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Inflatable Heat Shields solutions for hypersonic re-entry applications: the European Commission EFESTO-2 project

G.Guidotti F.Toso, A.Princi J.Briceno-Gutierrez[1]*, G.Governale N.Viola*[2]*, I.Dietlein S.Callsen K.Bergmann*[3]*, J.Zhai T.Gawehn*[4]*, R.Gardi B.Tiseo*[5]*, Y.Prevereaud Y.Dauvois*[6]*, C.Julien*[7]*, G.Gambacciani G.Dammacco*[8]*, L.Garcia-Basabe*[9]

Abstract

Inflatable Heat Shields (IHS) are getting an increased interest in the field of some hypersonic applications as the one of re-entry.

In Europe the "ram's head" project EFESTO-1 (**E**uropean **F**lexible H**e**at **S**hields: Advanced **T**PS Design and Tests for Future In-**O**rbit Demonstration), funded by the European Commission through the Horizon 2020 program and run form 2109 and 2021, allowed the scientific community to carry out an early exploration of the potential use of this technology to recover space systems re-entering from LEO (e.g.: launch vehicle stages, satellites, space station elements). ([1] to [3])

In track-lay of EFESTO-1, the project EFESTO-2, funded by the EU program Horizon Europe, aims to further increasing the European know-how in the field of Inflatable Heat Shields (HIS) and seeks to improve further the Technology Readiness Level (TRL) of IHS. ([4] to [6])

The EFESTO-2 project built on four pillars: (1) consolidation of use-case applicability through a business case analysis for a meaningful space application; (2) extension of investigation spectrum of the father project EFESTO; (3) increase of confidence-level and robustness of tools/models; (4) consolidation of European leadership among the scientific and industrial community in this specific field.

This paper presents the EFESTO-2 project's work and achievements up to completion going: execution of a mission and system design loop for a reference application; implementation of a testing effort covering structural characterization of the inflatable structure as well as deformable shape investigation from the aerodynamic standpoint including stability; verification and improvement of numerical models both at structure and aero-shape levels; identification of the roadmap for near-future maturation.

This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 1010811041.

Keywords: *inflatable heat shields, hypersonic re-entry, innovative re-entry solutions*

Nomenclature

Business Case Analysis (BCA)
Computational Fluid Dynamic (CFD)
European Union (EU)
Fluid Structure Interaction Loop (FSI)

[1] *Deimos Space S.L.U, Tres Cantos 28760, Spain, giuseppe.guidotti@deimos-space.com*
[2] *Politecnico di Torino, Department of Mechanical and Aerospace Engineering, Turin – Italy*
[3] *German Aerospace Center (DLR), Space Launcher System Analysis, Bremen 28359, Germany*
[4] *German Aerospace Center (DLR), Supersonic and Hypersonic Technologies, Köln, Germany*
[5] *Centro Italiano Ricerche Aerospaziali (CIRA), Capua – Caserta, Italy*
[6] *Office National d'Etudes et de Recherches Aerospatiales (ONERA), Toulouse, France*
[7] *Office National d'Etudes et de Recherches Aerospatiales (ONERA), Chatillon, France*
[8] *Pangaia Grado Zero SRL (PGZ), Firenze 50056, Italy*
[9] *Deimos Engenharia, Lisbon 1070-061, Portugal*

Flexible TPS (F-TPS)
Ground Vibration Testing (GVT)
Inflatable Structure (IS)
Inflatable Heat Shields (IHS)
In Orbit Demonstration (IOD)
Launch Vehicles (LVs)
Rigid TPS (R-TPS)
Technology Readiness Level (TRL)
Thermal Protection System (TPS)
Wind Tunnel Test (WTT)

1. Inflatable Heat Shield: recent developments in EU

1.1. EFESTO-1 precursor

The EFESTO-1 project can be considered the initiator of developments in EU in the field of Inflatable Heat Shields (IHS). Funded by the European Union under the Horizon-2020 program, it was executed from 2019 to 2022 contributing to inject the bloom for a renewed interest toward inflatable heat shields in EU and succeeding into raise the TRL from 3 to 4/5 ([1] to [3]), with a broad scope of activities inherent to the two key technologies of Flexible Thermal Protection Systems and Inflatable Structures. Indeed, EFESTO-1 project hints were: (1) identification of mission classes enabled by the use of advanced Inflatable Heat Shields both for Mars and Earth re-entry (IHS); (2) definition of meaningful case study scenarios re-entry applications; (3) execution of mission and system design loops to obtaining the operative environment to properly feed the engineering of the IHS key components (F-TPS and IS); (4) verification of both the F-TPS and the IS design solutions through manufacturing of breadboards and testing in relevant environment (respectively, F-TPS lay-ups in high-enthalpy arc-jet facility in both Earth and Martian atmospheres, and an IS demonstrator via a dedicated vacuum test-rig); (5) conceptual design of an In-Orbit Demonstration (IOD) mission for future flight testing and verification of the matured IHS technologies.
The Fig 1 depicts in-a-raw the project outcomes mentioned above.

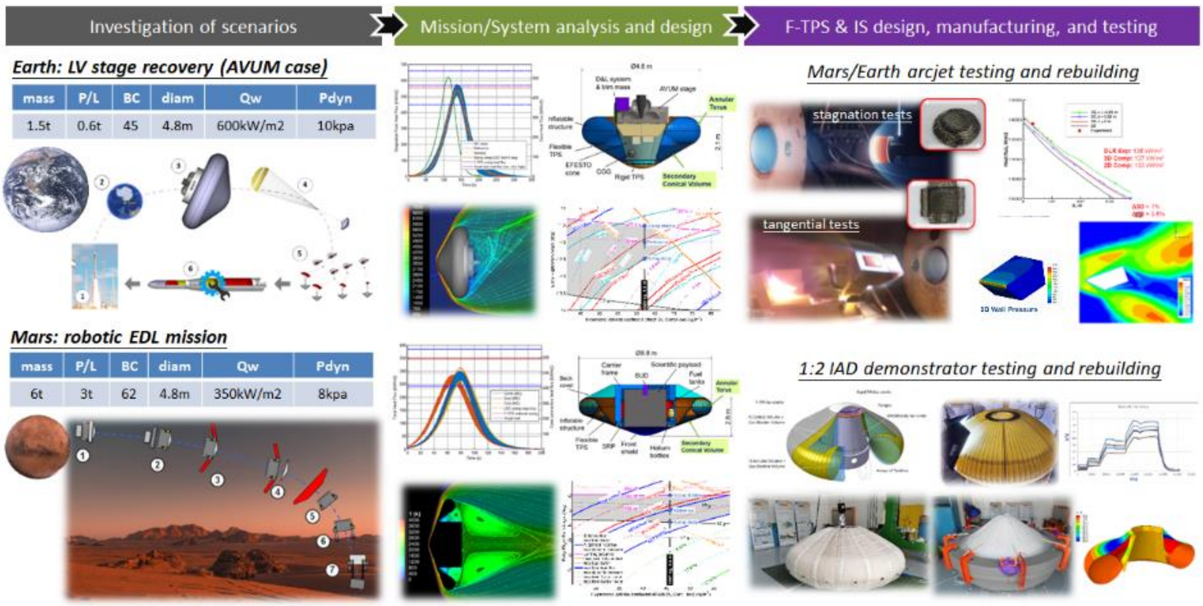

Fig 1. EFESTO-1 performed work in-a-raw.

1.2. EFESTO-2 objectives and set-up

The EFESTO-2 project ([4] to [6]) is a follow-on of EFESTO-1 with the objective to further increase EU know-how in the strategic field of re-entry leaning on exploitation of an innovative technology such as the Inflatable Het Shields.

Started in November 2022 the project is currently in its testing effort phase and it will end in October 2024. The project is managed by a European consortium (see Fig 2) under technical and programmatic coordination of Deimos Space (ES), and with involvement of beknown partners as ONERA (FR), DLR (DE), CIRA (IT), POLITO (IT), DEIMOS ENGENHARIA (PT), and PANGAIA-GRADO-ZERO (IT).

Valuable support is also ensured by CIRA subcontractor "ALI Scar" (IT) along with partners "SRSED srl" (IT) and "Thin Red Line Aerospace" (Canada) for all is about the inflatable structure technology.

Fig 2. EFESTO-2 project consortium.

The EFESTO-2 project is conceived to put in-place four main macro-tasks (Fig 3) as follows:

- consolidate the use-case applicability through a business case analysis for a LEO applications
- support the selected reference use-case with an engineering loop at mission and system level
- extend the investigation spectrum in complementary way to what was done in the frame of EFESTO father project to increase the confidence-level and robustness of tools/models developed so-far
- consolidate the definition of the roadmap toward a near-future development up to TRL-7

While the first and the second tasks were run in stacked timeline, the third one was rather organized with in parallel execution of two independent experimental parallel efforts, focused respectively on aeroshape characterization and structural characterization, plus an additional technology development related to GN&C design and validation up to Processor-in-the-loop. A final task of future evolutions was also appointed. The sections below will provide insight on each of the above.

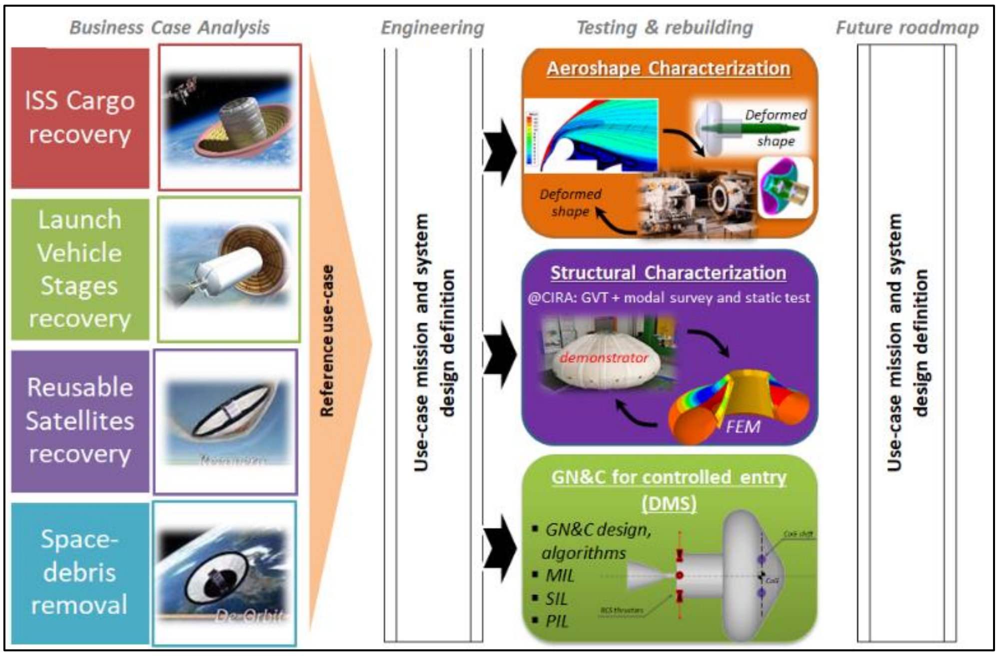

Fig 3. EFESTO-2 project objectives.

2. EFESTO-2 achievements

2.1. Business case

A Business Case analysis (BCA) has been carried out under coordination of POLITO (IT) and with involvement of Deimos (ES) and DLR-Bremen (DE). This very first step of the project had the objective to select a reference study-case for a baseline application and then properly feed the mission and system design loop meant to be addressed soon after. The Fig 4 depicts the BCA work-flow.

A literature review allowed to screen different applications potentially using IHSs for recovery and re-use purposes as: LV stages, of ISS cargo systems, reusable satellites ([7] to [9]).

Then a BCA was executed across an articulated workflow (Fig 4) by the following steps:

a. overview of reference target markets;

b. identification of most promising applications;

c. trade-off based on key performance indicators (interest, timeline, complexity, and technological fit);

d. evaluation of marketable applications using SWOT and PESTEL frameworks;

e. cost-oriented assessment of the reference use-case.

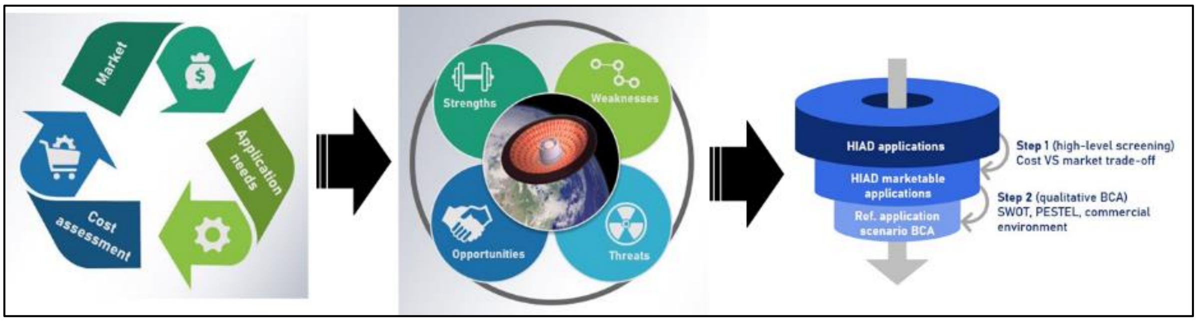

Fig 4. EFESTO-2 BCA work-flow

Potential reasonable applications were identified in the realm of re-entry wide-spectrum including Earth and Mars cases (Fig 5). Afterwards a cross-comparison was carried-out in terms of system-scale and commercialization time-line to down select the most interesting ones from a commercial point of view based on a total of 4 evaluation criteria: Market Size; Market Timeline (MT); Complexity (IC); Technological Score (TS).

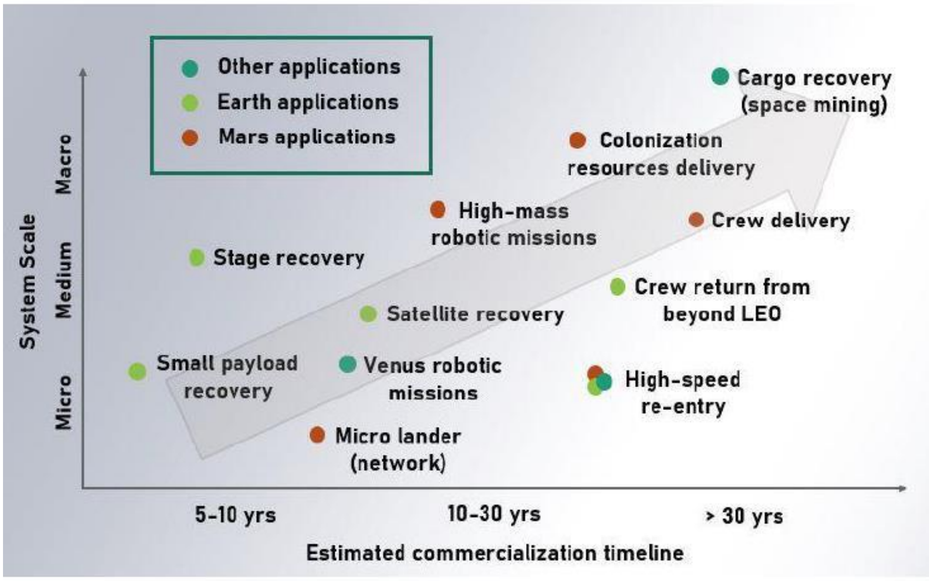

Fig 5. BCA applications

A preliminary assessment allowed to shrink the trade-off to launch vehicle stage reusability (A1) and small LEO payload recovery (A3) for Earth re-entry, and micro-lander (A7) and large cargo delivery (A10) for Mars re-entry, respectively.

Afterwards, pros and cons of the Earth and Mars cases were further assessed within the frameworks of SWOT and PESTEL techniques to down-select one unique reference use-case for the final step of the BCA (Table 1 for Earth; Table 2 for Mars).

Being the Horizon Europe program exclusively focused on Earth re-entry applications, then the project team decided to retain only the Earth scenario cases for the subsequent stage of the BCA. According to this further assessment, the best candidate use-case in the frame of Earth re-entry is the recovery of a reusable launch vehicle stage in the class of 2tons, which is so kept as the reference study-case for the subsequent stage of the EFESTO-2 project.

Table 1. LEO applications appraisal

	Launcher stage recovery (A1)	Satellite recovery (A2)	Small PL recovery (A3)	High-speed cargo entry (A4)	Crew return from LEO (and beyond) (A5)	Cargo recovery for space mining (A6)
Strengths	Packability, buoyancy, adaptability	Packability, adaptability	Packability, buoyancy	Packability, lower BC, buoyancy	Lower BC, buoyancy	Packability, cost
Weaknesses	Impact on LV mass	Impact on satellite mass & volume	Existing recovery solutions	F-TPS ATD limits	F-TPS ATD limits, delivery accuracy, lower reliability,	F-TPS ATD limits, delivery accuracy, high-perf. DES system needed
Tech. score [fit complexity]	[3.5 3.5]	[2.0 3.0]	[4.5 5.0]	[3.0 2.0]	[2.0 1.0]	[4.0 2.0]
Market interest [size timeline]	Launcher reusability [4.0 4.5]	Satellite reusability [1.5 2.5]	In-orbit experiment ation [1.5 4.5]	Solar System exploration [3.0 3.0]	Space tourism, Lunar missions, Mars colonization [4.0 2.0]	Future space economy [5.0 1.0]

Table 2. Mars applications appraisal

	Mars micro lander network (A7)	Venus robotic mission (A8)	Mars robotic missions (A9)	Mars cargo delivery (A10)	Crew delivery to Mars (A11)
Strengths	Packability, adaptability	Packability	Lower BC	Lower BC, cost	Lower BC
Weaknesses	Existing simpler solutions	Existing simpler solutions	Rigid shield comp. up to 2 tons, lower delivery accuracy	High-perf. DES system needed	F-TPS ATD limits, delivery accuracy, lower reliability, high-perf. DES system needed
Tech. score [fit complexity]	[5.0 4.0]	[4.0 4.0]	[3.0 3.0]	[4.0 2.5]	[3.0 1.0]
Market interest [size timeline]	Mars exploration [2 3.5]	Solar System exploration [1.5 3]	Mars exploration [3 3]	Mars colonization [4 2.5]	Mars colonization [3.5 1.5]

2.2. Mission and system design

With respect to the reference use-case of Earth re-entry 2-tons reusable launcher stage, a design loop has been executed under the coordination of DLR-Bremen and Deimos and with the support of all the other partners. Based on a multi-disciplinary engineering process it allowed defining the key aspects of the mission and of the system along with the critical aspect of mechanical and thermal sizing of the inflatable heat shield.

The Fig 6 is an illustration of the reference mission scenario for the recovery of a launch vehicle stage.

The ascent until fairing separation and main payload ejection is conventional. Afterwards the upper stage will perform a de-orbiting burn followed by a re-orientation maneuver such to exhibit the right attitude during re/entry. When this is achieved, the IHS itself is inflated before it enters the atmosphere.

After the re-entry phase is completed, a decelerator is deployed for final passive descent until a rendezvous area is reached to allow for mid-air-retrieval execution. It is remarked that the EFESTO-2 project focused only on the re-entry phase of the mission.

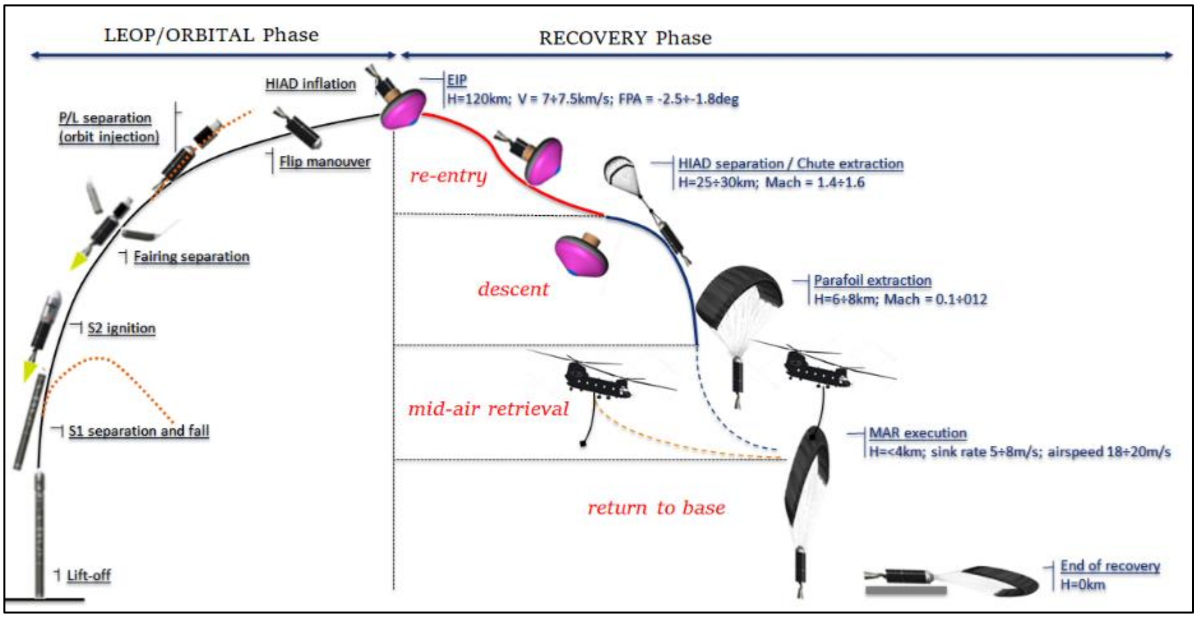

Fig 6. EFESTO-2 mission concept-of-operations

Starting from the ConOps, a system design effort was carried out. First, an investigation was done to identify the best aeroshape, playing with the outer diameter of the inflated heat shield and the cone angle. Different shape variants were defined and traded against each other. This design step was supported by aerodynamics and aerothermodynamic assessment, flexible TPS and inflatable structure design as well as by mission analysis and flying quality assessment.

Fig 7 shows the final retained aeroshape and the CFD flow-filed simulations in a flight condition most critical for the inflatable structure (i.e.: maximum dynamic pressure), and the internal layout.

Fig 8 shows instead the trajectory envelope as function of the Mach number (left), and the heat-flux distribution around the external shape for different critical trajectory points (right).

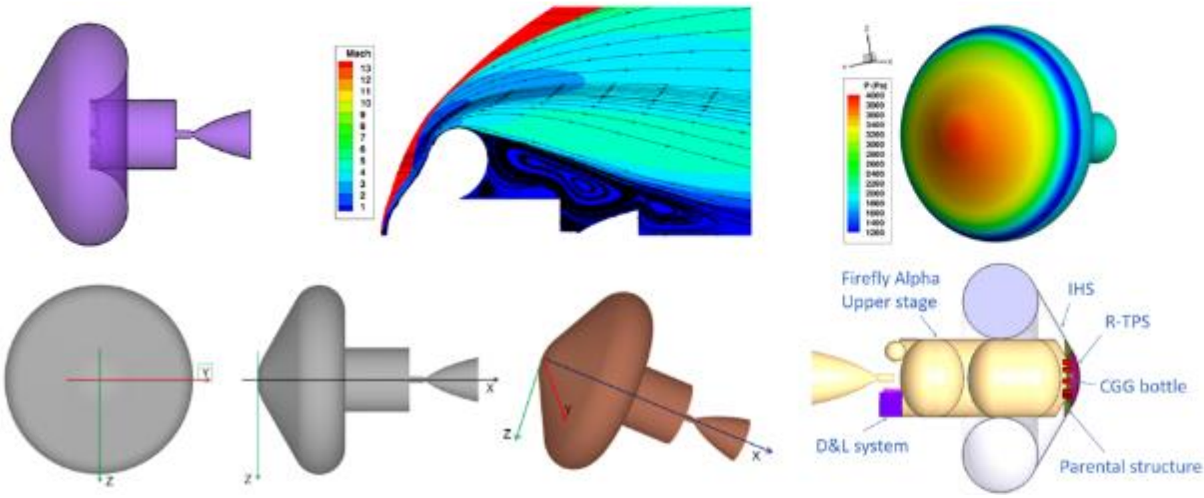

Fig 7. EFESTO-2 system: aeroshape, flow-field and internal layout

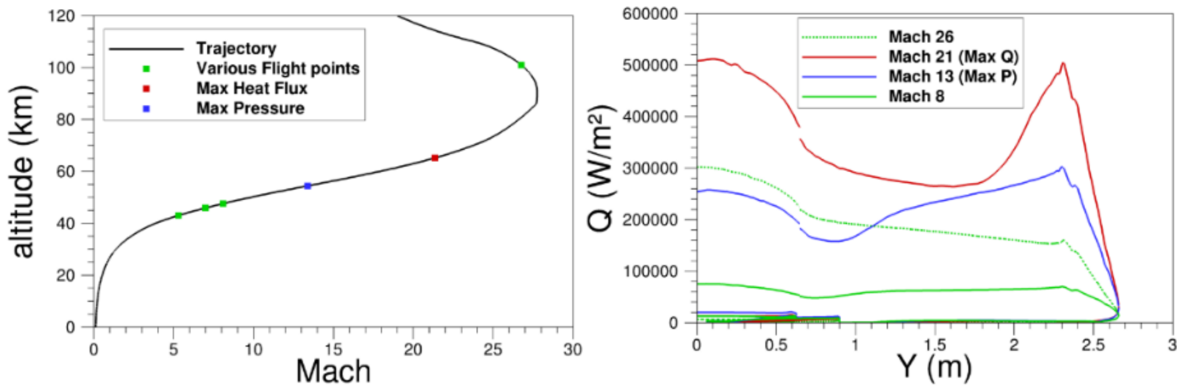

Fig 8. EFESTO-2 trajectory envelope (left), heat flux distribution (right)

The Flexible TPS and Inflatable Structure sub-systems being the most critical items of the re-entry spacecraft, underwent a dedicated design action through modelling and analysis efforts based on models and material data inherited from the previous project EFESTO.

As far as the F-TPS, different solutions of material stack-up were investigated and verified against the aerothermal loads. Then a final optimized architecture was taken as a baseline with a fixed stack-up of material layers and thickness. (Fig 9, right)

As far as the IS, again the EFESTO engineering know-how was widely applied to define the geometry and size of the inflatable volumes as well as the material to be adopted. From a structural standpoint the IS was verified against the main mechanical load that is the external flow-field pressure pattern. (Fig 9, left)

For both the F-TPS and the IS, consequently, mass and volume budgets were obtained to feed the system synthesis.

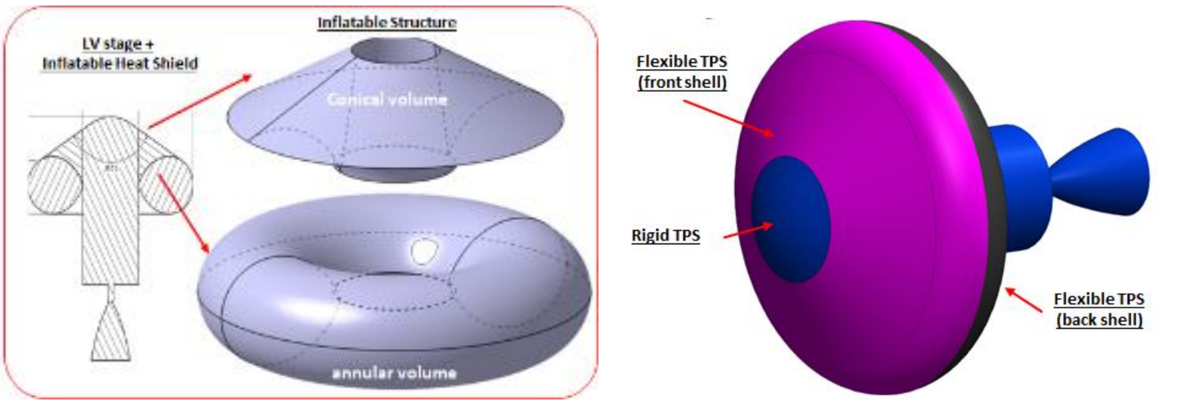

Fig 9. EFESTO-key technologies layout and overview

2.3. Ground testing and numerical post-rebuilding

Of paramount importance in the frame of the project is the implementation of a wide spectrum investigation effort focused on aerodynamics and mechanical characterization of the Inflatable Heat Shields with two parallel activities:

- the aerodynamics investigation, under coordination of ONERA-Toulouse for the numeral aspects and DLR-Cologne for the experimental aspects;
- the mechanical characterization, under coordination of CIRA with the support of the subco, by testing the 1:2 scale demonstrator test-article produced within the EFESTO project, to explore structural modal survey (by Ground Vibration Testing) and static strength;

As far as it concerns the aerodynamics characterization, cold-flow wind tunnel tests of 2 sub-scaled models were conducted (are being conducted) to get static and dynamic stability with a focus on deformed shapes. Afterwards an extensive numerical rebuilding by CFD will be appointed.

Wind-tunnel tests were performed at DLR-Cologne premises involving two facilities (namely TMK and H2K) to determine the static and dynamic behavior of the inflatable capsule in its deformed and undeformed shape. In particular, static stability tests in hypersonic regime in H2K (at Mach numbers 5.3 and 7.0) and in supersonic regime in TMK (Mach number range of 1.4 to 4) were executed under equivalent upstream flow conditions in terms of Reynolds number and dynamic pressures. Two different shape variants of the vehicle were design and manufactured, featuring deformed and undeformed status respectively, with scaled geometries (namely 2% in H2K and 1.5% in TMK). At the end of the testing effort, an experimental Aerodynamic Data Base (AEDB) for static and dynamic aerodynamic coefficients will be created.

At the time this paper is being written, the whole set of runs of static wind-tunnel testing was completed, while the dynamic test at TMK will be due in April 2024. The Fig 10 below refers to the models under test at the TMK and H2K wind-tunnels in DLR-Cologne premises.

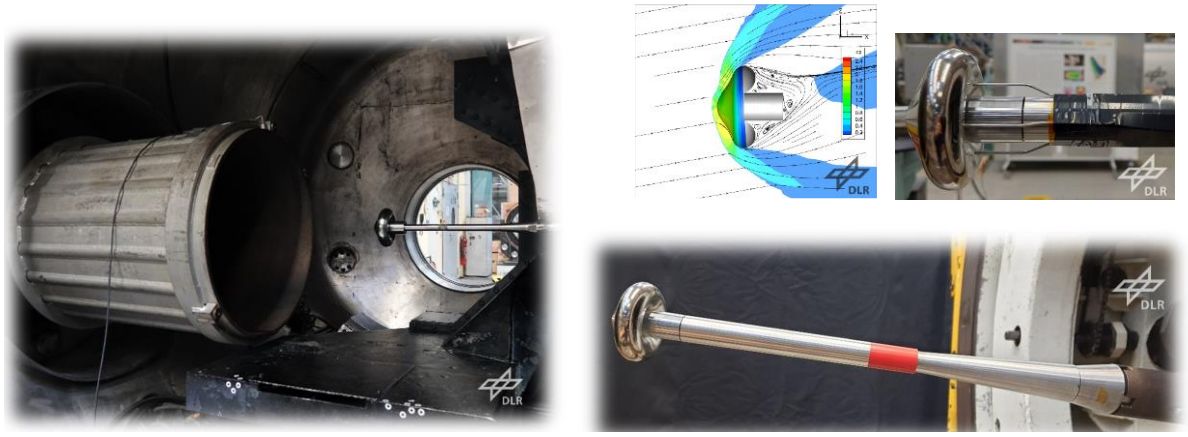

Fig 10. EFESTO-2 aeroshape models in WTT at H2K (left) and TMK (right) @DLR Cologne premises.

Afterwards, ONERA will perform the numerical rebuilding of the experiments carried out at DLR-Cologne aiming at evaluating the uncertainties associated to numerical simulation by comparing numerical and experimental results.

Fig 11 reports a very early anticipation of the numerical rebuilding of a wind-tunnel test. This work will be extended to many of the runs. Some simulations will be modeled in 2D and some other in in 3D. The whole work will allow to revisit the AEDB and ATDB to consolidate the mission and system design.

For further details on the topic please refer to the papers [10] and [11].

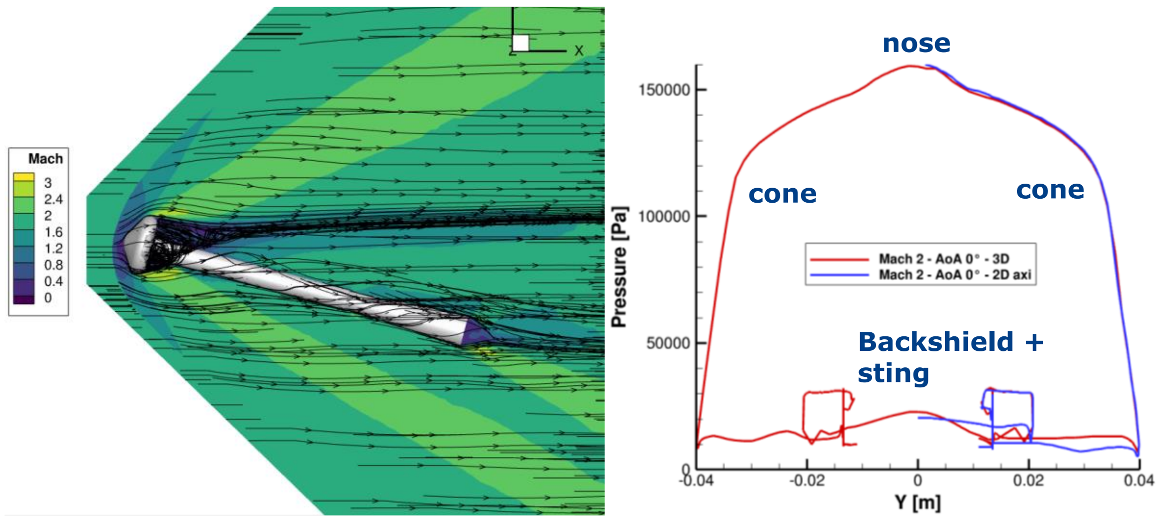

Fig 11. EFESTO-2: CFD simulation of WTT run at Mach 2, AoA 15° (ONERA)

As far as it concerns the mechanical experimental characterization, it is foreseen execution of static and dynamic tests on the ground demonstrator of the Inflatable Structure inherited by the father project EFESTO-1 (see respectively Fig 12 and Fig 13). The activity is taking place at CIRA (IT) premises under CIRA responsibility with valuable support by the subcontractor "ALI Scarl" (IT) along with partners "SRSED srl" (IT) and "Thin Red Line Aerospace" (Canada) for all is about the inflatable structure modeling and manufacturing technology.

At the time the paper is being written the dynamic test campaign (GVT) is under execution with the aim to investigate the modal behavior to the inflatable structure. The test article is excited by means of shakers in specific locations with periodical solicitation at controlled frequencies. The surface of the IS is instrumented with a number of accelerometers suitable to identify the global modes of the system.

A specific set-up has been already identified and optimized thanks to an exploratory shaking loop where the test article has been first excited on-ground and later on in a suspension-mode. The final test configuration for the GVT will be the one best suited for free-free- modal survey with the test article suspended under a set of elastic ropes chosen accordingly.

Preliminary results show a good matching with the numerical FEM modelling with the inflatable structure exhibiting first global modes at low frequency, as expected from this membrane-like systems.

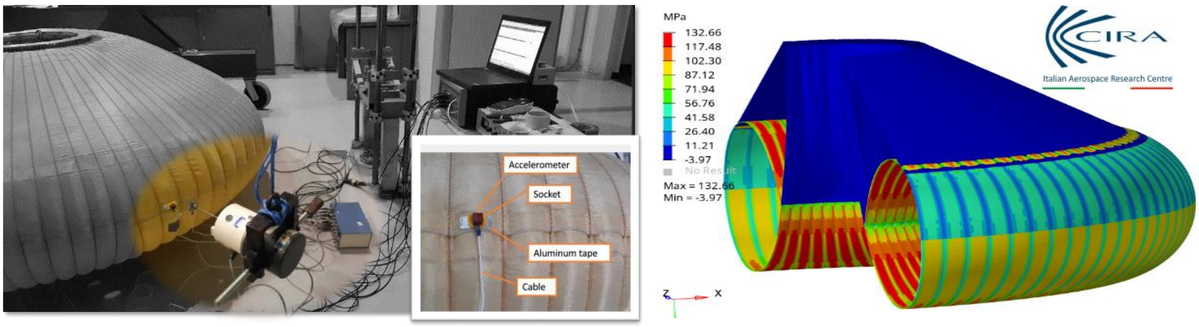

Fig 12. EFESTO-2: experimental set-up during the GVT @CIRA and FEM of the IS demonstrator

After the GVT campaign, a static-test campaign will be started using the same test article along with an ad-hoc test-rig able to replicate the pattern of mechanical load produced by the aerodynamic pressure during re-entry. The static-load test campaign will allow for verification of strength under pressure load as well of stiffness measurements and deformation and morphing observation.

Outcomes of the dynamic and static tests campaign will be injected into the 3D FEM of the inflatable structure to make model rebuilding in order to crease its confidence level and prediction capabilities.

Fig 13. EFESTO-2: structural demonstrator and test-rig (vacuum-pool) at CIRA premises

In parallel to the experimental investigation, a numerical effort is being carried out on behalf of ONERA-Chatillon department focused on the modelling and simulation of all is about morphing behavior of such a peculiar structure (Fig 14). Leveraging the EFESTO-1 project achievements in that filed, an enhancement will be pursued for the definition of a multi-step simulation strategy dedicated to the analysis of the folding and the inflation of the inflatable system.

A close correlation between the simulation and CIRA activities will be ensured to inject a certain level of fidelity to the real world with a specific focus on the main elements that compose the inflatable structure.

For further details on the topic please refer to the papers [12].

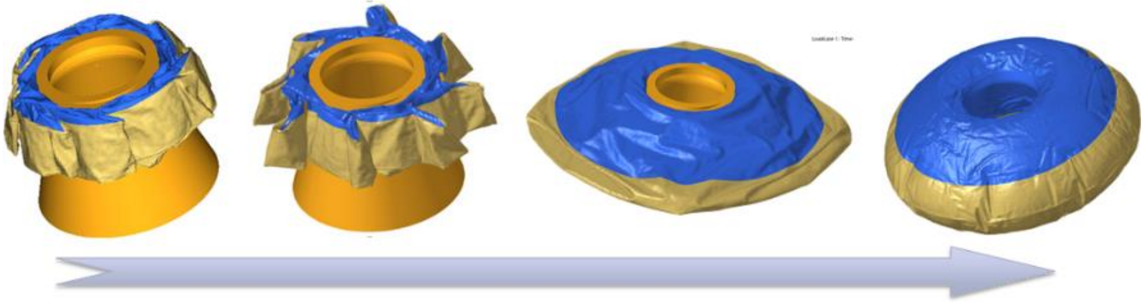

Fig 14. EFESTO-1 morphing model and simulation (ONERA-Chatillon)

2.4. GNC development

An important novelty of the EFESTO-2 is injection of an additional objective as development of the GN&C with a particular focus on implementing a guided re-entry for systems based exclusively on IHS. The aim is to recover the high dispersions produced by uncertainties at re-entry, and then allow for the Mid-Air Retrieval to be executed with reasonable resources and fair-good operational feasibility.

The GN&C development is in responsibility of Deimos Enghenaria (PT) and it targets implementation of active control/planning of down-range and cross-range through a combination of lift generation, lift-over-drag modulation, and bank manoeuvring. (Fig 15)

The controller under design has the following features: 1) Structured H-infinity for a robust closed-loop system; 2) Decoupled control for longitudinal and lateral channels through RCS and MCS commands; 3) Gain scheduling along the trajectory to tackle different operating conditions and changes in the aerodynamic properties.

Currently being at its model-in-the-loop stage, the GN&C work will enter soon the verification phase through classical stages of software-in-the-loop and finally process-in-the-loop validation.

For further details on the topic please refer to the paper [13].

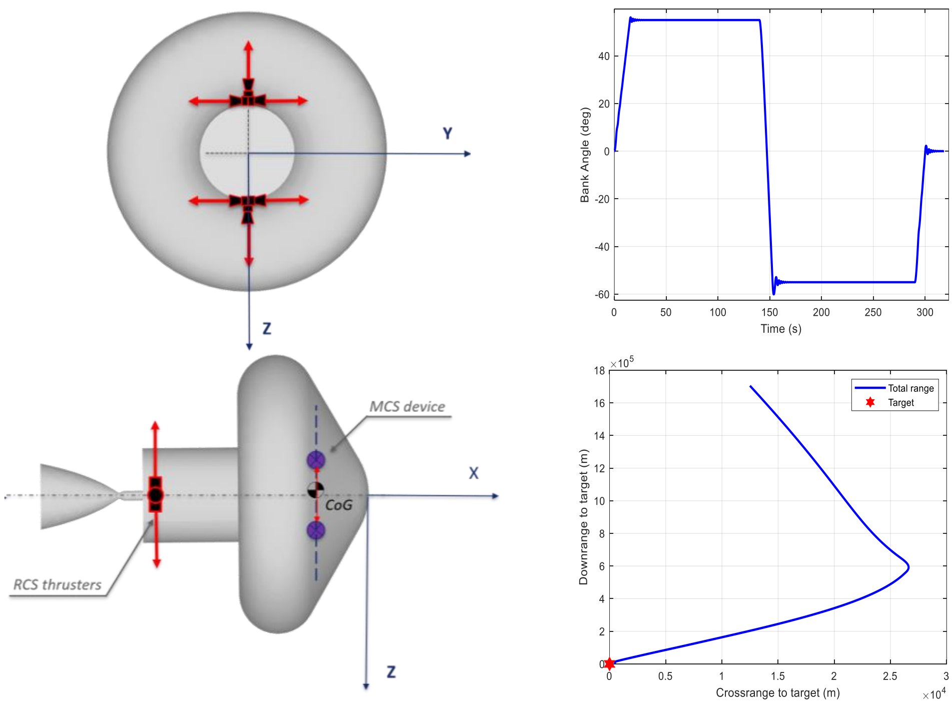

Fig 15. EFESTO-2 GN&C development (system actuators, left; early output, right)

3. EFESTO-2 technology advance and roadmap to the future

The achievements obtained so far in the frame of EFESTO-1 and EFESTO-2 projects can be considered significant, however a further maturation step shall be appointed for consolidation of the TRL of the IHS technologies. A potential roadmap for near-term development is depicted in the Fig 16.

In order to demonstrate applicability of this innovative solution, the following goals shall be targeted post-EFESTO legacy:

i. complete the maturation on ground of the key technologies that are enabler for the Inflatable Heat shields (i.e.: Flexible TPS and Inflatable Structure) with ground-qualification of 3D demonstrators of a size higher than what has been released so far;

ii. design, realize and fly (in relevant environment) meaningful-scale demonstrators of an Inflatable Heat Shield and execute a number of flight tests of incremental complexity (e.g.: on board a sounding rocket first, and then on aboard a space launcher for a LEO-demo mission);

iii. execute post-flight analysis and rebuilding for technology performance evaluation, system behavior identification, and models improvement;

The challenging plan defined above may allow reaching out a TRL of 6/7 as prelude to a pre-operational use of this technology in the realm of space applications for either Earth return or Mars re-entry.

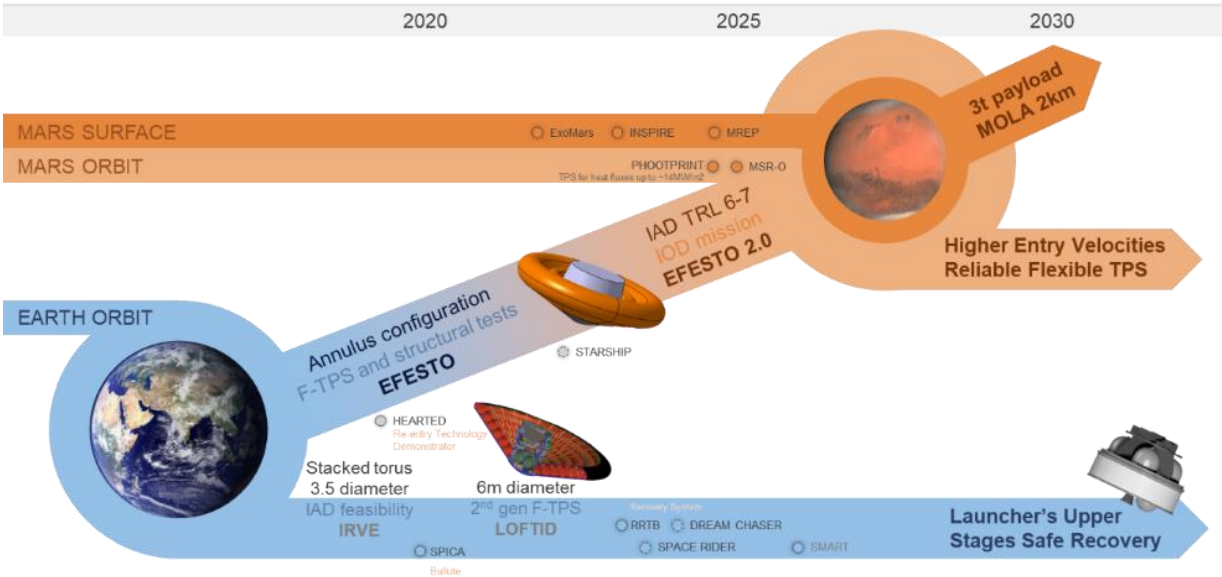

Fig 16. Roadmap for the consolidation of the European IHS technology capability

4. Conclusions

This paper presented the work carried out so far in the frame of the EFESTO-2 project with a focus on the engineering outcomes produced in the first phase of the project on the one hand, and the experimental/numerical effort being put in place currently and meant to be completed before the summer 2024 on the other.

Also, it anticipated some of the work planned to be done up to completion, including the potential injection into near-future initiatives for an in-flight demonstration endeavor as further maturation step.

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More information available at: http://www.efesto-project.eu.

The EFESTO-2 consortium acknowledges the essential contributions from ALI Scarl Italia (IT), SRSED srl (IT) and Thin Red Line Aerospace (CA) concerning the inflatable structure technology.

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