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THE ACHIEVEMENTS OF THE EFESTO-2 PROJECT: INFLATABLE HEAT SHIELDS AS INNOVATIVE SOLUTION FOR A SAFE RE-ENTRY OF REUSABLE LAUNCH VEHICLES' SEGMENTS

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Abstract

EFESTO-2 (European Flexible Heat Shields: Advanced TPS Design and Tests for Future In-Orbit Demonstration – 2) is a project funded by the EU program Horizon Europe. It aims to further increase the EU know-how in the field of Inflatable Heat Shields, an innovative technology adoptable for thermal protection during re-entry and effective in the realm of space transportation systems to safely re-enter and protect elements of reusable launch vehicles.

The project builds upon the great achievements of the father project EFESTO (H2020 funds No 821801) and seeks to improve further the Technology Readiness Level (TRL) of Inflatable Heat Shield (IHS) by implementing four main macro tasks: (1) consolidation of use-case applicability through a business case analysis; (2) extension of investigation spectrum of the father project EFESTO to other critical aspects of the IHS field; (3) increase of confidence-level and robustness of tools/models; (4) identification of a roadmap for future initiatives.

This paper presents the project's work and achievements up to completion obtained during the 24-month project cycle. It will go across the project's main work-items of: execution of a mission and system design loop for a reference application in a baseline use-case scenario; implementation of significant testing effort covering the key aspects of structural characterization of the inflatable structure as well as deformable shape investigation from the aerodynamic standpoint including static and dynamic stability; verification and improvement of numerical models both at structure (FEM) and aero-shape (CFD) levels; identification of the roadmap and near-future effort toward maturation of the IHS technology for a systematic use on real re-entry missions.

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, Re-entry, Reusability, Reusable launchers.

Acronyms/Abbreviations

AEDB (Aero Data Base)
ATDB (Aero Thermal Data Base)
BCA (Business Case Analysis)
CFD (Computational Fluid Dynamic)
CoG (Center of Gravity)
FEM (Finite Element Model)
F-TPS (Flexible TPS)
GNC (Guidance Navigation Control)
H2K (Hypersonic wind tunnel)
IHS (Inflatable Heat Shields)
IS (Inflatable Structure)
LVs (Launch Vehicles)
MAR (Mid Air Retrieval)
OBC (On-Board Computer)
P/L (Payload)
MCS (Mass Control System)
PESTEL (Political Economic Social Technological Environmental Legal)

RCS (Reaction Control System)
R-TPS (Rigid TPS)
SWOT (Strengths Weaknesses Opportunities Threats)
TMK (Trisonic wind tunnel)
TPS (Thermal Protection System)
TRL (Technology Readiness Level)
WTT (Wind Tunnel Test)

1. Introduction

The EFESTO-2 project is the natural follow-on of the father project EFESTO ([1], [13]).

EFESTO-2 received funds from the European Union's Horizon Europe program under grant agreement No.1010811041 [12] and it has been executed by a European consortium (see Fig.1) coordinated by DEIMOS Space (ES), that includes ONERA (FR), DLR (DE), CIRA (IT), POLITO (IT), DEIMOS ENGHENARIA (PT), and PANGAIA-GRADO-ZERO (IT).

The project builds upon four macro-tasks:

- consolidate the use-case applicability through a business case analysis;
- extend the investigation spectrum in complementary way to what was done in the frame of EFESTO father project [1];
- increase the confidence-level and robustness of tools/models developed so-far, by implementation of an extensive testing effort;
- consolidate the definition of the roadmap toward a near-future development up to TRL7.

The paragraphs here below collect the main elements of the tasks providing the insights and the related outputs.

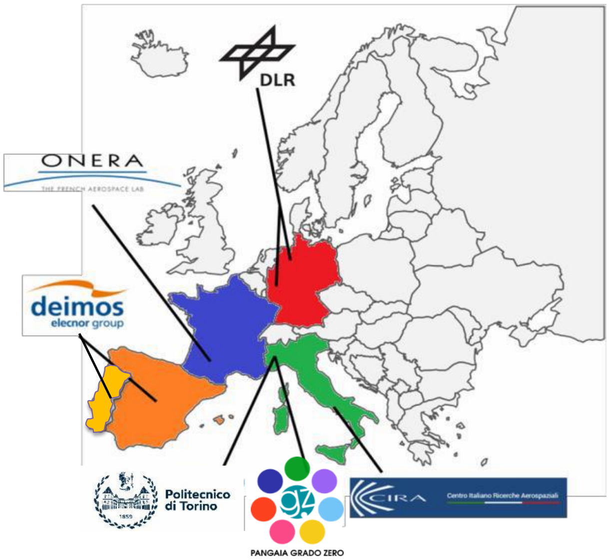

Fig. 1: EFESTO-2 project consortium.

2. Business Case Analysis

At the very beginning, the BCA supported the selection of a reference study-case for a baseline application in order to allow afterwards execution of the engineering loop. The BCA was executed across an articulated workflow (see Fig.2) by analysing both technology and market aspects, adopting SWOT and PESTEL frameworks.

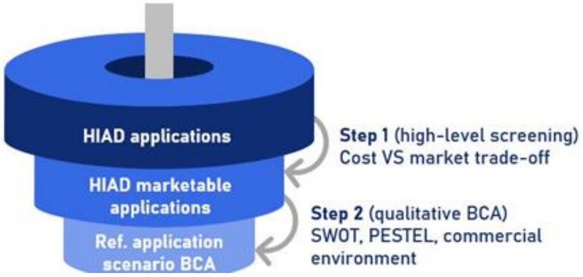

Fig. 2: BCA workflow.

Different applications potentially adopting IHSs for recovery and re-use purposes were identified ([7] to [9], Fig.3). The most promising applications were retained in the field of Earth-re-entry and a traded-off was carried out based on key performance indicators. Finally, a baseline use-case was down-selected for the remaining part of the project.

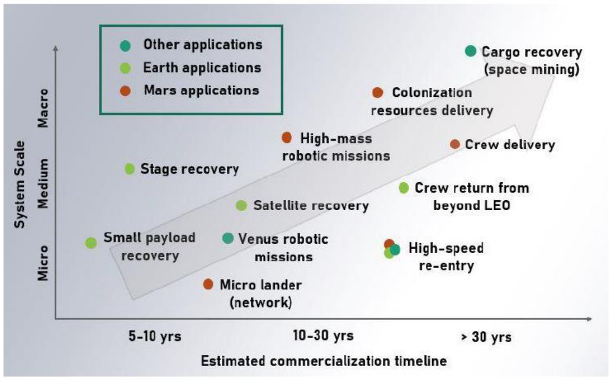

Fig. 3: Application range for the BCA.

According to the BCA assessment, the best candidate use-case in the frame of Earth re-entry appeared to be the '**recovery of a Launch Vehicle stage"** in the class size '*Cluster II 0.5-2 tons*'.

In turn, the identified reference study-case for the subsequent stage of the EFESTO-2 project was the recovery of a medium-size LV stage in the range [500÷2000] kg, e.g. the Firefly Alphas LV.

3. Reference mission and system design loop

For the selected study case, the concept of operations was defined (Fig.4, Fig.5).

Briefly, after separation of the main P/L, the LV upper stage performs a de-orbiting manoeuvre and before re-entry the IHS is inflated. Afterwards, the re-entry system, a combination of the LV upper stage and the IHS, starts its own mission from the atmospheric entry interface down to landing. The descent is supposed to be managed through a parachute with a guided parafoil until reaching out the appropriate altitude for an helicopter to catch the system by Mid-Air-Retrieval.

It is remarked that the EFESTO-2 engineering effort was strictly focused on the entry leg of this mission concept from EIP down to parachute deployment, being this phase strictly related to the IHS technology.

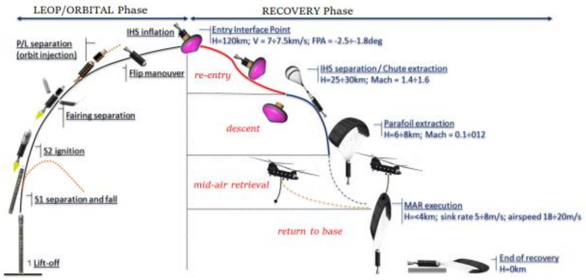

Fig. 4: End-to-end mission ConOps.

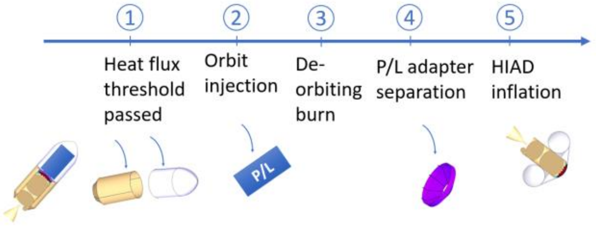

Fig. 5: ConOps details for the Firefly Alpha study case.

As fundamental step of the system engineering loop, the aeroshape design was first addressed by investigating four variants, playing with the geometry (diameter and aspect-ratio) of the shield (Fig.6).

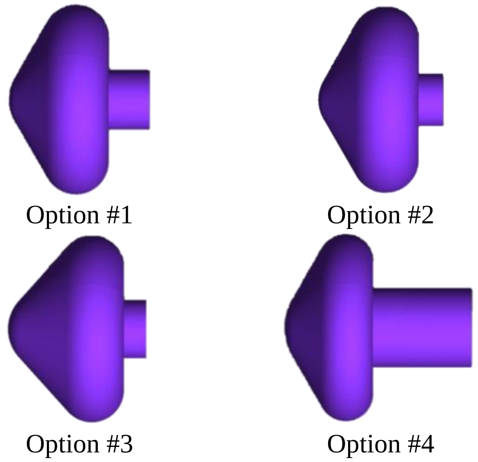
Option #1
Option #2
Option #3
Option #4

Fig. 6: Aero-shapes investigated.

For each aero-shape, CFD-based numerical simulations were carried-out to develop an aerodynamic database and to investigate aerodynamics and aerothermodynamics physical phenomena along the reference trajectory.

CFD simulations focused on critical flight points as maximum heat flux and maximum dynamic pressure (Fig. 7). That work allowed to get distributions of loads (pressure and heat flux) along the body in support of the system design loop.

Based on that extended analysis, a trade-off was performed that took to down-selection of the best aero-shape with respect to maximization of the entry corridor as well as compliance to the system constraints (namely, maximum allowable heat flux, heat load, dynamic pressure and g-load).

Fig.8 shows the final retained system configuration, while Fig.9 represents the mass distribution allocated to the re-entry system at the end of the design process.

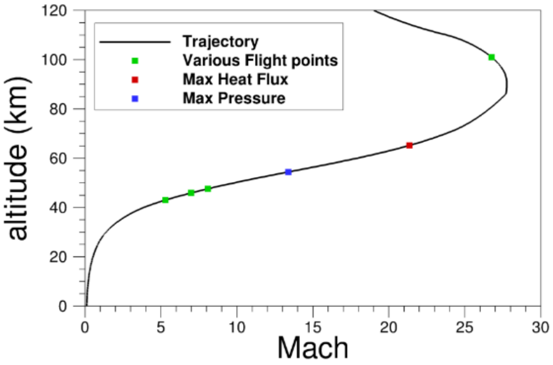

Fig. 7: Flight point under investigation for the CFD simulations for the reference shape (option #1.1).

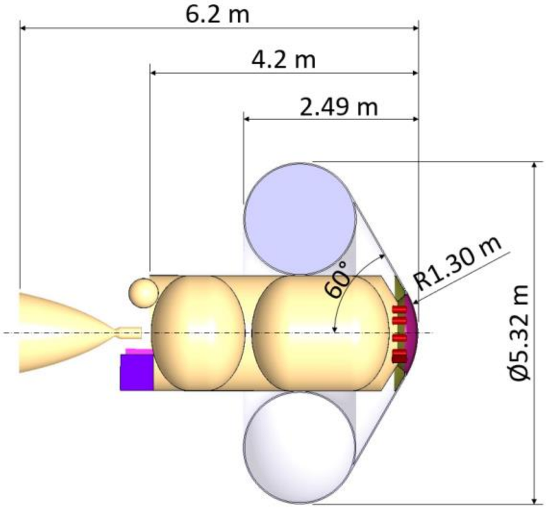

Fig. 8: Final configuration at re-entry.

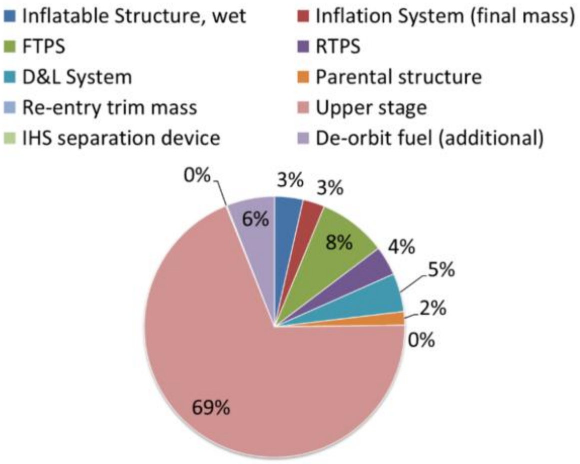

Fig. 9: Re-entry system mass distribution.

Based on the aeroshape performance, an extensive mission analysis was conducted to verify the mission feasibility in terms of entry corridor existence and compliance with constraints.

Different trajectories were propagated from the Entry Interface Point (i.e.: 120 km above ground) down to the ground, considering a ballistic entry.

The analysis was fed by fundamental data such as aero-shape, aerodynamics, system mass, as well as external factors (wind, atmosphere, etc.). Monte Carlo runs were also executed to ensure the feasibility of the re-entry mission vis-à-vis injection of uncertainties.

The mission analysis allowed to retrieve a set of outputs for the pursuit of the system design, namely mechanical and aerothermal loads (Fig.10).

The aero-shape flying quality performance was also addressed to provide a suitable CoG position for the trimmability and the Lift-over-Drag performance (Fig.11).

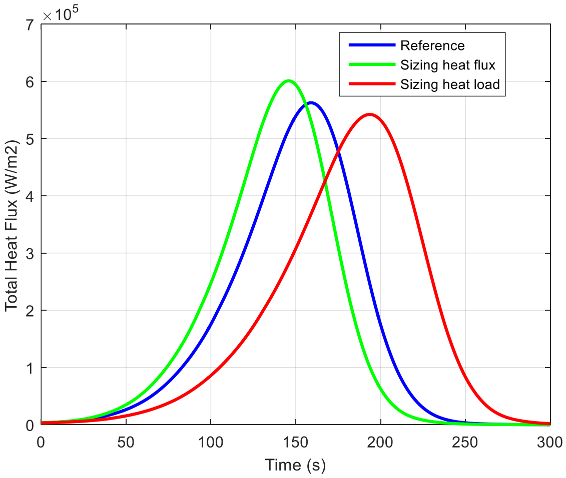

Fig. 10: Re-entry loads – heat flux.

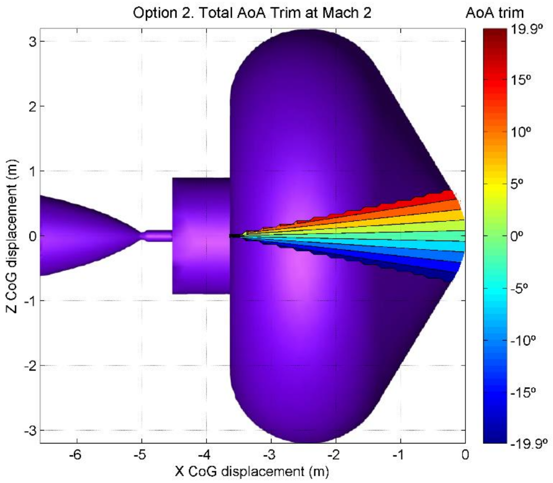

Fig. 11: Vehicle flying quality – trim angle of attack.

Entry loads and system aeroshape and geometry fed the system design loop with a particular focus on the Flexible TPS and Inflatable Structure sub-systems. Being the most critical items of the re-entry spacecraft, those two subsystems underwent a dedicated design action through modelling and analysis efforts based on approaches, models and material data inherited from the previous project EFESTO ([1], [13]).

Regarding the F-TPS, different solutions of material stack-up were investigated and verified against the aerothermal loads. Then a final optimized architecture was identified as a baseline, with a fixed stack-up of material layers and thickness. (Fig.12)

Regarding 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.13)

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

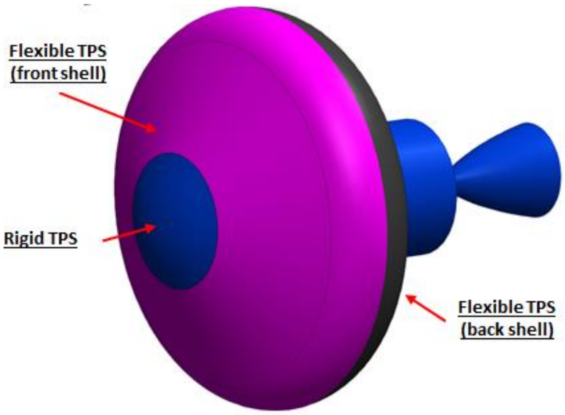

Fig. 12: TPS layout.

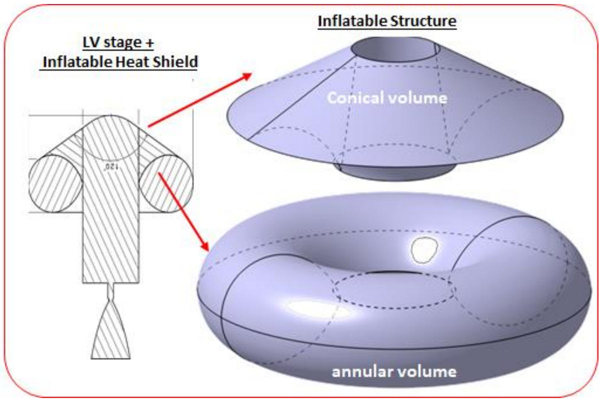

Fig. 13: Inflatable Structure layout.

With respect to the father project, an important novelty of the EFESTO-2 was the injection of the GNC development with a particular focus on implementing a guided re-entry in order to reduce dispersion due to both uncertainties and re-entry boost accuracy [4].

This capability can allow for the Mid-Air Retrieval operation to be executed with reasonable resources and with a fair-good operational feasibility.

The GNC (Fig.14) was designed to manage the re-entry leg of the trajectory by implementing active control/planning of down-range and cross-range through a combination of lift generation, lift-over-drag modulation, and bank manoeuvring.

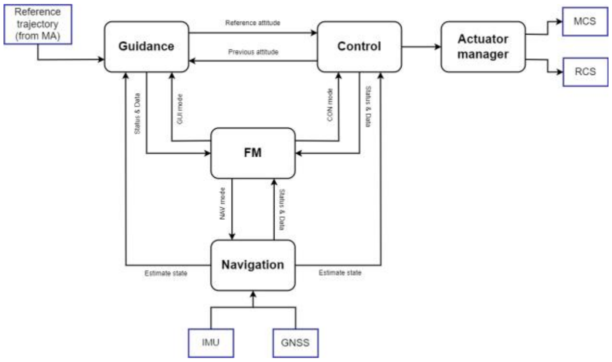

Fig. 14. GNC architecture adopted in EFESTO-2.

As a result of a trade-off analysis, the final solution adopted is based on RCS and MCS devices best satisfying a range of criteria (system complexity, weight and volume, maturity, accuracy, robustness).

A sketch of the final re-entry system configuration is presented in Fig.15.

Afterwards, the GNC design went through the chain of Model-in-the-Loop, Software-in-the-Loop and then Processor-in-the-Loop thanks to exploitation of a real OBC platform. Results were successful from any standpoint (i.e.: design, software verification and integration).

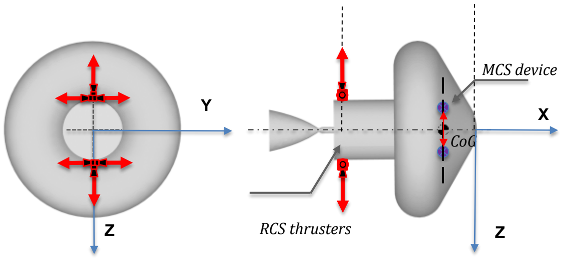

Fig. 15. Vehicles configuration with control devices.

3. Ground development effort

The second important stage of the project life-cycle has been dedicated to two ground-testing actions conducted in parallel, as described here below.

3.1 Wind-tunnel test effort

Wind-tunnel tests were performed at DLR-Cologne premises involving two facilities (namely TMK and H2K) to determine the static and dynamic behaviour 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 or dynamic pressures. Fig.16 shows on of the sub-scale model during the WTT runs at TMK @DLR.

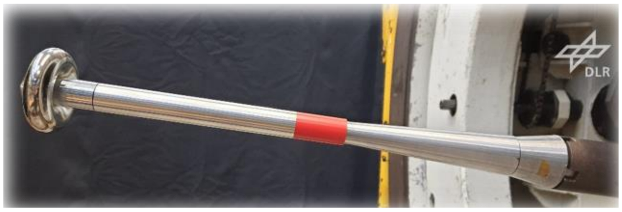

Fig. 16. Aeroshape models in WTT at TMK @DLR.

In addition, dynamic stability tests were performed in TMK using the free oscillation measurement technique with a wind-tunnel model which embedded as key element an elastic cross-flexure, designed to provide the necessary motion around the CoG. The test conditions for the dynamic tests were identical to that of the static test campaign. This part of the effort allowed to collect experimental data about damping derivatives.

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 was also created.

The WTT tests results were subjected to numerical rebuilding executed by ONERA (Fig.17), the main objective being to evaluate the uncertainties associated to simulations (Fig.18 to Fig.20), namely the aerodynamic deviation between deformed and non-deformed heatshield, and to revisit the AEDB/ATDB to consolidate the mission and system design.

The revisited AEDB along with the dynamic derivatives data allowed also to re-assess the nominal trajectory, as well as the flying qualities.

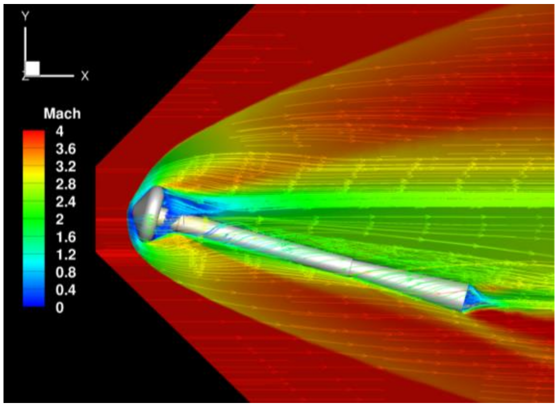

Fig. 17. CFD simulation of WTT (Mach 4, AoA 15°).

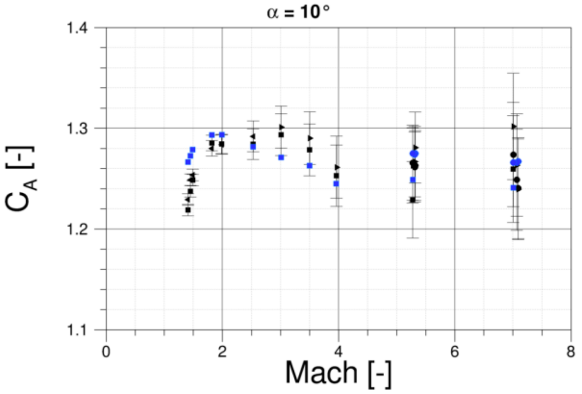

Fig. 18. Rebuilding of WTT runs (black: WTT results; blue : CFD data): axial coefficient C_A

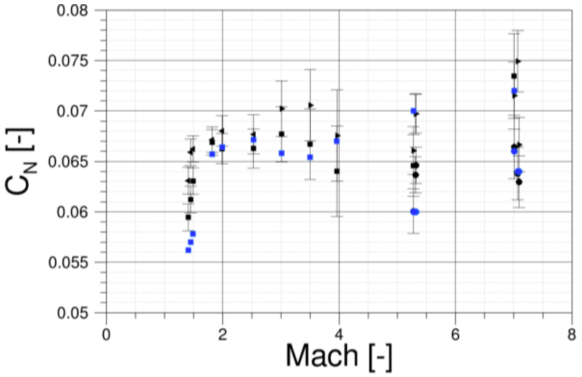

Fig. 19. Rebuilding of WTT runs (black: WTT results; blue : CFD data): normal coefficient C_N

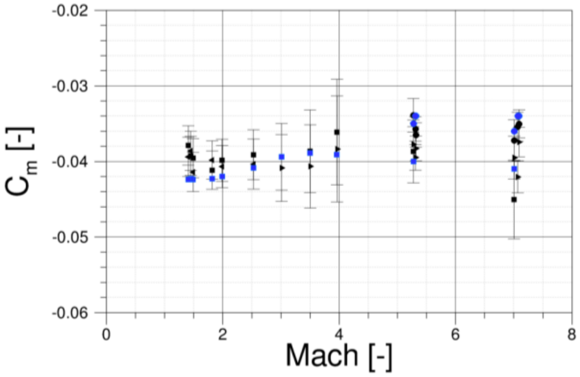

Fig. 20. Rebuilding of WTT runs (black: WTT results; blue: CFD data): pitch moment coefficient C_m

3.2 *Structural test effort*

The second testing effort focused on the mechanical characterization of the Inflatable Structure to explore the structural behaviour of this unique system, with a focus on modal survey, stiffness, deformation measurements, and morphing observation.

The activity was run at CIRA 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) regarding the inflatable structure technology.

A 2.4m diameter ground demonstrator, inherited from EFESTO project, was exploited along with a dedicated test rig (Fig.21).

Fig. 21. IS demonstrator under excitation (free-free).

Two different tests were performed: dynamic excitation (or modal survey) and static load.

The former (modal survey, Fig.21 and Fig.22) was put in place through a shaker (fixed to the ground) connected to the inflatable structure suspended in free-free condition (Fig.21).

The shaker force transmitted to the IS has been measured through a dedicated load cell, while many monoaxial accelerometers, installed on the demonstrator, acquired data to identify the modal behaviour.

The latter (static load test, Fig.23) was executed by means of an ad-hoc vacuum-pool to exert an equivalent delta-pressure on the inflatable structure surface simulating the dynamic pressure load during re-entry.

During the static test several load-cells have been acquired (Fig.24) and a 3D digitalization of the IS has been carried out following a photogrammetric reconstruction logic (Fig.25).

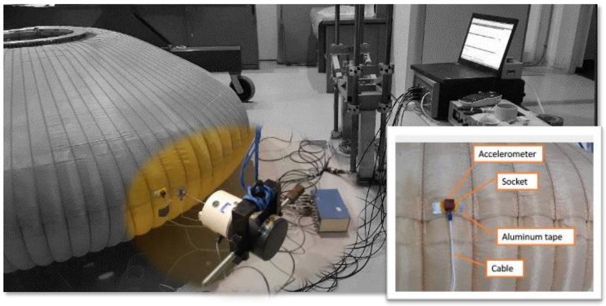

Fig. 22. IS demonstrator under excitation (grounded).

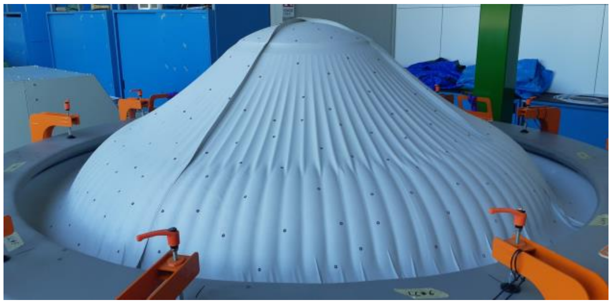

Fig. 23. IS demonstrator under vacuum pressure-load

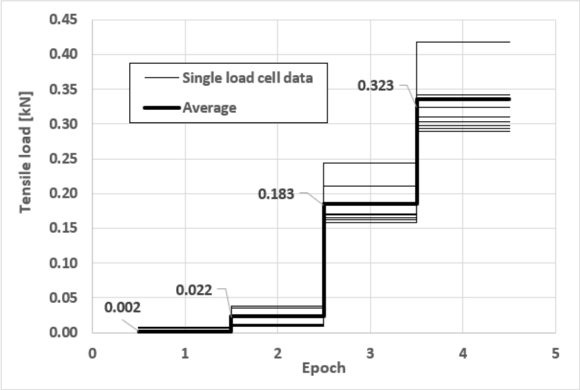

Fig. 24. IS demonstrator under excitation (free-free).

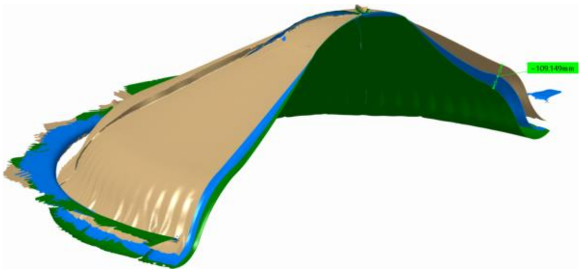

Fig. 25. Deformed shapes acquired by 3D Laser Scanner

Test results permitted to rebuild loads (locally and globally) as well as the deformation envelope.

This extended test campaign allowed to correlate numerical and experimental results, then improving not only the knowledge of the system behaviour but also the fidelity level of the models.

4. Morphing modelling and simulation

A dedicated effort has been made to model and simulate the morphing behaviour of the inflatable structure and the flexible TPS attached to it, during both folding and unfolding. During the parent project EFESTO, a folding and inflation analysis process was designed and set up. The activities were reviewed in EFESTO-2, and several areas of improvement were identified with respect to: definition of the FE model, characterization of the materials, as well as folding hypotheses and strategy.

Both folding and inflation were modelled and simulated with very satisfying outcomes (Fig.26, Fig.27).

This numerical effort will be very useful in the future for estimation of the stowing volume needs, definition of the folding process and analysis of inflation dynamics, in support of design, manufacturing and integration.

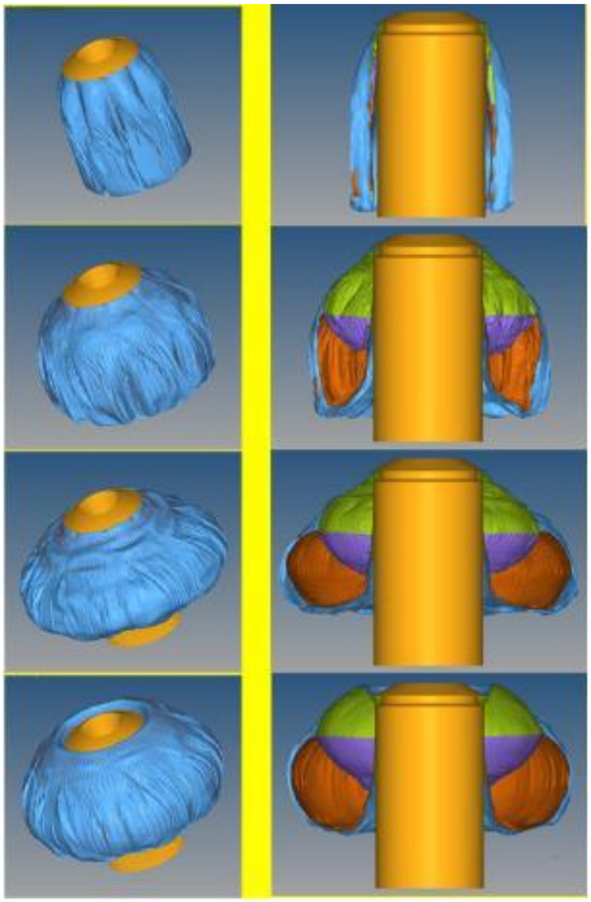

Fig. 26. Inflation process simulation.

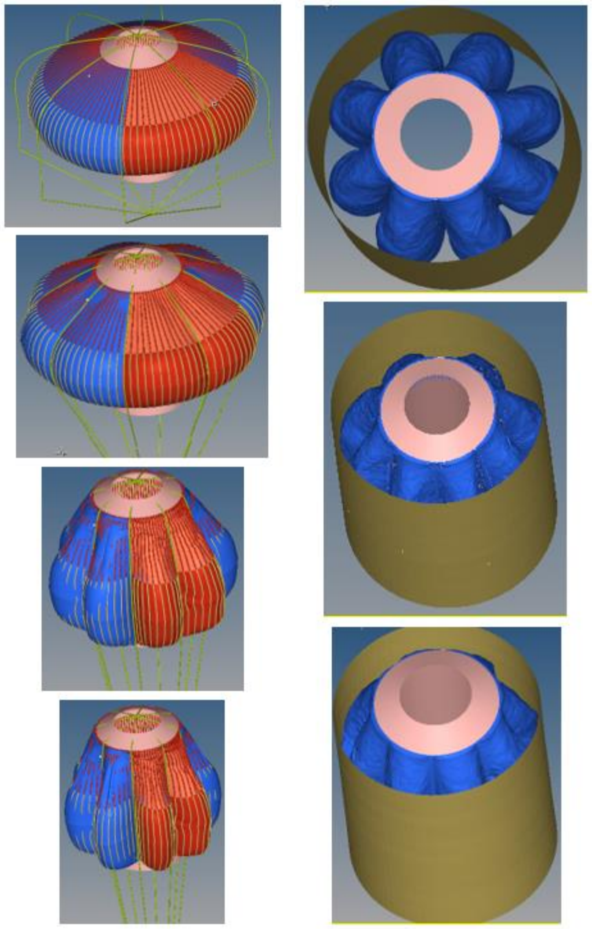

Fig. 27. Folding process simulation.

5. Conclusions and future steps

The objectives identified at the very beginning of the EFESTO-2 project can be considered reached out with a very satisfactory grade from any point of view because EFESTO-1 perimeter of investigation has been increased and applicability to the recovery of specific space assets has been proved positively.

As a general remark although achievements obtained so far in the frame of EFESTO-1 and EFESTO-2 projects can be considered significant, a further maturation step shall be appointed for consolidation of the TRL of the IHS technologies.

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

i. complete the maturation on ground of the key technologies 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) a 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 behaviour identification, and models' improvement;

It is worthwhile to mention that part of the goals listed above will be covered by the ICARUS project funded by the EC again under the Horizon Europe program (grant nr. 101134997).

ICARUS ([10], [11]) started in June 2024 and will end up with a demo flight on board a sounding rocket to demonstrate the capacity to recover an upper stage of a lunch system, in 2028.

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

Acknowledgments

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The EFESTO-2 consortium acknowledges essential contributions from ALI Scarl (Italy), S.R.S. Engineering Design Srl (Italy), and Thin Red Line Aerospace (Canada) concerning the inflatable structure aspects.

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