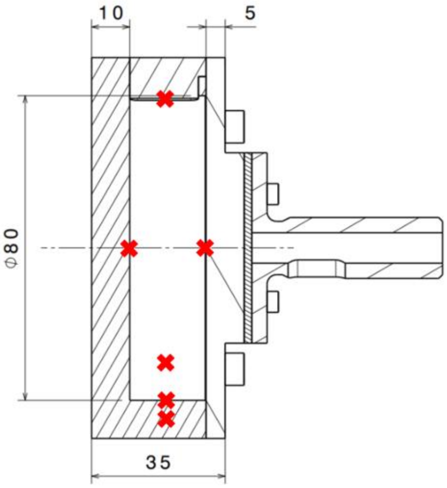

Figure 2: SADM geometry. The red crosses indicate the position of the thermocouples

An important feature of the mock-ups is the safety lid that closes the geometry on the top. This design solution was adopted to limit the pressure build-up inside the sample and to assure the safety of the arc-heated wind tunnel. In the majority of the tests, this safety lid was equipped with additional venting holes and maintained in place by a couple of tungsten wires.

3.2 Thermite charge

The selected thermite for the SPADEXO experimental campaign is a formulation involving aluminium and hematite (iron oxide). This composition is the most widely used thermite in terrestrial applications and one of the most broadly characterized in literature. Thermochemistry computations can give some useful insights on its properties. Its reaction can be described as per Eq. 1.

$$2Al + Fe_2O_3 \rightarrow Al_2O_3 + 2Fe + \boldsymbol{\Delta H} \tag{1}$$

Its theoretical heat release in stoichiometric combustion ΔH is equal to 3958.20 kJ/kg, its adiabatic flame temperature is 3135 K, and in adiabatic conditions the 7.84% of its products (in mass) gasifies. The starting aluminium and iron oxide powders characteristics are shown in Table 1.

Table 1: Characteristics of the starting powders

	Characteristics
Al	Spherical, 30 µm
Fe_2O_3	-325 Mesh (<44 µm)

In some tests a fraction of the thermite charge has been mechanically activated through high-energy ball milling to increase its reaction rate or to lower its temperature of ignition. In these cases, the loose activated powder was mechanically mixed to the standard formulation using a spoon. Other tests involved the dispersion of pellets of activated thermite in the charge, randomly distributed. The energetic material was placed in the central void of the samples, as shown in Figure 3. The production, activation, and pelletization of the thermite was performed by ReActive Powder Technologies.

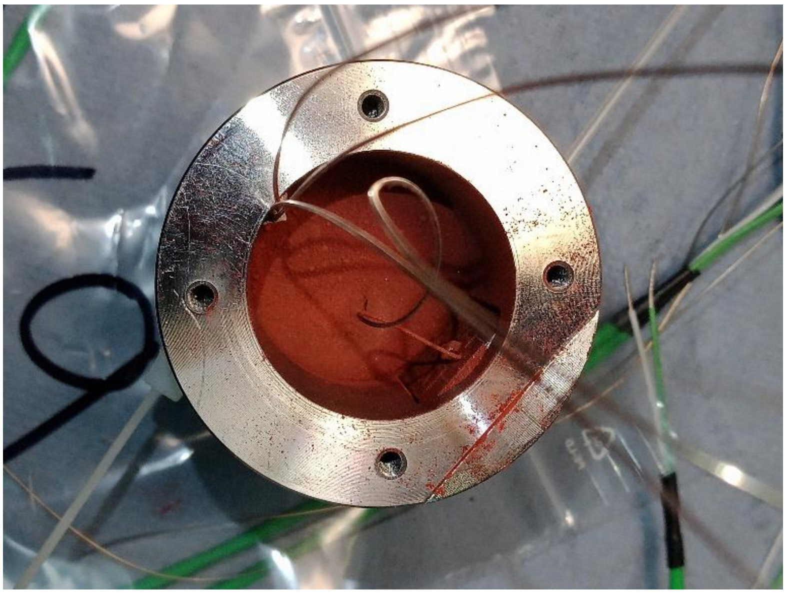

Figure 3: Thick-walled BBU sample partially filled with Al+Fe_2O_3 thermite

4. Methodologies

4.1 Arc-heated wind tunnel

The experimental campaign was performed at DLR-Cologne's L2K facility. This premise is an arc-heated wind tunnel (WT). This category of WT is able to produce particularly high heat loads on the sample, therefore is suitable for studying the late phase of atmospheric re-entry. As in this project the objective is to study the effect of T4D on equipment level, assuming a passive ignition, the use of such facility is perfectly coherent. Indeed, it is reasonable to assume that the onset of the energetic material will happen after the main spacecraft break-up (commonly considered around an altitude of 78 km [14]) and the equipment exposure to the re-entry environment.

The L2K uses a Huels-type arc-heater with a maximum electrical power of 1.4 MW and can reach cold wall heat fluxes of up to 3.0 MW/m^2 at stagnation pressures up to 250 hPa. A convergent-divergent nozzle provides hypersonic free stream velocities. The nozzle's expansion part is conical with a half angle of 12°. Various throat diameters can be combined with different nozzle exit diameters to provide the necessary flexibility. Moreover, it is possible to vary the test gas. An extensive discussion of its characteristics and of the type of studies conducted in this facility can be found in [32]. In the SPADEXO campaign, the nozzle was set up with a 29 mm nozzle throat and a 200 mm wide exit. The samples were placed at 120 mm from the nozzle. The working gas was air. For the tests discussed in this paper, the tunnel conditions resulted in a reference cold wall heat flux of 750 kW/m^2 for 50 mm diameter samples (BBUs) and a reference cold wall heat flux of 590 kW/m^2 for 100 mm diameter samples (SADM).

4.2 Numerical analysis

The numerical model used in the SPADEXO project to foresee the measurability of the thermite effect and to define the WT conditions to be used is HTG's SCARAB 3.1L in its Wind Tunnel Mode (WTM). This embodiment of the SCARAB software was created with the purpose of simulating and rebuilding test campaigns in hypersonic wind tunnels as L2K. Please notice that a new version of the software, SCARAB 4.0, is now in the last phases of its development. If the simulations were repeated with the new model, different results could be obtained.

During this project, a new model for exothermic reactions was developed. The thermite charge was represented as an internal heat source, without a proper geometry and mass. Nevertheless, the presence of the pyrotechnic charge influences the thermal response of the system. To take it into account, both the mass and the specific heat of the vessel were modified during the simulation. The thermite density was considered constant, and it was defined through a series of direct measures. The thermite specific heat was modelled as temperature dependent, and it was computed starting from the NIST-JANAF tables [33] considering the species in the formulation. The reaction was considered one-step, happening at the temperature chosen by the user. For this reason, once the thermite is ignited the reaction products species are used to compute the specific heat of the charge. The vessel thermal properties were taken from ESA's ESTIMATE [34] database.

Once the reaction starts, additional heat is applied to the internal panels of the geometry. The user can select the duration and the time profile of the released heat. In case of fragmentation during the time span in which the heat release from the thermite is prescribed, the application of the additional enthalpy is not stopped. Instead, the thermite continues to apply heat on the surviving fragments. This behaviour is chosen as it is expected to have residence of molten thermite even if the front face is demised or the top lid is opened. A variable of paramount importance for the model is the efficiency of the heat transfer between the reacting thermite and the surrounding vessel. For this set of simulations this quantity was defined to 60%, based on preliminary tests in non-relevant environment performed at Politecnico di Milano [35]. To reach the best possible comparison between the experimental and numerical data, the temperature of the closest volume to the position of the real thermocouple is registered. A last remark on the numerical simulations is that the thermal gradient of the front face has been computed as well. Normally, surface thickness in SCARAB is represented by a single element. For these simulations, instead, the front face was represented by a layered set of 5 disks, allowing to see a thermal gradient in that direction.

5. Results and discussion

The main objective of the research presented in this paper is to verify the adequateness of both the design of the samples and of the numerical model to rebuild the thermal behaviour of the application. In this respect, three cases will be reported: the SADM geometry without thermite, the thick-walled BBU filled at 50% with a blend of loose activated and standard thermite, and the thin-walled BBU filled at 26% with a mix of activated pellets and loose standard powder. The detailed numerical rebuilding and sample analysis of the complete campaign will be presented in further publications. Figure 4 shows a frame obtained during the tests.

Figure 4: An image of the thin-walled BBU geometry, partially filled with thermite, after the pyrotechnic charge ignition

5.1 SADM – No thermite

The first case hereby analysed is the SADM geometry without thermite load. In Figure 5 the thermal data of both the real acquisition and of the numerical simulation are presented. Figure 5a shows in solid line the temperature registered by the thermocouple and by the two pyrometers. In dashed line, the numerical data for the front face is reported, both on the external and on the internal side. The thermal gradient across the front face is slight, according to the simulation. The numerical model is in very good agreement with the thermocouple during the temperature ramp, while nearer the steady state the numerical data approaches the one registered by the pyrometers. The irregularities of the thermocouple profile could indicate a partial detachment.

In Figure 5b and Figure 5c the lateral and rear surfaces are addressed. In this case the simulated temperature is lower than the experimental one, probably mainly due to the neglection of the internal radiation. The heat transfer inside the sample in this numerical model is governed only by conduction. This is the reason of the delay that can be observed in Figure 5c. Nevertheless, the trend of the temperature is well captured, with the steady state that is reached in comparable time in the wind tunnel and in SCARAB.

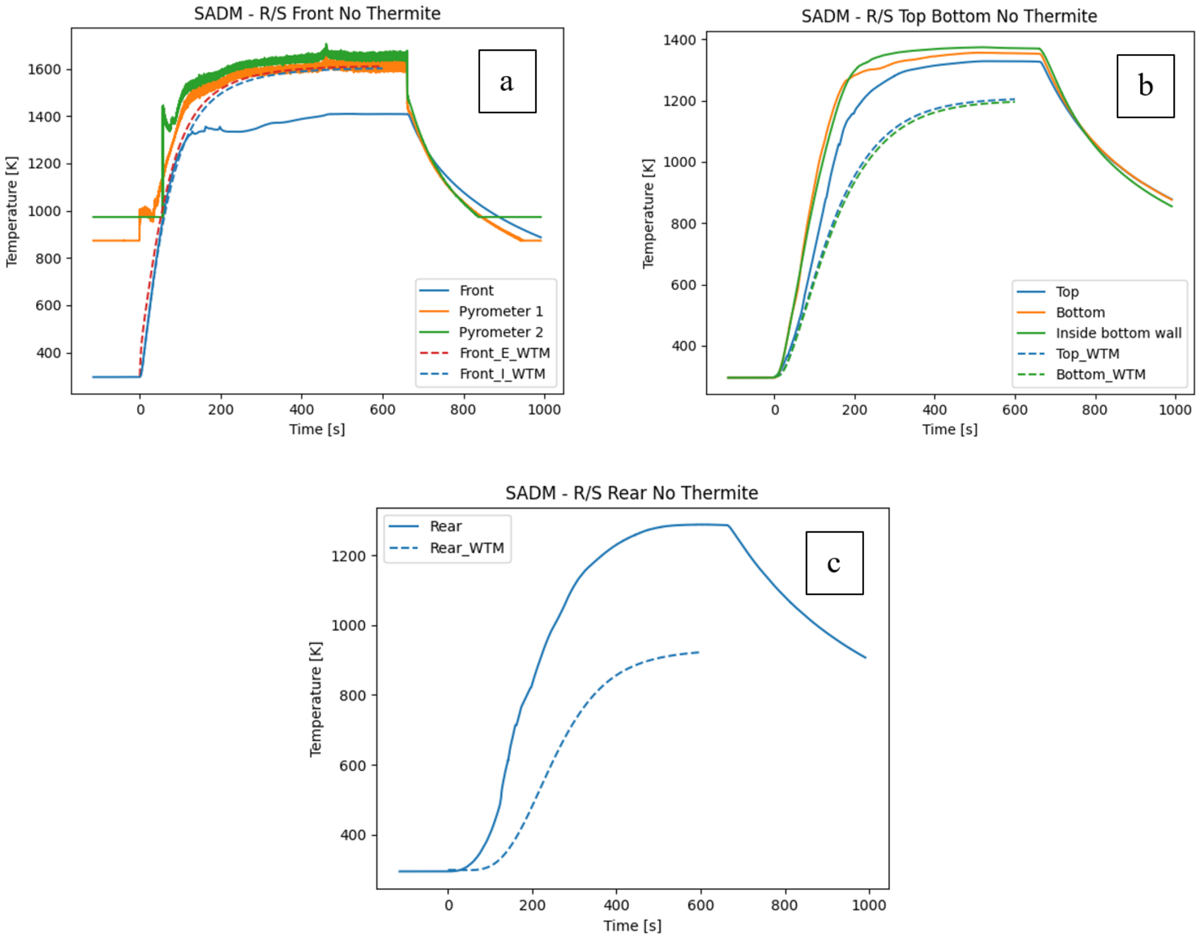

Figure 5: Thermal data obtained for SADM geometry with no thermite load. Solid line is real acquisition, dashed line is numerical simulation. a) Front face. b) Lateral surface. c) Rear face

5.2 Thick-walled BBU – 50% filling, loose blend

Figure 6 presents the comparison of the experimental and numerical data for the thick-walled BBU at 50% filling, loaded with an activated loose thermite blend. In Figure 6a, that shows the behaviour of the front face, it is possible to see that the initial temperature rise is very well captured by SCARAB. The ignition of the energetic material is foreseen by the numerical model 16 s after what is experienced in the arc-heated wind tunnel. An important remark is that in this test multiple ignitions have happened. This can be seen by the temperature traces of the pyrometers, where a second peak is present at around 300 s. The numerical model is not able to capture this behaviour, so all the additional enthalpy provided by the pyrotechnic load is released at ignition. Nevertheless, the shape of the heat release is in strict concordance with the experimental trace. Figure 6b shows the comparison for the top and bottom thermocouples. As these sensors do not survive the first ignition of the energetic material, the only interval that can be observed is the one before the thermite onset. Again, as in Figure 5b, the numerical traces are lower than the experimental ones. Moreover, in this case a difference between the top and the bottom thermocouple data can be observed. This is due to a numerical effect in the computation of the orientation of the surfaces. As for the rear face temperature, presented in Figure 6c, the thermocouple data after the thermite ignition should not be considered reliable anymore. Even if the temperature increase due to the thermite combustion seems appropriate, this insight must be pondered with caution.

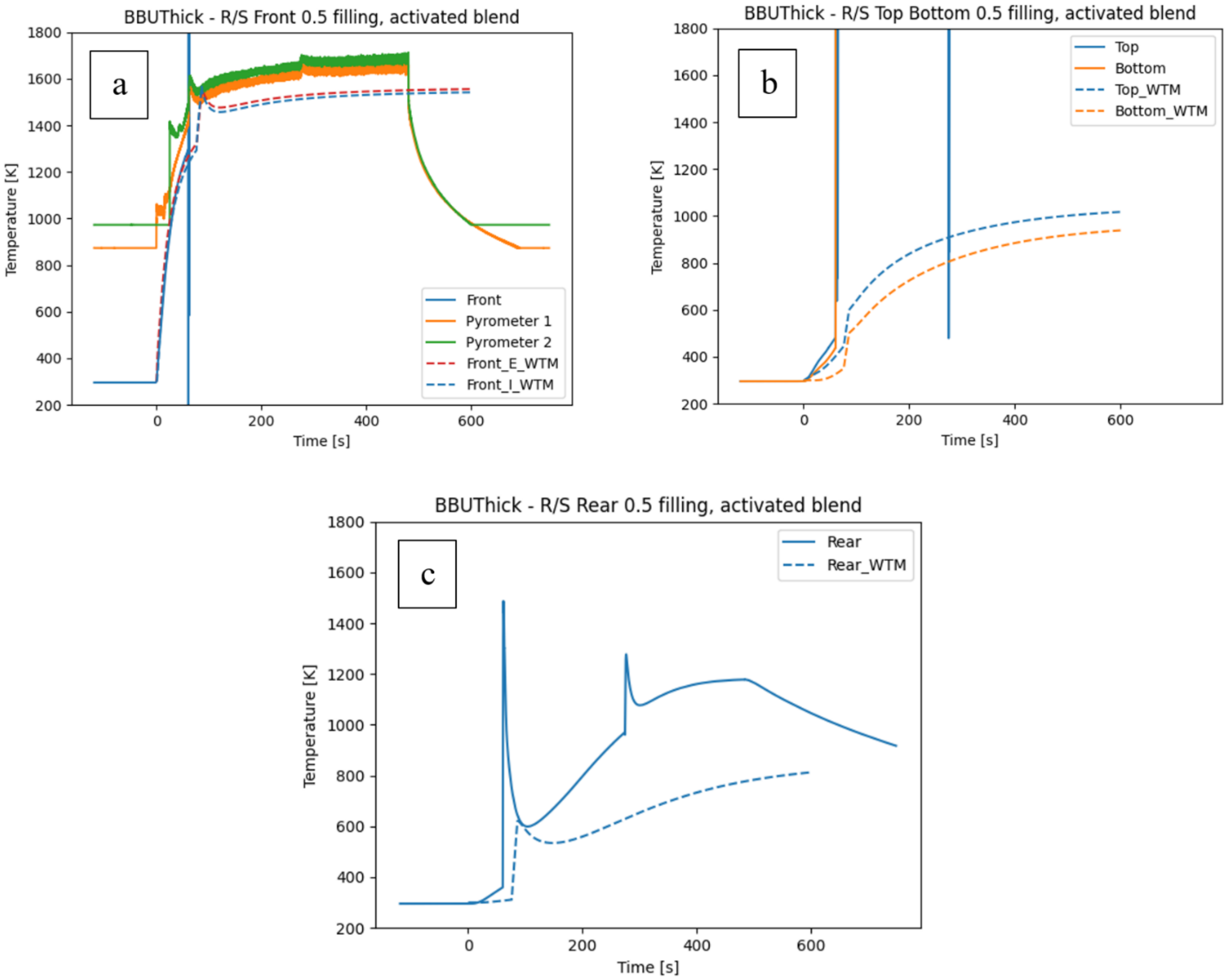

Figure 6: Thermal data obtained for thick-walled BBU geometry, at 50% filling, activated blend. Solid line is real acquisition, dashed line is numerical simulation. a) Front face. b) Lateral surface. c) Rear face

5.3 Thin-walled BBU – 26% filling, pellet mix

The comparison between the experimental and numerical temperature data for the thin-walled BBU geometry, filled at 26% with a mix of standard thermite and activated pellets, is shown in Figure 7. Again, the sample temperature rise before the ignition is very well captured. In this case the instant of the pyrotechnic charge activation is foreseen with an error of 1 s. It is particularly interesting to see that the destruction of the rear thermocouple happens with a significant delay with respect to the ignition. This suggests that the progression of the combustion front in the sample was not immediate. However, the additional enthalpy provided by the thermite seems appropriate, as the numerical temperature slope resembles the one registered by the pyrometers, as well as the magnitude of the temperature increase due to the additional enthalpy.

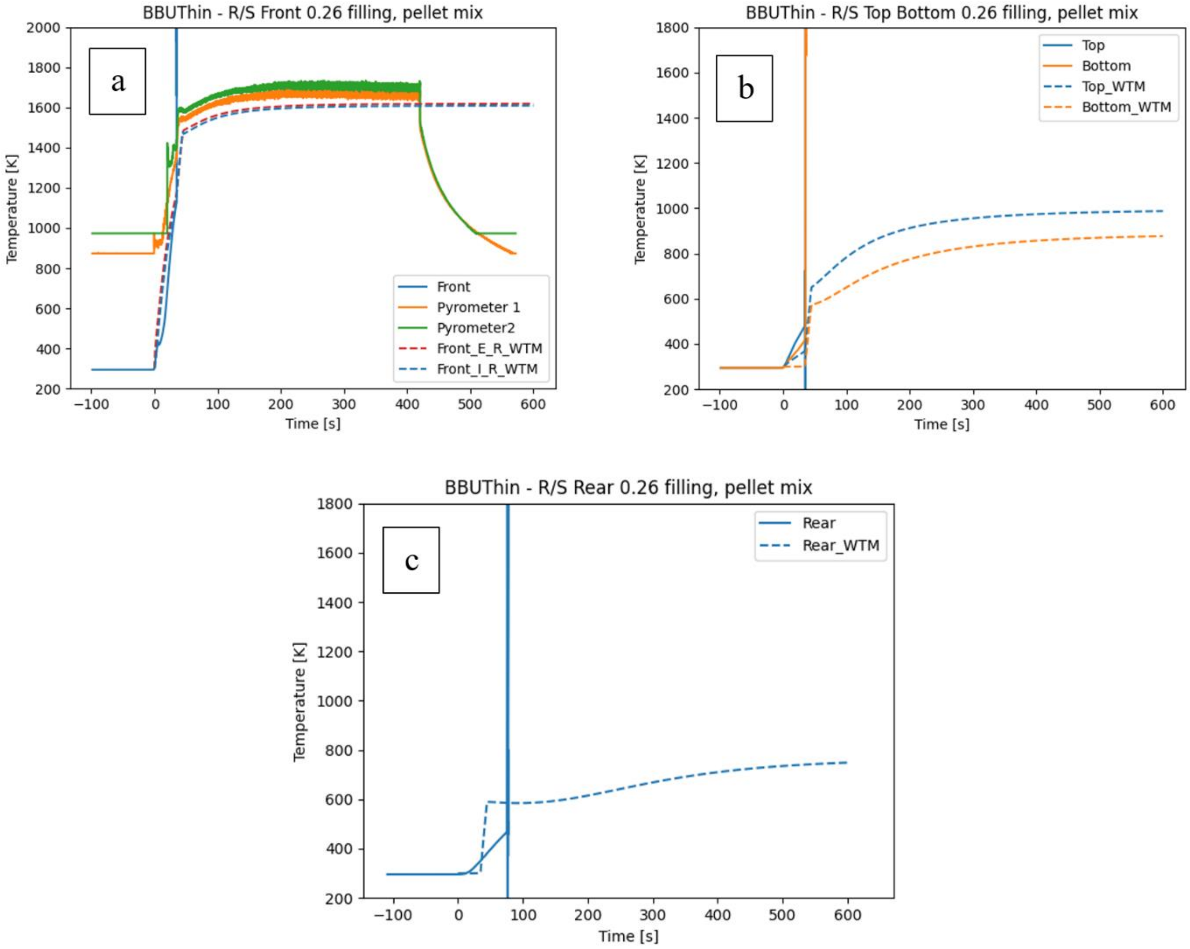

Figure 7: Thermal data obtained for thin-walled BBU geometry, at 26% filling, pellet mix. Solid line is real acquisition, dashed line is numerical simulation. a) Front face. b) Lateral surface. c) Rear face

6. Conclusion

In this paper, the preparatory activities to the experimental campaign of the SPADEXO project, as well as its preliminary results, were presented. Simple mock-ups were preferred to more complex shapes, preferring a geometry that could be reliably represented in detail by SCARAB to a more representative one. This approach has the strong advantage of simplifying the quantification of the additional enthalpy provided by the exothermic reaction. A safety lid was introduced in the design to prevent the pressure build-up inside the mock-ups and to guarantee the safety of the L2K facility. A numerical model was developed to tune the heat load to be applied on the samples in the arc-heated wind tunnel. Moreover, a second objective of the simulations was the definition of a quantity of thermite that could give measurable effects by the sensors. The new extension of the SCARAB software has been compared with the results of three tests, showing that the analytical results can suitably foresee and represent the experimental data. Three cases were presented, comprising an example without thermite, one loaded with an activated blend, and one with a mix of standard thermite and randomly distributed activated pellets. A heat transfer efficiency of 60% was used. This value was previously determined through tests in non-relevant environment. The extra enthalpy provided by the pyrotechnic formulation was correctly foreseen. The use of SCARAB in its Wind Tunnel Mode allowed a good prediction of the thermite ignition time. In further publications the experimental results obtained in the ESA-TRP SPADEXO project will be presented and analysed in detail.

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