THE EFESTO PROJECT: ADVANCED EUROPEAN RE-ENTRY SYSTEM BASED ON INFLATABLE HEAT SHIELD

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**ABSTRACT**

EFESTO is a project funded by the European Union H2020 program aiming for a revamp and growth of European know-how and systems engineering capabilities in the strategic field of Inflatable Heat Shield technology for re-entry vehicles. This project analyzes the use of Inflatable Heat Shields for Mars exploration and Earth re-entry applications that served as representative study-cases. In addition to design activities at system and sub-system levels, the EFESTO team focused on testing the aerothermodynamic properties of the Flexible TPS and the mechanical characteristics of the shield, the latter exploiting a manufactured high-fidelity Inflatable Structure demonstrator. The data gathered from the two test campaigns additionally served for experimental-numerical rebuilding and cross-correlation. Finally, a phase-0 feasibility study defined a preliminary IOD mission design to enable in-flight verification and validation of the critical technologies. This paper will present the whole excursus of the project, including the key phases of use-cases survey and investigation, mission scenarios definition and analysis, system engineering and sub-system design, technology development and ground demonstration, future roadmap identification with reference IOD feasibility analysis and early definition. The project achievements have improved the European TRL of Inflatable Heat Shields from 3 to 4/5, thus paving the way towards further developments in the mid-term future. This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 821801.

**Keywords:** Inflatable Heat Shields, Re-entry Technologies, Aerodynamic Decelerators, Flexible TPS, Inflatable Structure, Launchers Reusability, Mars Exploration, Entry Descent Landing.

## 1. INTRODUCTION

EFESTO is a project funded by the European Union H2020 program aiming for a revamp and growth of European know-how and systems engineering capabilities in the strategic field of Inflatable Heat Shield technology (IHS) for re-entry vehicles [1] [2].

The project was carried out by a European consortium led by Deimos Space (ES) which also includes CIRA (IT), ONERA (FR), DLR (DE), Aviospace (IT), and Politecnico di Torino (IT).

The team also leveraged the valuable external support of Thin-Red-Line Aerospace (CA) and ALI Aerospace Laboratory for Innovation (IT) [3].

EFESTO project hints were: (1) identification of mission classes enabled by the use of advanced Inflatable Heat Shields (IHS); (2) definition of meaningful case study scenarios for both Earth and Mars re-entry applications; (3) execution of mission and system design loops for obtaining the operative environment to properly feed the engineering of the IHS key components (i.e., Flexible Thermal Protection System, F-TPS, and Inflatable Structure, 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.

## 2. STATE OF THE ART

Inflatable Heat Shields (IHS) are considered a “game changer” because they exhibit intrinsic key features for re-entry, particularly in regards to low ballistic coefficients and reduced volume impact vis-à-vis launchers’ fairing envelope [4] to [6].

IHS are an appealing solution for different planetary re-entry applications (Earth, Mars and Venus) enabling an effective implementation of new missions such as: LEO and sub-orbital return (ISS cargo/payloads, reusable upper stages, debris removal), planetary aerobraking/aerocapture, Mars robotic/human exploration [7] to [11] (Figure 1, Figure 2).


**Figure 1: Earth re-entry applications based on IHS**

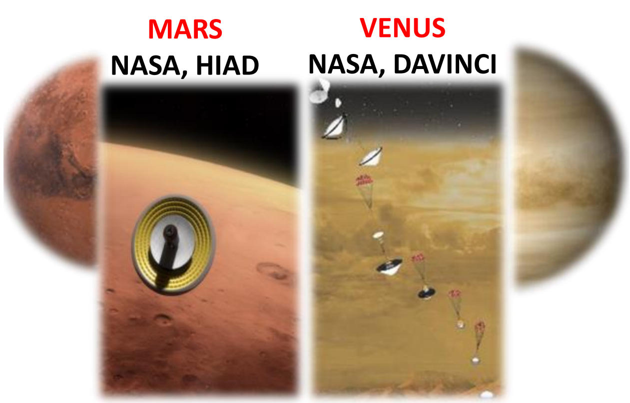


**Figure 2: Planetary re-entry applications based on IHS**

HIAD systems are a relatively young technology. As far as the technology status is concerned, projects date back to the early 2000’s when EU/ESA promoted and implemented 2 flight tests of IRDT experimental vehicles based on IHS [13] [14]. Shortly thereafter, many technological challenges behind these kinds of complex systems were presented and it was decided to go further with ground development [15] [16]. The current highest TRL has been achieved by US/ NASA via many initiatives ranging from ground development to testing and flight verification [17] to [22].

More recently, China space actors put their highest priorities on IHS technology with an initiative flown unsuccessfully in May 2020 on Chang Zheng 5B/Long March 5 [27].

With regards to European levels, ESA and European Commission have been recently fostering development of IHS with some dedicated initiatives including EFESTO [1][2][23][24].

However, if EFESTO achievements are set at TRL 4, much more shall be done at European levels to increase the TRL.

Based on the EFESTO team perceptions of achievements obtained worldwide, the tentative TRL map currently applicable has been depicted Figure 3, including projections for the future through possible further initiatives.

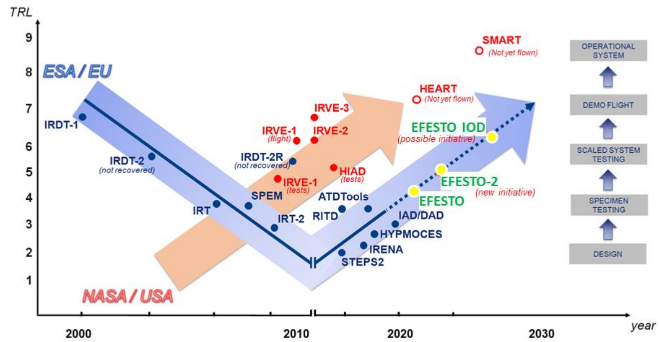


**Figure 3: IHS TRL map**

## 3. MISSION DESIGN

As a first step, the EFESTO project ran a wide range of literature reviews, allowing us to down-select a specific mission class for realistic scenario applications pertaining to Earth and Mars [9] to [12] (Figure 4 and Figure 5, respectively).

Afterwards, for each mission class a meaningful case study has been identified by means of a trade-off based on engineering assessment of critical feasibility aspects.

For the Earth application, the recovery of the AVUM VEGA upper stage has been chosen as baseline study case. In this scenario, after deorbiting from Polar Orbit a 4.8m diameter class IHS is exploited for atmospheric deceleration while allowing for range control.


**Figure 4: Earth mission classes**

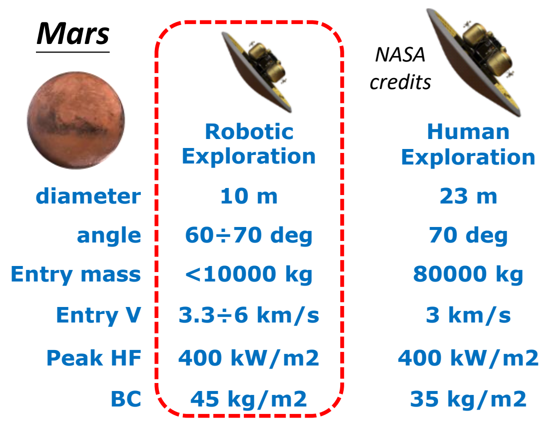


**Figure 5: Mars mission classes**

This hypersonic entry phase is followed by a parachute descent phase which brings velocity down to enable recovery operations with a helicopter Mid-Air-Retrieval (Figure 6).

| mass | P/L | BC | diam | Qw | Pdyn |
|---|---|---|---|---|---|
| 1.5t | 0.6t | 45 | 4.8m | 600kW/m2 | 10kpa |

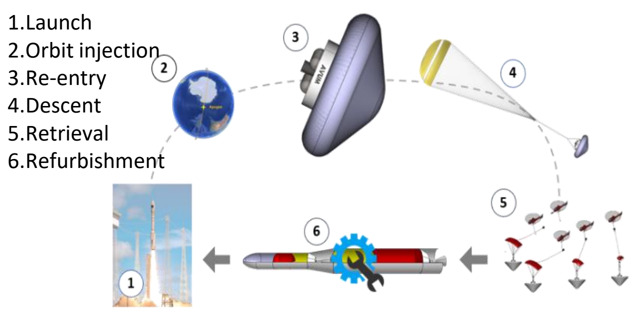


**Figure 6: VEGA-AVUM study-case ConOps**

| mass | P/L | BC | diam | Qw | Pdyn |
|---|---|---|---|---|---|
| 6t | 3t | 62 | 10m | 350kW/m2 | 8kpa |

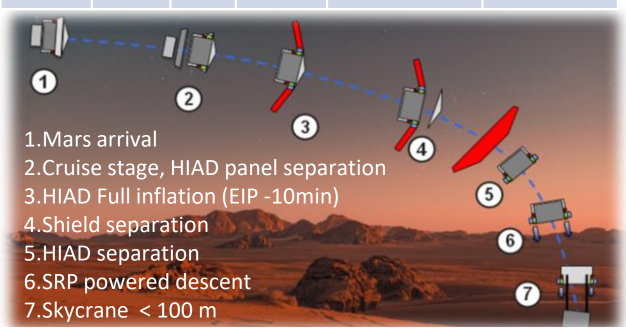


**Figure 7: Mars exploration study-case ConOps**

For the Mars application a 6tons exploration mission has been envisioned. The ~3tons re-entry module adopts a 9m diameter IHS combined with Supersonic Retro-Propulsion (SRP) for safely manage the EDL sequence down to MOLA +3km target altitude (Figure 7).

For both of the study cases a design loop was completed to assess the mission and system feasibility with involvement of key disciplines such as aeroshape design, aerodynamics, aerothermodynamics, trajectory analysis and flying qualities. This loop allowed the identification of each scenario: the best aeroshape for a trimmed and stabilized flyable trajectory, a viable flight corridor in compliance with the mission constraints (e.g., material and structural limits), and the entry aerothermal/mechanical environment to feed the subsequent engineering of the key IHS elements (Figure 8, Figure 9).

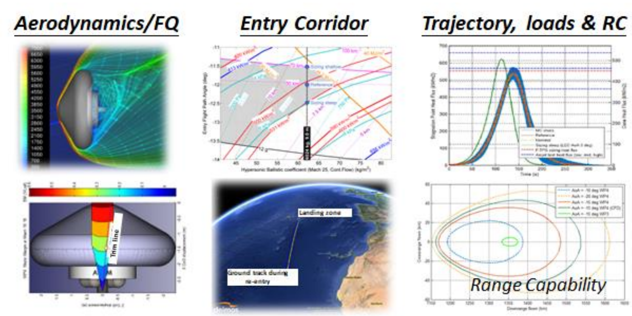


**Figure 8: Earth study-case mission/system analyses**

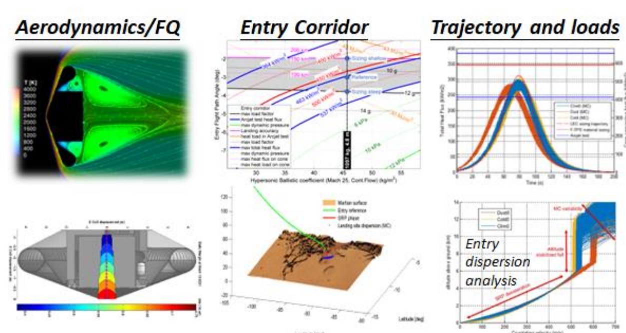


**Figure 9: Mars study-case mission/system analyses**

## 4. SYSTEM DESIGN

Once the mission envelope was established, an engineering loop was then carried out in two stages, preliminary and consolidation, to address the system-level design aspects (e.g., configuration, architecture, internal layout, materials, lay-up, etc.). Flexible TPS and Inflatable Structure were modeled and analyzed through a dedicated effort covering thermal and structural behavior adopting literature-based material data and in-house developed models. The numerical investigation allowed us to evaluate different architectural solutions and to identify the optimal ones. Finally, system budgets were obtained for mass and volumes (Figure 10 to Figure 12).

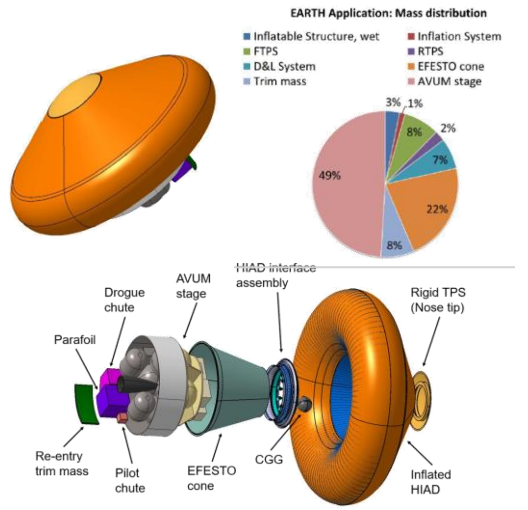


**Figure 10: Earth study-case configuration**

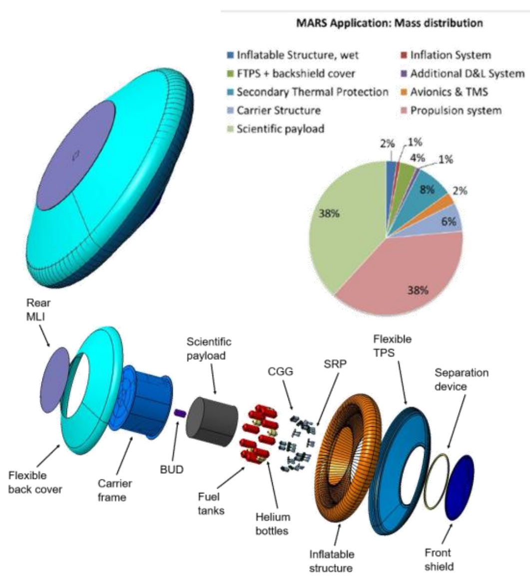


**Figure 11: Mars study-case configuration**

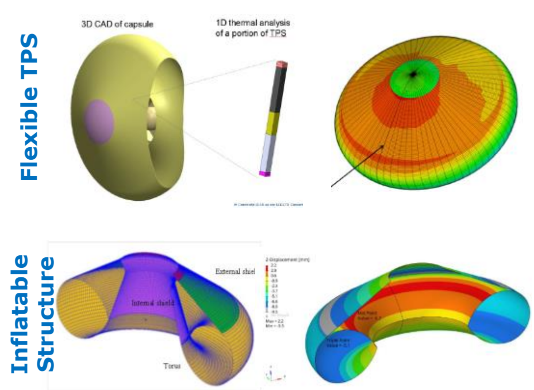


**Figure 12: Earth study-case models and analyses**

# 5. TECHNOLOGY DEVELOPMENT

The consolidation of material choices, design figures and environmental conditions to be replicated, obtained during the system-engineering loop was exploited to start an extensive and sound ground development effort run-out in three critical steps: material procurement and experimental characterization; breadboards/demonstrators design, manufacturing, and testing; numerical-experimental cross-correlation and model refinement.

## 5.1. Flexible Thermal Protection Systems

As far as the F-TPS technology is concerned, selected materials were purchased during the design phase for all of the F-TPS layers (external fabrics; insulation; and bottom-closure fabrics). Part of the material was used to produce small coupons that underwent a variety of measurements assessing to accurate thermo-physical characteristics such as: thickness, density, thermal conductivity, heat capacity, (relevant only for external fabrics), reaction kinetics and decomposition (Figure 13).

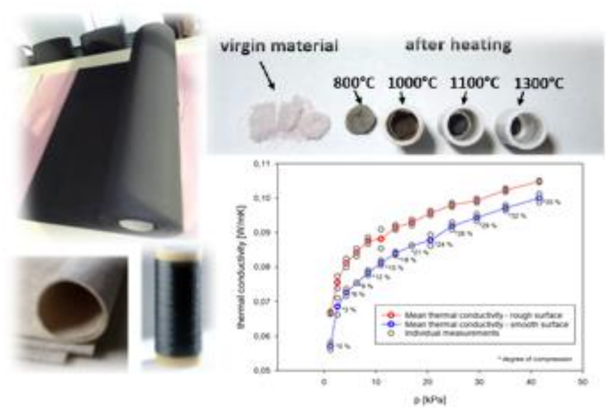


**Figure 13: F-TPS coupons and thermophysical tests**

A large part of the material was also used to produce breadboards of the F-TPS layup in the form of Ø70mm disks and 180cm2 patches. (Figure 14).

Therefore, lay-ups replica designed for Earth and Mars heat-shield configurations underwent as many as ≈70 runs at the DLR arc-jet facility L2K/L3K in both Earth and Martian atmospheres with replication of the aerothermal environment adopted in the design phase in tangential and stagnation flows (Figure 15). Heat and temperatures measurements allowed us to verify the capability of the different stack-up configurations to withstand the re-entry environment, as well as validating numerical models and CFD tools adopted during the design phase. Test results have been widely explored for a numerical-experimental cross-correlation and numerical rebuilding allowing for refinement of mathematical models (e.g.: 3D CFD/thermal coupling and engineering 1D-thermal model) with a good improvement of their confidence level in ground-to-flight extrapolation methodology (Figure 16).

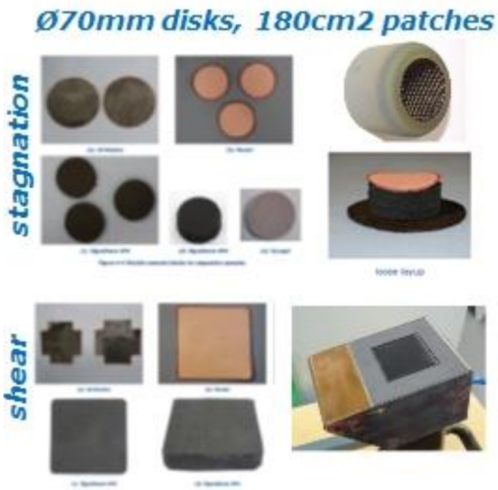


**Figure 14: F-TPS breadboards and test-holders**

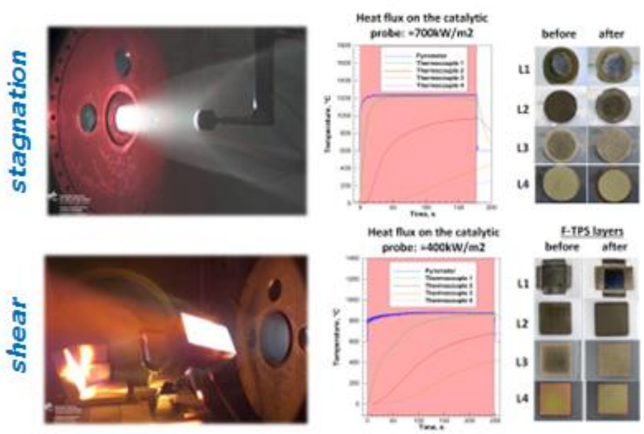


**Figure 15: F-TPS breadboards arc-jet testing / Earth**

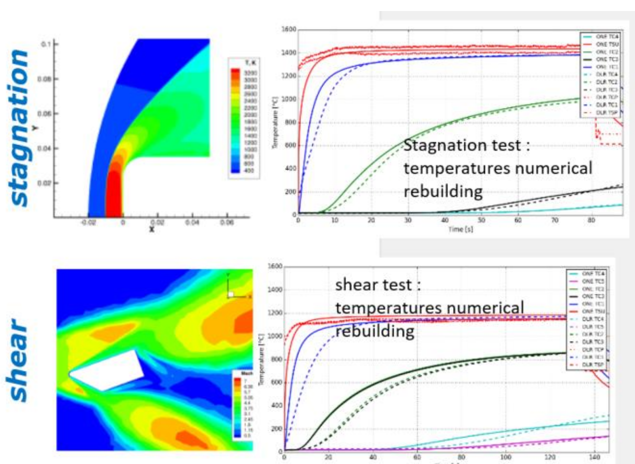


**Figure 16: F-TPS test results cross-correlation / Earth**

For a technical and deeper insight of the EFESTO F-TPS technology achievement refer to [25].

**5.2. Inflatable Structures**

As far as IS technology is concerned, the same approach was adopted with respect to the three selected basic materials: load-carrier, cordage and gas-bladder. Part of the material was used to produce small coupons that underwent a mechanical characterization test: cordage linear density and diameter measurement, fabrics stress-strain and breaking strength.

Moreover, a large part of the material was used to produce a 1:2 scale Ø2.4m Ground Demonstrator (AVUM study-case) replicating the architecture (interfaces, geometry) with: a high-fidelity breadboard of the Inflatable Structure (materials, volumes, layers); a simplified replica of the F-TPS skirt; and a conical support structure (Figure 17).

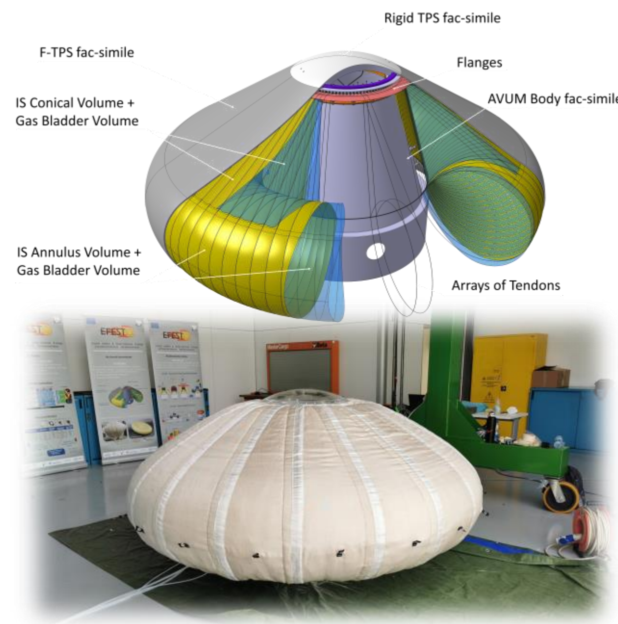


**Figure 17: IS Ground Demonstrator**

The Ø2.4m Ground Demonstrator was exploited to execute a wide-range test campaign including folding, stowing, deployment, and inflation (Figure 18).

An ad-hoc vacuum test-rig was also designed and built to perform also static-load tests under flight-representative pressure pattern. Loads and pressures measurements along with a pseudo-photogrammetric shooting allowed to verify the Inflatable Structure structural strength and validate the models' predictions with respect to deformations (Figure 19).

Likewise for F-TPS tests, numerical-experimental cross-correlation and rebuilding allowed for the refinement of mathematical models (e.g., FEM) with a significant improvement of expected confidence levels.

For a technical and deeper insight of the EFESTO IS technology achievements refer to [26].

**Figure 18: IS folding/stowing test and simulation**

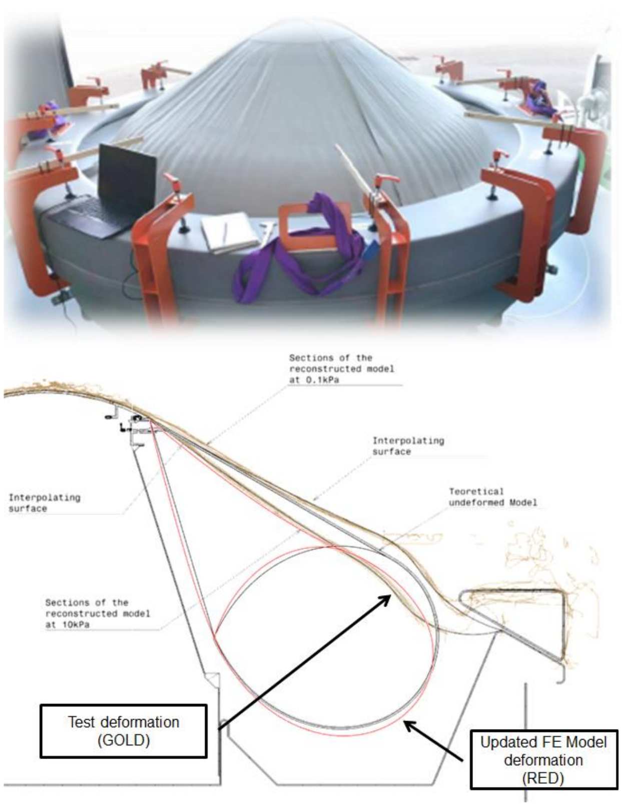


**Figure 19: IS static-load test and rebuilding**

## 6. IOD MISSION CONCEPT

The final part of the EFESTO project has been dedicated to the preliminary definition of a possible In-Orbit Demonstration mission thus enabling in-flight verifications of the IHS technology. In that regard, both scientific objectives and needs were first addressed and then translated into a set of high-level mission and system requirements.

Afterwards, potential launch strategies were investigated and evaluated, concluding into a selection of a small-medium launch vehicles class as the preferred option able to comply with the identified programmatic and technical constraints– including cost and operational constraints (Figure 20).


**Figure 20: Possible LV for EFESTO IOD mission**

Therefore, a conceptual design loop was completed to assess the IOD feasibility from the technical standpoint both at mission and system levels.

The compatibility with the launch vehicle was evaluated with respect to payload accommodation, mass at launch as well as required entry conditions to adequately trigger the re-entry flight. Trajectory analysis was carried out down to landing assuming a sea splashdown scenario. The key figures-of-merit were obtained to feed the early sizing of the system and its critical elements (Inflatable Structure and Flexible TPS). Visibility and recovery aspects were also taken into account at preliminary level.

The initial design has been demonstrated to be 100% effective in allowing an operational validation of the EFESTO technological achievements with respect to the mission envelope (aerothermal and mechanical environment, ConOps, use-case application), as well as to the system firm elements (heatshield geometry and size; vehicle architecture and configuration, overall mass and volume budgets) (Figure 21 to Figure 23).

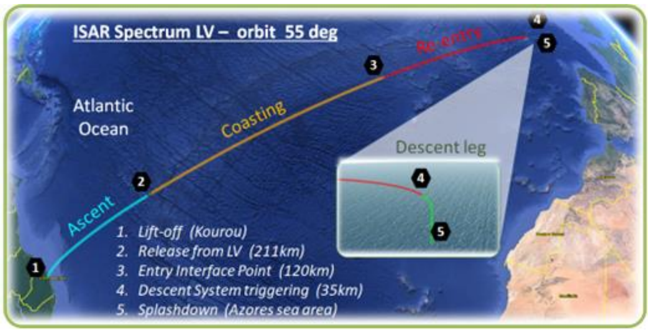


**Figure 21: EFESTO IOD mission concept**

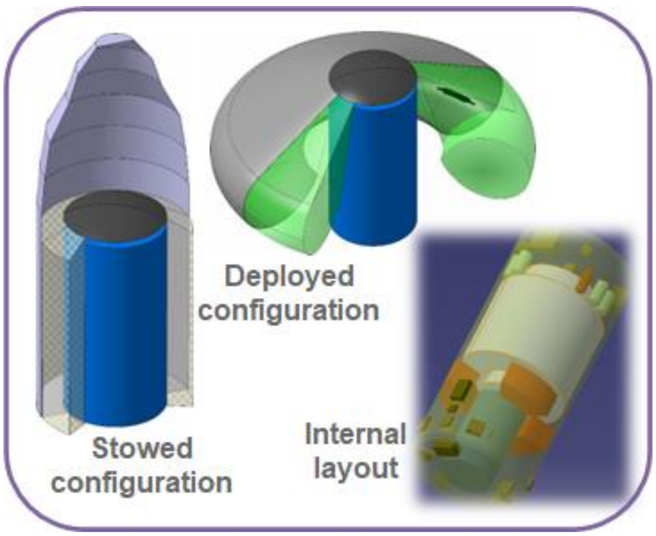


**Figure 22: EFESTO IOD system concept**

- Max HF: 500kW/m2
- Max HL: 45MJ/m2
- FPA: -2°
- Max Pdyn: 4kPa
- Max G-load: 9g
- Entry mass: 800kg
- Ballistic coeff.: 40kg/m2
- Diameter: 4.8m
- Sphere-cone shape
- 1.3m nose radius
- 70deg half-cone angle

| Mass budget | |
|---|---|
| Inflatable Structure, wet | 52.21 kg |
| Inflation System | 21.39 kg |
| FTPS | 100.6 kg |
| RTPS | 61.2 kg |
| Avionics | 42.0 kg |
| In-flight Measurements | 64.23 kg |
| Thermal Management | 5.75 kg |
| Recovery System | 44.00 kg |
| Descent System | 82.50 kg |
| Separation Devices | 2.30 kg |
| Structure | 318.90 kg |
| **SUM** | **795.10 kg** |

**Figure 23: EFESTO IOD requirements**

## 7. CONCLUSIONS AND WAY FORWARD

The EFESTO project team succeeded in:

- revamping European interest in the field of Inflatable Heat Shields
- increasing European knowledge and capability in that field at mission, system and technology level
- obtaining significant material and mechanical achievements reaching TRL 4
- defining a feasible demonstration mission

Beyond EFESTO it would be worth to:

- consider exploitation of inflatable heatshields for real space missions
- promote new initiatives to further mature design capabilities and progress TRL of key technologies with ground developments
- plan implementation of an in-flight verification, validation and demonstration effort to close the loop and reach higher TRL
- envisage a phase B study at European level supported by ESA, eventually in synergy with the European Commission, to develop a preliminary design definition at mission and system level

## 8. ACKNOWLEDGMENTS

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 821801. More information available at: http://www.efesto-project.eu.

The EFESTO consortium acknowledges essential contributions from Thin Red Line Aerospace (CA) and ALI Scarl Italia (IT) concerning the Inflatable Structure design as well as the Ground Demonstrator design, manufacturing, integration and testing.

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