DOI: 10.13009/EUCASS2025-736
11TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Thermite-For-Demise (T4D): What Comes Next?

Filippo MAGGI [1†], Alessandro FINAZZI[1], Christian PARAVAN[1], Stefania CARLOTTI[1], Jacopo DOMASCHIO[1], Tobias LIPS[2], Martin SPEL[3], Matteo FERRARI[4], Sylvain GIRARD[4], Thorn SCHLEUTKER[5], Stefano DOSSI[6], Chiara BUTTIRONI[6], Rui Miguel MAGALHAES[7], Shayna SLOBIN[8], Martin WEIHRETER[8], Alessia CEMMI[9], Ilaria DI SARCINA[9]

[1]*Dept. of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, Milan, Italy*
[2]*Hyperschall Technologie Göttingen GmbH, Am Handweisergraben 13, 37120 Bovenden, Germany*
[3]*R-Tech, 10 impasse Jean Mermoz, Parc Technologique Delta Sud, Verniolle France*
[4] *Université Jean Monnet, Saint-Etienne, CNRS, Institut d'Optique Graduate School, Laboratoire Hubert Curien UMR 5516, F-42023 Saint-Etienne, France*
[5]*Dept. of Supersonic and Hypersonic Technology, DLR, Linder Höhe, 51147 Köln, Germany*
[6]*ReActive - Powder Technology s.r.l., Via Lambro 7/3, 20068, Peschiera Borromeo, Italy*
[7]*CEiiA, Av. Dom Afonso Henriques, 1825. 4450-017 Matosinhos, Portugal*
[8]*Airbus Defence and Space GmbH, Claude-Dornier-Straße, 88090 Immenstaad am Bodensee, Germany*
[9]*Nuclear Department, ENEA Casaccia Research Center, 301, via Anguillarese, 00123 Rome, Italy*

filippo.maggi@polimi.it, alessandro.finazzi@polimi.it, christian.paravan@polimi.it, stefania.carlotti@polimi.it, jacopo.domaschio@polimi.it, t.lips@htg-gmbh.com, martin.spel@rtech.fr, matteo.ferrari@univ-st-etienne.fr, sylvain.girard@univ-st-etienne.fr, thorn.schleutker@dlr.de, stefano.dossi@reactivepowders.com, chiara.buttironi@reactivepowders.com, rui.magalhaes@ceiia.com, shayna.slobin@airbus.com, martin.weihreter@airbus.com, alessia.cemmi@enea.it, ilaria.disarcina@enea.it

[†] Corresponding Author

Abstract
The use of thermites in space missions is more and more considered for different scopes. Assisting satellite demise represents an innovative potential field of application. Recent projects have demonstrated that the concept can work in specific case studies. THREAD is a new international collaboration financed by the European Union through the European Innovation Council Pathfinder program. The work will investigate the Thermite-for-demise (T4D) technology and will assess whether this approach can be feasible and can lead to benefits, both from the technical and from the industrial perspective. Regulatory and ethical aspects will be also covered within the 42 months of activity.

1. Introduction

The space economy keeps growing at fast pace as access to orbit is becoming more and more affordable for commercial applications. Despite Europe has suffered a launch rate contraction due to technical and geopolitical contingencies, globally the market is dynamic. Digital services, communications, and observation missions are benefiting from convenient access to space resources. Constellations are growing and space logistics is reaching new visionary perspectives, with the possibility of a multi-billion-dollar market [1]. A prediction in 2020s foresaw more than 15000 new satellites to be inserted into orbit within 10 years, due to private companies and nations, the former ones to provide new services, the latter ones to have proprietary critical assets (e.g., navigation systems) [2]. Saturation of orbital resources is becoming an important risk that can limit this expansion. In addition, the probability of in-orbit collision is increasing, and in case of catastrophic events, sudden worsening of the current space debris situation can occur.

Containment of orbit crowding is necessary to avoid the « Kessler Syndrome », a condition in which the number of space debris continuously increases due to collisions and fragmentations. For this reason, it is important to keep the collisional risk between operating satellites and both debris and non-cooperating spacecrafts within acceptable levels [3]. Re-entry of spacecrafts after the end of their operative life is an important mitigation cornerstone for satellites in low earth orbit (LEO). Several guidelines have been developed by international institutions and agencies to drive the effort toward a more sustainable space exploitation. Recent updates have changed the rules to more restrictive conditions. One of the most important amendments regarded the reduction of the admissible permanence in orbit after the end of the mission. Since 2023, ESA has adopted for its own activities the policy of re-entering space platforms

DOI: 10.13009/EUCASS2025-736

within 5 years from the end of operations [4]. The same commitment was taken by the US Federal Communication Commission in 2022 [5].

When a satellite is expected to completely ablate during atmospheric re-entry, lowering its orbit to a point where atmospheric drag will cause its destruction within the planned timeframe is sufficient. If the space platform is too massive or it contains components that may survive to atmospheric re-entry, a controlled deorbiting maneuver must be planned, unless its foreseen associated ground casualty risk is below 10^{-4}. In case a final maneuver is needed, it must target uninhabited areas and grant a ground casualty risk below the threshold. A controlled re-entry requires a high-energy propulsion maneuver by a chemical rocket unit. Prediction at the end-of-life of propellant budget, satellite mass, overall efficiency of the firing, and possible degraded performance is difficult [6]. The fraction of spacecrafts that failed their re-entry maneuver on an yearly basis spanned from about 0 to 20% in the last 10 years [4].

Design-for-demise is an engineering philosophy that searches for design solutions easing satellite destruction by the natural aerothermal environment, suffered by the system during the re-entry trajectory. Several strategies have been conceived and studied to make a satellite demisable by natural re-entry; all of them are summarized in Figure 1.

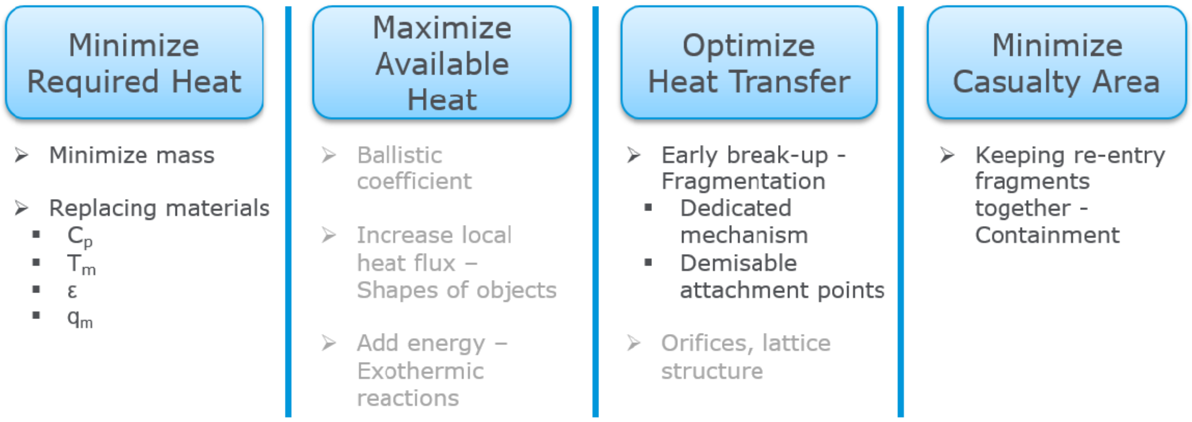

Figure 1 Design-for-demise strategies. The greyed out entries have not been studied in depth to date [7]

Within the group based on the maximization of available heat, adding exothermic reactions consists of introducing a chemical mechanism that can produce heat either through an energetic charge or by interaction of some reactants with materials already available on board. This pioneering idea named Thermite-for-Demise (T4D) has been first postulated by Dihlan and Omaly, who patented a solution where a charge of thermite was implemented inside a spacecraft component. A similar approach was followed and refined by Seiler and Smet, whereas initial experimental tests were performed by Monogarov and co-authors [8–10]. The concept was studied during three European Space Agency (ESA) programs called ERASD, SPADEXO, and T4D-ER [11]. These campaigns have created the awareness that such solution can effectively satisfy the need of reaching spontaneous ignition under relevant aerothermal heating conditions. At the same time, the use of free-flowing powders could not grant a predictable heat transfer mechanism to the confining body. Moreover, normal thermites could not grant the flexibility of selecting the proper ignition temperature.

The T4D concept is under evolution. A project named THREAD (THermite REactions Assisting satellite Demise) has been financed by the European Innovation Council and kicked off in mid-May 2025. The project aims at the maturation of thermite-based concepts for the demise of satellites, unravelling the different aspects of this technology. This paper describes the project, the starting point, the key points to be addressed, and the planned methodology. In section 2 the reader can find a brief description of the T4D starting knowledge, section 3 contains a resume of the important aspects on thermite application that need to be clarified, section 4 presents the planned approaches, while section 5 wraps up the paper discussion.

2. Status of T4D

2.1 What is a thermite

A thermitic reaction is a self-propagating high temperature synthesis (SHS) mechanism. It is a spontaneous process involving an oxide and a metal, exchanging oxygen. Its fundamental embodiment allows to obtain a metal from its oxide, while the original metal is oxidized. Simultaneously, heat is released. The generic stoichiometric reaction is

DOI: 10.13009/EUCASS2025-736

represented in Eq. (1). In there, M^1 is the starting metal oxidized by the oxygen contained in the metal oxide ($M^2_{x2}O_{x3}$), which eventually becomes a new metal M^2, and forming a new metal oxide ($M^1_{x4}O_{x5}$).

$$M^1 + \frac{x_5}{x_3\, x_4} M^2_{x2}\, O_{x3} \rightarrow \frac{1}{x_4} M^1_{x4}\, O_{x5} + \frac{x_2 x_5}{x_3\, x_4} M^2 \quad (1)$$

Being the reaction spontaneous, Gibbs free energy reduction is a necessary condition [12]. A diagram elaborated from the principles described originally by Ellingham in 1944 helps in the identification of possible reactant combinations, whereas a wide collection reporting ideal performance data (including heat of reaction, temperature, and amount of condensed products) was published by Fischer and Grubelich [13,14].

Thermodynamics defines spontaneity and ideal reaction properties. Non-ideal behavior, ignition, and reaction rate are defined by material properties, such as particle size, compaction, and processing. The joint role of particle size and composition on linear reaction propagation and on mass burning rate was studied by Weismiller and co-authors comparing micrometric and nanometric ingredients, demonstrating strong benefits from smaller oxidizer size (the oxide) [15]. In the same paper, the authors wrote a disclaimer about the high sensitivity of the powders to friction, impact, and sparks. On compaction, Pantoya and co-authors showed that microthermites and nanothermites follow opposite trends when density is increased, with the latter ones slowing down for higher densification [16].

2.2 Former T4D activities

Since 2017 Monogarov and co-authors performed experimental tests aiming at the damage of simple aerospace components (mainly, metallic panels for tanks) through ignition of thermites with the declared intention of supporting demise [9]. The authors investigated one thermite family (based on cobalt oxide), after a thorough screening of other possible choices. The project ERASD represented a small activity financed by the European Space Agency (ESA) in preparation of a more extended campaign [7]. The work consisted in demonstrating the enhancement of demisability with the addition of thermites inside a bulky component, once exposed to the aerothermal conditions of an arc-heated wind tunnel at the Deutsches Zentrum für Luft- und Raumfahrt (DLR) of Cologne. The test involved some mock-ups of a ball bearing unit filled with standard thermite. In parallel, the first ever implementation of thermite reaction inside the SCARAB demise code was performed by Hyperschall Technologie Göttingen (HTG) GmbH for numerical rebuilding of experiments. Initial findings underlined that the energy supplied by thermites was limited, with respect to the one coming from the aerothermal heating. This result was a consequence of the small volume where the energetic powder could be accommodated. Once the container was partially molten, part of the powder was vented away, further reducing the heat transferred to the metallic component. In addition, the refractory oxide produced by the reaction could generate a compact block of material with superior heat-resistant properties, eventually leading to higher casualty risk, in case of a real-world application. Even though the activity had a limited scope, the project derived some important conclusions:

- Thermite reactions could be triggered by environmental conditions, although earlier than expected.
- The energetic material was partially lost during the test, once the confining vessel was partially damaged.
- Reaction products could solidify and create ceramic-like materials which could be difficult to demise.

A systematic approach to developing the T4D principle was performed in the SPADEXO project. It was a collaborative TRP project financed by ESA and managed by HTG GmbH, involving representatives from industry, academia, and research institutes. The work consisted in understanding more of the fundamentals about thermites in demise application, proving the efficacy of the concept for two test cases in relevant environment. In addition, the work created the basis for the modelling of the demise action with two distinct approaches. A low fidelity 3-DOF engineering code (TRANSIT) was developed for quick evaluations by Politecnico di Milano [17]. A high-fidelity method was integrated within the 6-DOF SCARAB frame by HTG to accurately simulate the local damage of thermites. Experiments in DLR L2K arc-heated wind tunnel at Cologne facilities validated the high-fidelity numerical approach and proved experimentally the application of the energetic charges [11,18].
An initial trade-off based on energy density, gas production, and toxicity of both reactants and products, led to the selection of iron oxide and aluminum as the baseline ingredients. Reactivity was tailored on purpose and powders responding to prescribed ignition temperature were produced in batch by ReActive Powder Technology s.r.l. in collaboration with Politecnico di Milano through mechanochemical activation process [19]. The charges were delivered in the shape of both pellets and powder. The campaign was successfully completed, demonstrating some important outcomes.

DOI: 10.13009/EUCASS2025-736

- It is possible to embed the thermites inside space components and have them ignited under representative aerothermal heating. Fundamental role was played by the tuning of thermite blend through mechanochemical activation. The ignition temperature could be reproduced at laboratory scale, easing the material tuning.
- The damaging effect of thermites on samples could be predicted by the extended SCARAB code. The experimental campaign was carefully rebuilt, including the size of the provoked damage.
- When a component must be melted, the models showed that the best moment for thermite ignition is in proximity of material phase change temperature. An anticipated ignition would lead to accumulation of the generated heat in the material bulk which may not reach the melting condition. Moreover, if produced too early during the re-entry, the additional heat provided by the thermite charge could be lost due to radiation or convection toward the environment. In this respect, tuning of charge ignition temperature for the case of interest represents a cornerstone of the technology.
- Experimental results demonstrated that the confinement of powders is important to increase the effect of thermite. This confirmed the early observations by Monogarov and co-authors about the effect of gas products on the effective damage [9].
- Unexpectedly, during the wind tunnel test campaign thermites provoked much higher gas production than expected, causing the release of a fraction of the charge and the loss of performance.
- Shaping of charges needs improvement, as pressed pellets were partially destroyed during shipping. A mix of powders and pellets did not lead to significant control of ignition temperature, as a free-flowing thermite seems to be an insulating material.

3. Research needs

3.1 Material shaping

Experimental handling and use of thermites showed that loose powders did not fully satisfy the need of controlled heat generation imposed by the demise application. The idea of using thermite as a localized source of heat in space was explored even independently from re-entry applications. Habu and co-authors conceived the use of iron oxide and aluminum (or magnalium, an alloy of magnesium and aluminum) to generate the vaporization of low-boiling metals for a JAXA mission [20]. Test campaigns in wind tunnel demonstrated that unconfined charges lost part of their energy due to dispersion. Once confinement becomes a need, the aerothermal heating is bridged to the charge only through the surrounding walls, which plays a significant role within the ignition chain. Tumbling during re-entry makes the prediction of charge pre-reaction heating more complex.

Shaping charges appears to be a need for ease of installation, and to be certain about its position. This latter aspect is crucial to foresee the ignition temperature. It is worth noting that thermite shaping is under investigation in other applications. Welding in space has been developed through the production of shaped charges via 3D printing [21]. In the short literature survey of the paper authored by Neely *et al.*, the authors focus on polymer-based printing and mention several techniques applicable to thermites, including fused deposition and resin-based solutions. It seems that even complex shapes can be achieved. The authors also mention about a possible paste material, claiming good results for joining and printing.

3.2 Thermite in space

Thermites are progressively finding room in space applications. Investigations on Lunar or Martian regolith simulants have been published by different research groups [22,23]. Welding in microgravity conditions has been tested [24]. Safe and reliable use of thermite charges in space for demise applications can partially rely on these early-stage studies due to similarity of application, but development of specific knowledge is required. Past T4D experimental tests have shown that reactions are not progressing as predicted by thermochemistry calculations performed under standard-state conditions, generating more gaseous reaction products than expected. Pressure build-up can provoke catastrophic failure of containers where thermites are confined. This is not necessarily a problem, if compliance with ESA guidelines is granted [25]. However, this solution may become difficult to develop and test in current on-ground infrastructures. Also, long term presence in space exposes the charge to high vacuum, thermal cycling, and high doses of radiation of different types, unless properly shielded. Progressive damage or uncontrolled ignition during pre-re-entry phase of the charges may cause safety problems during satellite lifetime and reduction of reliability during the re-entry.

DOI: 10.13009/EUCASS2025-736

3.3 Strategy of application

Past experiments have shown that the energy transferred from the thermite to the item to demise is smaller than the one obtained by the aerothermal heating. The charge cannot be considered the main contributor to the melting of a bulky component, as the volume of the thermite would probably exceed the one available for its lodging. In this respect, other options are feasible and can represent an interesting D4D option. Commanding separation of components at prescribed re-entry position, activating shape changes to ease demisability, or pre-damaging components and increasing their interaction with the aerothermal environment represent potential effective applications with direct consequence on demisability. In these cases, charges would be smaller. Guidelines to drive the selection of charge type, mass, position, and shape are missing. Deeper understanding of the effect on the final application of ignition, energetic, and mechanical properties is still missing.

3.4 Cradle-to-grave perspective

Application of a thermite charge aims at making platforms compliant with uncontrolled re-entry rules, containing design and management costs. Nevertheless, in the perspective of a real industrial application, it is important to understand the upstream flow of the future potential thermite-based products, as well as the downstream process of spacecraft being deployed. Production, transportation, and handling inside a real-world workflow will create challenges due to necessary changes for safety and security reasons. Restrictions to launch may be applied due to regulations. In addition, dual use and rules for road/flight transportation should be verified to identify potential problems.

4. The project

The approach of the project THREAD follows the logical scheme reported in Figure 2, aiming at the development of materials, methods of application, and guidelines.

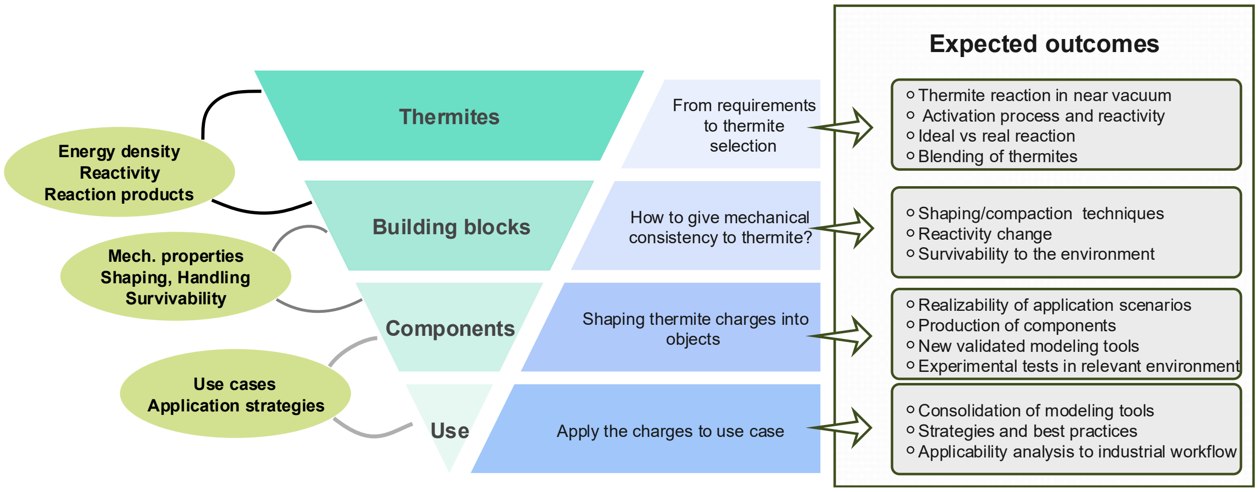

Figure 2 THREAD logical path

The project contains strong connection between research & development, testing, and industrial environment. Part of the analysis will consider the regulatory frameworks even outside the typical space standards, having these materials potential ethical implications related to dual use and safety topics (e.g., transportation, workers, risk of misuse). The team is very wide and includes competence at different levels.

- Academic partners: Politecnico di Milano (Italy), University Jean-Monnet (France)
- SMEs: HTG GmbH (Germany), R-Tech (France), ReActive Powder Technology s.r.l. (Italy)
- R&D labs and centers: CEiiA (Portugal), DLR (Germany), ENEA (Italy)
- Large integrator: Airbus Defence and Space GmbH (Germany)

An essential summary of the project key points is reported hereafter.

DOI: 10.13009/EUCASS2025-736

4.1 Material development

In the past SPADEXO program, iron oxide / aluminum formulation was considered the best compromise to be used in initial demisability studies. The potential list of usable thermites was shortlisted due to performance considerations on energy density and programmatic constraints coming from sensitivity, toxicity of ingredients and/or products, gas generation, etc. This approach was justified by the scope of the research project, which consisted in the application of the T4D concept to a few specific case studies. In the THREAD project, the perspective is more general, and material selection will be revisited, discriminating between strong constraints and preferred features, considering different relevant mission scenarios.

Along with the use of different fuel/oxidizer couples, past studies performed the tuning of thermite reactivity using mechanical activation via ball milling, powder size blending (micrometric vs nanometric), or compaction. Monitoring of reactivity was mainly done through ignition temperature analysis and reaction progression rate. Moreover, kinetic studies were performed through calorimetry.

In general, all the work performed in this research field focused on powder or pellet reactivity. The project THREAD adds an additional discussion point: the structural consistency of the thermite charges. The possibility of shaping thermites eases manufacturing of charges with specific shapes and opens to the production of components that can demise autonomously during re-entry. The development of new building block materials integrating both the energetic needs and the manufacturing capacity is the initial cornerstone, under current development in the project. A schematic of the initial approach on material development is reported in Figure 3.

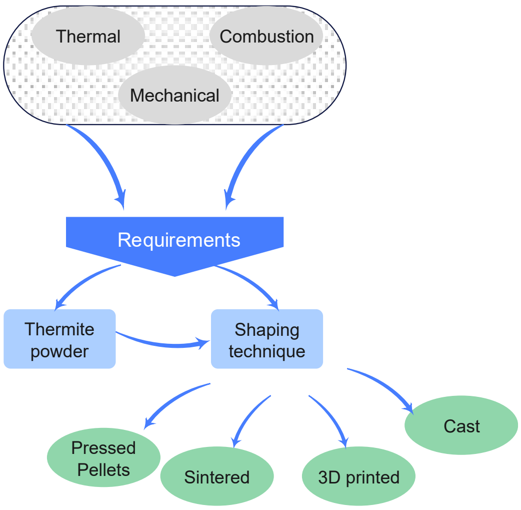

Figure 3 Material development preliminary approach

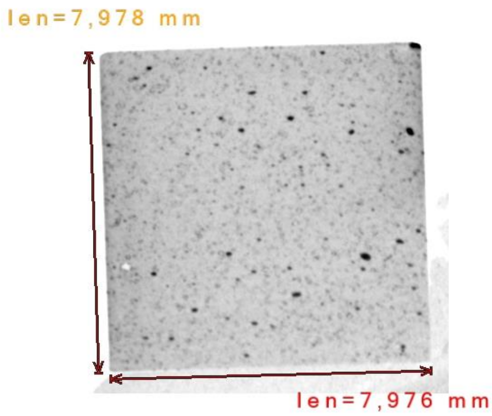

Figure 4 Sintered pellet (XCT)

Four main pathways have been identified so far, two based on thermite powder only and two based on the use of a polymeric binder in addition to the powder. Thermite compaction into pellets has been used already in the former SPADEXO project, but experience evidenced problems of integrity after transportation. Sintering is a promising approach which is already giving some initial results [26]. The tomography of a sintered pellet is reported in Figure 4 and shows good compaction, although density differences can be identified.

On the polymer side, energy density reduction caused by the addition of an inert binder is a drawback. The polymeric part does not contribute substantially to the energetics of the reaction, since pyrolysis of inert binders is endothermic. In addition, chemical kinetics may suffer from low reaction rates, as polymer pyrolysis tends to keep low the temperature at the reacting interface. However, the polymer could give consistency to the powder and shape the charge even to complex geometries. Digital Light Processing (DLP) can be used to implement 3D printing of these materials. Using this technology, the only limitations in terms of geometry flexibility are related to small details and overhang shapes. A key aspect to be investigated is the layering phase during UV curing. The thickness is upper limited by slurry opacity and depends on the thermite type and size. An advantage of this approach is the possibility of combining 3D printing and sintering, which could grant the extended shaping capacity of the 3D printing technology and the mechanical consistency typical of sintered products. A second method that will be explored in the project is the casting

DOI: 10.13009/EUCASS2025-736

of thermite-based charges, exploiting the solubility of some polymers to shape the energetic material to simple geometries. In this case, the use of a mold is necessary, limiting the geometry that can be produced.

4.2 Testing

Testing activities will respond to a twofold need. On the one hand, the focus will be on the survivability in the most critical environmental conditions experienced by the thermite (i.e., on ground, at launch, and during the quiescent phase in space). On the other hand, wind tunnel tests will be implemented with the scope of validating the approach on specific case studies and obtaining data to be supplied for validation of numerical models.

Survivability

Thermites will suffer from several storage conditions during their entire life cycle. Storage accounting from production to installation inside the spacecraft is not critical, as it is possible to predict and monitor what is happening in these phases. Operations will be conducted in controlled conditions and will be compliant with space industry practices and to respective standards and guidelines.
Launch conditions will create a more complex situation, since the effective stress suffered by the material will be dependent on the implementation method (charge shape, position, confinement, etc.). Steady and unsteady acceleration fields, including vibrations, heating of the fairing bay, relatively quick ambient-to-vacuum pressure change represent only some of the possible conditions.
Finally, thermites must survive in the space environment for a time span that includes the operative life of a LEO satellite, plus the time needed to make the satellite naturally re-enter. Exposure to both vacuum, radiation, and thermal cycles is critical.

These conditions can be simulated on ground, at least in part. Modal shakers and thermal cycling can be used to reproduce the thermo-mechanical environment. Irradiation facilities are necessary for radiation. Definition of correct test conditions and protocols is a critical aspect to obtain significant data, within a limited timeframe. In general, it will not be possible to cover all possible operational conditions. Prioritization will be necessary.

Validation
Two wind tunnel test campaigns will be conducted during the THREAD project. The activities will target both the application of the general approach and the derivation of experimental data, which is useful for validation of models. Experiments will be conducted through an arc-heated wind tunnel. Instrumentation of the samples will be conceived to provide a detailed characterization of the ignition conditions and of the capacity to transfer heat from charges to components. Wind tunnel outcomes will experimentally prove the failure mechanisms induced by thermite charges on specific components and case studies.

4.3 Modelling

The project aims at developing and validating models for prediction of charge ignition and of its effect on components. Tests on the low-fidelity 3-DOF code TRANSIT will show if the code can be considered an engineering tool for quick estimate of the demise effect. In parallel, high-fidelity instruments such as PAMPERO (by R-Tech) and SCARAB (by HTG) will be extended with more refined thermite models, while FEM simulations will provide a numerical tool to study and understand the local heating propagation, from charge to metal.
These models will be coupled with kinetic analyses, aiming at ignition prediction and reaction propagation inside the single charge.

The whole set of models, supported by corresponding validation campaigns, will supply different levels of interpretation of the thermite application, supporting the development of guidelines and use case scenarios.

4.4 Application and exploitation

The use of thermites in space applications is recently under evaluation for several use cases, including welding, in-situ metal extraction, and spacecraft demise. Technical implementations must be confronted with both industrial best practices and regulatory frameworks. Currently, guidelines for T4D application in the workflow of space platform development are missing. Moreover, it is still unclear whether this practice can effectively bring economic and societal

DOI: 10.13009/EUCASS2025-736

benefits to the space industry. The project THREAD aims at the identification of benefits, drawbacks, and showstoppers.

From the safety viewpoint, handling thermite charges at satellite installation and pre- or post-installation storage and transportation are ethical issues that must be addressed through identification of material sensitivity aspects, adequate training, and industrial practices of protection and prevention. Finally, the understanding of the current regulatory framework is of paramount importance for launch clearance, export control (e.g., dual use), and transportation safety.

5. Conclusions

The THREAD project started in May 2025 and will last 3.5 years. Its final scope is to understand whether Thermite-for-demise can bring a benefit to the space industry and to on-ground re-entry safety. Investigations will cover a wide range of multidisciplinary subjects, spanning from technological development up to regulatory frameworks. One important benefit of this project consists of the interaction between research institutions, international entities, end users, and supply chain, allowing a complete vision over the whole problem, and creating a preferential channel of discussion and exchange among the stakeholders of this innovative technology.

6. Acknowledgement

Funded by the European Union through the European Innovation Council (EIC) within the THREAD project (Grant agreement ID: 101186901). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Innovation Council (EIC). Neither the European Union or the granting authority can be held responsible for them.

European Innovation Council — Funded by the European Union

References

[1] Opromolla, R., Grishko, D., Auburn, J., Bevilacqua, R., Buinhas, L., Cassady, J., Jäger, M., Jankovic, M., Rodriguez, J., Perino, M. A., and Bastida-Virgili, B., 2024, "Future In-Orbit Servicing Operations in the Space Traffic Management Context," Acta Astronaut., **220**, pp. 469–477. https://doi.org/10.1016/j.actaastro.2024.05.007.

[2] Murtaza, A., Pirzada, S. J. H., Xu, T., and Jianwei, L., 2020, "Orbital Debris Threat for Space Sustainability and Way Forward (Review Article)," IEEE Access, **8**, pp. 61000–61019. https://doi.org/10.1109/ACCESS.2020.2979505.

[3] Kessler, D. J., 1991, "Orbital Debris Environment for Spacecraft in Low Earth Orbit," J. Spacecr. Rockets, **28**(3), pp. 347–351. https://doi.org/10.2514/3.26250.

[4] AA.VV., 2025, *ESA's Annual Space Environment Report*, GEN-DB-LOG-00288-OPS-SD, ESA-ESOC, ESA Space Debris Office, Darmstadt, Germany.

[5] Anon., 2022, *Space Innovation IB Docket No. 22-271 Mitigation of Orbital Debris in the New Space Age IB Docket No. 18-313*, FCC-22-74.

[6] Moreschi, L., and Gomes, R., 2025, "Implications of Space Debris Mitigation Requirements on Mission Design, Propellant Budget, Disposal Lifetime and Operations," *Proc. 9th European Conference on Space Debris, Bonn, Germany*, S. Lemmens, T. Flohrer and F. Schmitz, ESA Space Debris Office, Darmstadt, Germany, p. Paper No. 306.

[7] Smet, G., and Seiler, R., 2021, "What to Do When Re-Entry Just Isn't Hot Enough?", Aerothermodynamics and Design for Demise (ATD3) Workshop.

[8] Dihlan, D., and Omaly, P., 2011, "Element de Vehicule Spatial a Capacite d'autodestruction Amelioree et Procede de Fabrication d'un Tel Element (Patent FR 2975080B1)."

[9] Monogarov, K. A., Pivkina, A. N., Grishin, L. I., Frolov, Y. V., and Dilhan, D., 2017, "Uncontrolled Re-Entry of Satellite Parts after Finishing Their Mission in LEO: Titanium Alloy Degradation by Thermite Reaction Energy," Acta Astronaut., **135**, pp. 69–75. https://doi.org/10.1016/j.actaastro.2016.10.031.

[10] Seiler, R., and Smet, G., 2018, "Exothermic Reaction Aided Spacecraft Demise during Re-Entry (Patent EP 3604143A1)."

[11] Finazzi, A., Daub, D., Maggi, F., Paravan, C., Dossi, S., Lips, T., Smet, G., and Bodjona, K., 2024, "Thermite-for-Demise (T4D): Experiments and Numerical Modelling on Ball-Bearing Unit Mock-Ups Containing Thermite in an Arc-Heated Wind Tunnel," Acta Astronaut., **223**, pp. 550–576. https://doi.org/10.1016/j.actaastro.2024.06.013.

[12] Smith, E. B., 2004, *Basic Chemical Thermodynamics*, Imperial College Press.

[13] Ellingham, H. J. T., 1944, "Reducibility of Oxides and Sulphides in Metallurgical Processes (Part of Communications and Transactions)," J. Soc. Chem. Ind., **63**(5), pp. 125–160. https://doi.org/10.1002/jctb.5000630501.

DOI: 10.13009/EUCASS2025-736

[14] Fischer, S. H., and Grubelich, N. C., 1998, "Theoretical Energy Release of Thermites, Intermetallics, and Combustible Metals," *24th International Pyrotechnics Seminar*.

[15] Weismiller, M. R., Malchi, J. Y., Lee, J. G., Yetter, R. A., and Foley, T. J., 2011, "Effects of Fuel and Oxidizer Particle Dimensions on the Propagation of Aluminum Containing Thermites," Proc. Combust. Inst., **33**(2), pp. 1989–1996. https://doi.org/10.1016/j.proci.2010.06.104.

[16] Pantoya, M. L., Levitas, V. I., Granier, J. J., and Henderson, J. B., 2009, "Effect of Bulk Density on Reaction Propagation in Nanothermites and Micron Thermites," J. Propuls. Power, **25**(2), pp. 465–470. https://doi.org/10.2514/1.36436.

[17] Finazzi, A., Finocchi, P., Carlotti, S., and Maggi, F., 2024, "Thermite-for-Demise (T4D): Experimental Analysis of Heat Transfer Principles and Preliminary Sizing of an Application," Int. J. Heat Mass Transf., **220**, p. 124957. https://doi.org/10.1016/j.ijheatmasstransfer.2023.124957.

[18] Finazzi, A., Daub, D., Maggi, F., Paravan, C., Dossi, S., Lips, T., Smet, G., and Bodjona, K., 2025, "Thermite-for-Demise (T4D): Experiments and Numerical Modelling on Solar Array Drive Mechanism Mock-Ups Containing Thermite in an Arc-Heated Wind Tunnel," CEAS Space J. https://doi.org/10.1007/s12567-025-00598-8.

[19] Finazzi, A., Carlotti, S., Paravan, C., Maggi, F., Dossi, S., Lips, T., Daub, D., Schleutker, T., Smet, G., and Bodjona, K., 2024, "Thermite-for-Demise (T4D): From Material Selection to Test Campaign," *AIAA SCITECH 2024 Forum*, American Institute of Aeronautics and Astronautics, Orlando, FL. https://doi.org/10.2514/6.2024-2162.

[20] Habu, H., Okada, M., Ito, M., Nozoe, K., Kawano, T., Matsumoto, S., and Yoshida, Y., 2012, "Thermite as a Chemical Heat Source for the Science Payload," Sci. Technol. Energ. Mater. J. Jpn. Explos. Soc., **73**(5・6), pp. 147–152.

[21] Neely, K. E., Strauss, A. M., and Galloway, K. C., 2021, "Additively Manufactured Reactive Material Architectures for Exothermic Brazing," Addit. Manuf. Lett., **1**, p. 100005. https://doi.org/10.1016/j.addlet.2021.100005.

[22] Delgado, A., Cordova, S., and Shafirovich, E., 2015, "Thermite Reactions with Oxides of Iron and Silicon during Combustion of Magnesium with Lunar and Martian Regolith Simulants," Combust. Flame, **162**(9), pp. 3333–3340. https://doi.org/10.1016/j.combustflame.2015.05.024.

[23] MacRobbie, C. J., Wang, A., Hickey, J.-P., and Wen, J. Z., 2025, "In-Situ Thermite Combustion of Micro Magnesium Fuel and Lunar Regolith Simulant Nanoparticles," Fuel, **382**, p. 133722. https://doi.org/10.1016/j.fuel.2024.133722.

[24] Álvarez, F., Delgado, A., Frias, J., Rubio, M., White, C., Narayana Swamy, A. K., and Shafirovich, E., 2013, "Combustion of Thermites in Reduced Gravity for Space Applications," J. Thermophys. Heat Transf., **27**(3), pp. 576–583. https://doi.org/10.2514/1.T3876.

[25] AA.VV., 2023, *ESA Space Debris Mitigation Compliance Verification Guidelines*, ESSB-HB-U-002, Issue 2, Revision 0, European Space Agency.

[26] Finazzi, A., Zanardi, C., Pratola, O., Domaschio, J., Grande, A. M., Panerai, F., Carlotti, S., Paravan, C., and Maggi, F., 2025, "Thermite-for-Demise (T4D): Thermite Charge Shaping Advancements," *11th European Conference of Aerospace Sciences (EUCASS)*, Rome, Italy.