Advanced European Re-Entry System Based on Inflatable Heat Shields: Detailed Design (EFESTO project)

Original
Advanced European Re-Entry System Based on Inflatable Heat Shields: Detailed Design (EFESTO project) / Bonetti, Davide; Dietlein, Ingrid; Fedele, Alberto; Gambacciani, Giovanni; Governale, Giuseppe; Prevereaud, Ysolde. - ELETTRONICO. - (2020), pp. 1-8. (Intervento presentato al convegno The CyberSpace Edition).

Publisher:
International Astronautical Federation (IAF)

Published
DOI:

71st International Astronautical Congress (IAC) – The CyberSpace Edition, 12-14 October 2020.

IAC-20-D2.3.4

Advanced European Re-Entry System Based on Inflatable Heat Shields Detailed Design (EFESTO project)

D. Bonetti[a]*, I. Dietlein[b], A.Fedele[e], G. Gambacciani[c], G. Governale[d], Y. Prevereaud[f]

[a] *DEIMOS Space S.L.U., Tres Cantos, Spain*
[b] *Deutsches Zentrum für Luft- Und Raumfahrt e.V. (DLR), Köln, Germany*
[c] *AVIOSPACE SRL, Torino, Italy*
[d] *Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Turin – Italy*
[e] *Centro Italiano Ricerche Aerospaziali (CIRA), Capua – Caserta, Italy*
[f] *Office National d'Etudes et de Recherches Aerospatiales (ONERA), Toulouse, France*
* Corresponding Author: davide.bonetti@deimos-space.com

Abstract

The European Union H2020 EFESTO project is coordinated by DEIMOS Space with the end goals of improving the European TRL of Inflatable Heat Shields for re-entry vehicles (from 3 to 4/5) and paving the way towards further improvements (TRL 6 with a future In-Orbit Demonstrator, IOD).

This paper presents the project objectives and the initial results of the detailed design of atmospheric entry missions based on the applications of advanced thermal protection systems (TPS) implementing inflatable heat shields (flexible TPS and inflatable structures), according to aerothermodynamics constraints for future in-orbit demonstration. Placing the future IOD mission in the context of ongoing and future efforts in the European context is also one of the project goals.

Two key applications, Mars Robotic Exploration and Reusable Small Launchers Upper Stages, have been identified. For the Mars Application, the robotic exploration mission class resulted in a 10 m diameter Hypersonic Inflatable Aerodynamic Decelerator (HIAD) class, combined with Supersonic Retro-Propulsion (SRP, activated about Mach 2.3) to deliver about 2800 kg of payload at MOLA (Mars Orbiter Laser Altimeter) +2 km. For the Earth Application, the VEGA upper stage (AVUM) has been selected as baseline case study. The current mission foresees a deorbiting from Sun Synchronous Orbit, a controlled entry phase (Ballistic Coefficient of about 30 kg/m2) and combines the use of a HIAD (4.5m diameter class) with parachutes and parafoil for Mid-Air-Capturing (MAR) with a helicopter.

Beyond feasibility of the entry mission phase and system design with an inflated IAD, integration aspects have a key impact in the specific design solutions adopted, due to the nature of an inflatable heatshield. For both considered application cases feasible architectures are developed responding to the challenge of integrating the HIAD into the system in compliance with geometric and functional requirements. While the HIAD in folded state prior to inflation must fit in the available volume, it has limitations with respect to the density imposing a minimum cross section of the stowage volume. Simultaneously requirements with respect to the centre of gravity position during re-entry with an inflated HIAD must be respected for stability and controllability reasons. Other architectural considerations such as payload integration for the application on a launcher upper stage must be considered. Finally, heat loads constraints are examined for the trajectory and TPS deign choices due to important fluid-structure interactions.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821801.

Keywords: Reusability, Mars Exploration, EDL, Flexible TPS, Inflatable Structure, Aerodynamic Decelerators.

1. Introduction

EFESTO will provide advances in the three areas of thermal control, materials and structures through the design and testing of innovative inflatable TPS solutions for re-entry vehicles. It will enable new space mission concepts, which require bringing a payload from space to ground of a planetary body with an atmosphere beyond the current limits imposed by launcher fairing size or rigid heat shields geometrical and structural aspects.

Morphing solutions will allow for example landing bigger or heavier payloads on Mars or will enable the reusability of launchers' upper stages enhancing European reusability and cost reductions in the access to space industry. Non space applications in the areas of materials and structures will also be considered. Leveraging on the consortium background and on past, current and planned tests results in the field, competitiveness in the space sector will be fostered and key contributions to the long-term European re-entry technology roadmap will be provided.

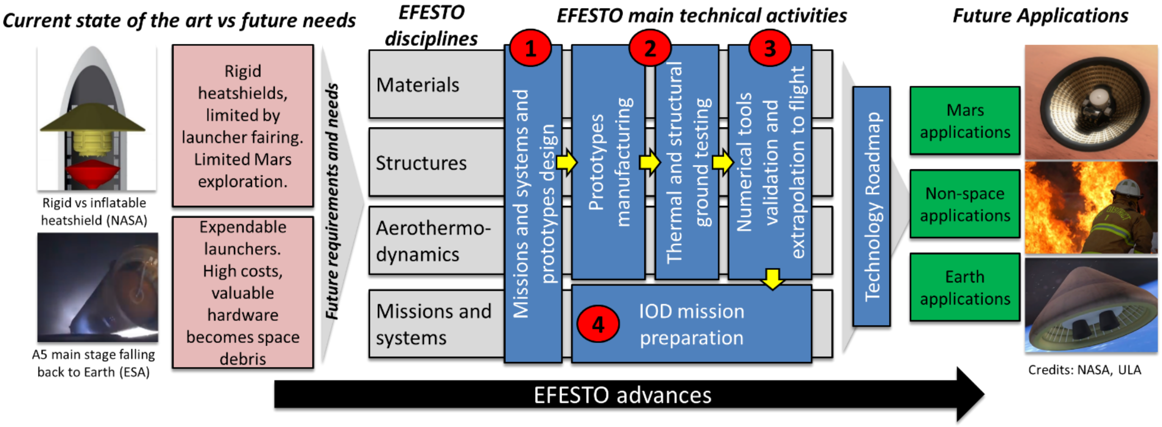

Figure 1: EFESTO study logic and key elements (red circles).

EFESTO is built on four key technical elements (red bullets in Figure 1 which shows the high-level EFESTO study logic) to advance from the current European state of art to the preparation of an IOD mission, overall increasing the TRL of this technology in Europe. In the first year of activities, the focus has been on the missions and system design, including preliminary structure and TPS design and supported by aerothermodynamic simulations [7]. The status of the current design solutions for two key applications (Mars Robotic Exploration and Reusable Small Launchers Upper Stages) is presented.

2. Earth Application

For the Earth Application, the VEGA upper stage (AVUM) has been selected as baseline study case. The current mission (see Figure 2) foresees a deorbiting from SSO orbit, a controlled lifting entry phase (BC of about 30 kg/m2) and combines the use of hypersonic IAD (HIAD, 4.5m diameter class) with parachutes and parafoil for Mid-Air-Capturing (MAR) with a helicopter. Refurbishment of the recovered stage is planned as a necessary step before another flight of the launcher stage.

After injecting its payload into the target orbit, the AVUM (VEGA upper stage) performs a deorbiting maneuver and burns up in Earth's atmosphere, demising in a safe area for ground population and unprotected by any TPS. This valuable hardware is lost at the end of each VEGA launch up to now. The first key aspect considered in EFESTO to make this stage reusable is the need to protect the AVUM with a HIAD from the harsh entry environment and fly a feasible trajectory respecting the set of applicable requirements for the mission, in particular thermo-mechanical constraints during the most critical entry phase and that define the entry corridor (see Figure 3, and [8]). The second key aspect considered is the possibility of recovering the AVUM at the end of the re-entry and with limited operations costs that justify the effort and the reusability of this hardware for reducing the overall cost of access to space. From a preliminary business case analysis, costs of operations should not exceed about 10% of the recovered hardware and at CONOPS this implies the minimum use of helicopters in the MAR operations. Having only one helicopter minimizes costs but imposes requirements on the landing accuracy of the system.

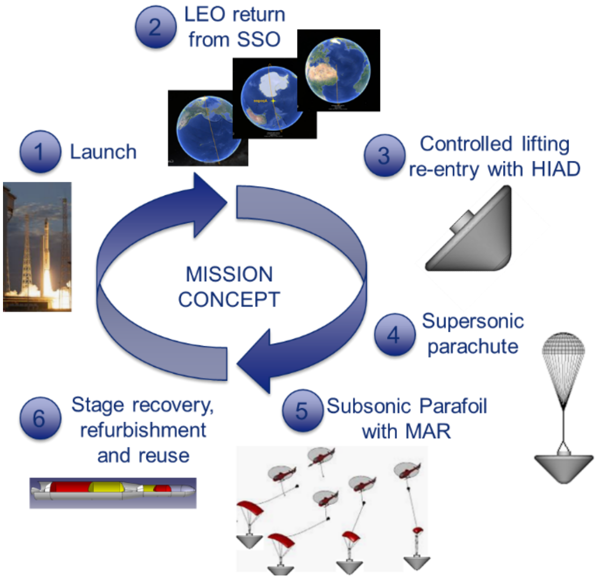

Figure 2: Earth application: concept of operations. EFESTO focus is on the HIAD design and flight phases.

To reach the area within the helicopter range capability, three key needs have been identified (similar to the ESA's Space Rider, evolution of the IXV): an accurate deorbiting burn to limit dispersion at the EIP, a controlled entry and a controlled descent phase (under a parafoil). The controlled entry makes use of the aerodynamic lift (obtained by the aeroshape with an offset in the CoG location with respect to the symmetry axis), and additionally to enabling a control of the position of the vehicle, reduces the loads on the HIAD by gliding a longer and shallower trajectory when compared to a passive, ballistic entry.

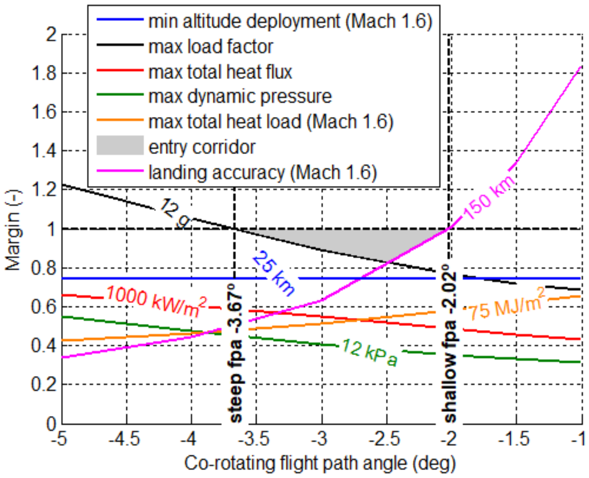

Figure 3: AVUM, entry corridor. Variability of trajectory margins with respect to constraints as a function of the flight path angle at the EIP.

At system level, the compact design of AVUM renders it particularly suitable for the selected application since it offers two major benefits with respect to the design for reentry:

- Comparatively forward position of the stage center of gravity in comparison to more elongated rocket stages, which is beneficial for flight stability during reentry.
- Reduced exposure to wake flow downstream of the inflatable heat shield.

During the design process, several challenges had to be overcome:

- Integration of the folded HIAD in ascent configuration with the commercial VEGA payload on top while providing sufficient volume to the packed HIAD.
- Conflicting requirements with respect to the lateral position of the center of gravity during ascent (see [2]) and descent.
- Integration of the Descent & Landing system to the stage.

The retained design features for the Earth Application, alongside the HIAD, include the use of an internal cone transmitting the reentry forces on the inflated HIAD to the stage structure, an IAD external cone (IEC) carrying the payload similar to the VEGA's VAMPIRE or VESPA to be jettisoned prior to inflation, a cold gas generator system (CGG) to provide the inflation gas and a descent & landing (D&L) system consisting of a pilot chute, a supersonic drogue chute and a parafoil for the final descent phase before being captured by a helicopter. Figure 4 presents an overview of the system in reentry configuration.

The design of the heat shield and in particular the inflatable structure has a significant influence on the aerodynamic forces and moments coefficients. The heat shield is a sphere-cone with 60º angle. An Aerodynamic Database (AEDB) has been generated by ONERA covering multiple design options and the current baseline. To do that, the team made use of both engineering code ARES (Atmospheric Re-Entry Software) and the CFD (Computational Fluid Dynamics) ONERA unstructured Navier-Stokes code CEDRE. Indeed, ARES allows to preliminary evaluate the various design options imagined while CEDRE is used to determine uncertainties and consolidate the final AEDB.

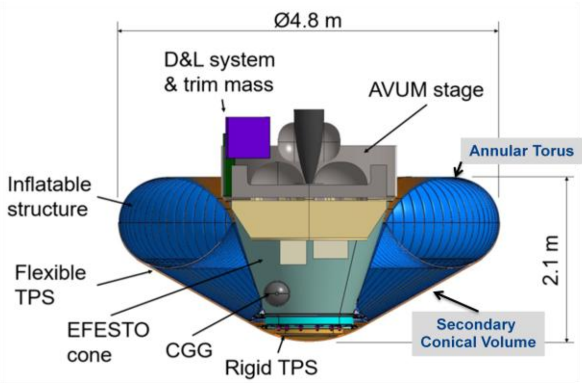

Figure 4: EARTH application: AVUM with inflated HIAD in reentry configuration.

An analysis of the aerodynamic database was performed by DEIMOS to evaluate the flying qualities associated to different shapes explored and to the baseline solution. The overall key performances monitored as a function of the CoG location were the trim angle (total AoA), the aerodynamic efficiency (L/D), and the trim stability (static margin). All these performances affect the system design on side (CoG location, and in particular the lateral CoG offset) and the mission performance (and business case, in particular the operations) on the other side. Overall a minimum L/D of about 0.15-0.2 is desirable for the controlled entry phase of the AVUM application.

The desired aeroshape is obtained by a dedicated inflatable structure and is protected by a specific flexible TPS membrane solution. This morphing heatshield solution overcomes the limitation imposed by the VEGA fairing geometry limits and achieves an efficient protection of the AVUM stage, enabling reusability of this valuable hardware.

The TPS membrane must therefore simultaneously have many characteristics to achieve its goals. On the thermal side it implies the ability to withstand high temperatures (up to 1800ºC), to radiate most of the incident heat (up to 450kW/m2), to isolate the payload. The maximal thermal heat loads, encountered during the atmospheric entry, have been established by aerothermodynamics 2D/3D simulations considering the influence of the turbulence and wall catalysis. On the mechanical side it implies the capability to withstand the external pressure and the tension imposed by the supporting structure while at the same time flexibility and foldability is mandatory, to be able to pack in a small space and then return to the ideal shape without opposing particular resistance.

There is no single material able to fully satisfy, on its own, all the requirements listed above: therefore, a mix of different materials must be integrated to obtain a very efficient membrane. In general, these types of membranes consist of the superposition of several different layers of fabric, each with different characteristics depending on its position in the stack. Typically, F-TPS are multi-layer structures where the outer layer, the one that interacts with the external environment, it's exposed to the highest temperature, and the inner layers are built to prevent the diffusion of heat in order to isolate and protect the internal structures of the system. Multiple F-TPS designs have been performed according to the required thermal isolation identified at mission level; each solution is obtained by optimizing the thickness of different combinations of layers of flexible materials by means of multiple thermal FEM analyses. The parameters to evaluate and choose among the F-TPS options have been defined for performance, foldability, manufacturing, and procurement properties of the layers. Applying the Analytically Hierarchical Process (AHP) method the parameters, or criteria, are weighted through pairwise comparison and a baseline solution is selected.

The final F-TPS used to protect the whole system during the reentry phase of the mission is made by a multi-layer rigid and flexible membrane with different thicknesses, optimized for each different area, see Figure 5. This approach guarantees to meet the requirements and at the same time reduce the mass and the stowed volume.

Beyond this F-TPS layer, the inflatable structure is designed to provide the structural stiffness required to maintain the aeroshape during the re-entry phase. The solution design adopted is based on two separate inflatable volumes (see Figure 4). The first one is an Annular Torus: the main task of this inflatable structure is to sustain the main loads along the trajectory. The second volume is a secondary conical volume with the function to maintain the external shape during re-entry and with the advantage compared to the stacked torus configuration of avoiding TPS scallops between the tori.

This configuration compared to the more classic "Stacked Torus" design for HIADs ([1], [5], [6]) is less complex and can be considered as an evolution of the "Tension Cone" configuration, avoiding in the same time the problem of buckling and cupping that affected that solution. The EFESTO solution is believed to provide superior shape stability to mass ratios and overcome limits of scalability and manufacturability of the structure.

The detailed design is ongoing: specific aspects of the integration in the system are shown on Figure 6. A 1:2 scale demonstrator will be built and tested by CIRA and TRLA/ALI subcos to understand how this innovative inflatable structure behaves during inflation and under external loads, compared to numerical analysis performed by ONERA. A 3D printed mockup of the rigid structure is shown in Figure 7.

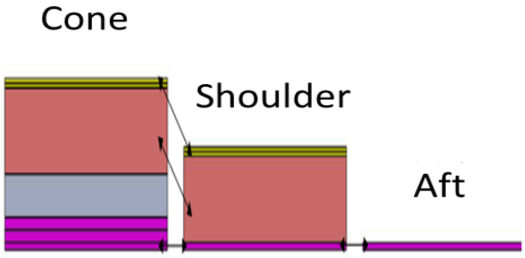

Figure 5: Final F-TPS structure.

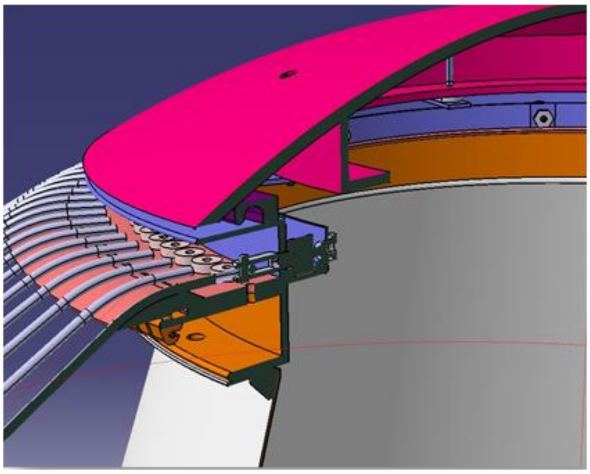

Figure 6: 3D CAD model detail (1:2 test article)

Figure 7: 3D printed mockup (1/4 sector)

3. Mars Application

For the Mars Application, a robotic exploration mission class is selected. It is based on a 10 m diameter IAD class, with about 6600 kg of entry mass, and a BC of about 50 kg/m². The current mission (see Figure 8) foresees a direct Mars entry and combines the use of hypersonic IAD (HIAD) in a ballistic entry with Supersonic Retro-Propulsion (SRP, activated about Mach 2.3) to deliver about 2500 kg of payload at a landing altitude of MOLA +2 km.

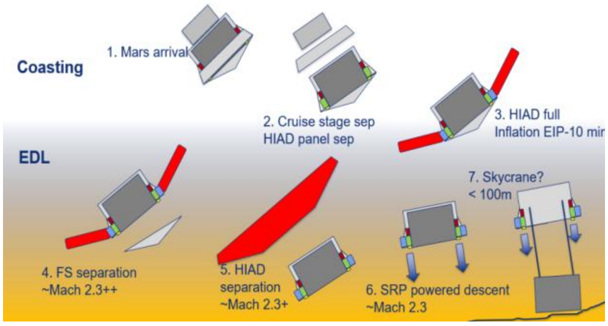

Figure 8: Mars application: concept of operations. EFESTO focus is on the HIAD design and flight phases.

Figure 9 presents an overview of the architecture resulting from the preliminary design phase. The scientific payload (envelope: diameter 2.8 m, height 2.5 m, mass 2.5t) is hosted by a carrier frame (blue) equipped with the supersonic retro-propulsion (SRP) system including the fuel and helium tanks, avionics and the crane equipment used to lower the scientific payload to the Mars surface similarly to the Skycrane maneuver. The SRP is based on a ring of multiple monopropellant Aerojet Rocketdyne's MR-80B3100 thrusters ([3]), activated at Mach 2.3 and used down to hovering, where the skycrane manoeuvre is performed.

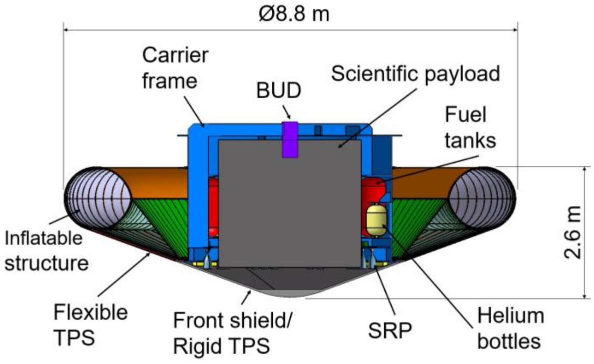

Figure 9: MARS application: Descent module after release (HIAD in re-entry configuration).

The design of the heat shield and in particular the inflatable structure has a significant influence on the aerodynamic forces and moments coefficients. The heat shield is a sphere-cone with 70º angle. Like for Earth, an Aerodynamic Database (AEDB) has been generated by ONERA and an evaluation of the flying qualities was performed by DEIMOS Space. Different from the Earth scenario, where lift is actively used to control the trajectory, on Mars the ballistic entry is achieved spinning the vehicle around a nominal AoA of 0º. The entry flight path angle is selected around -13º, based on DEIMOS Space's entry corridor results, see Figure 10 (and [8]).

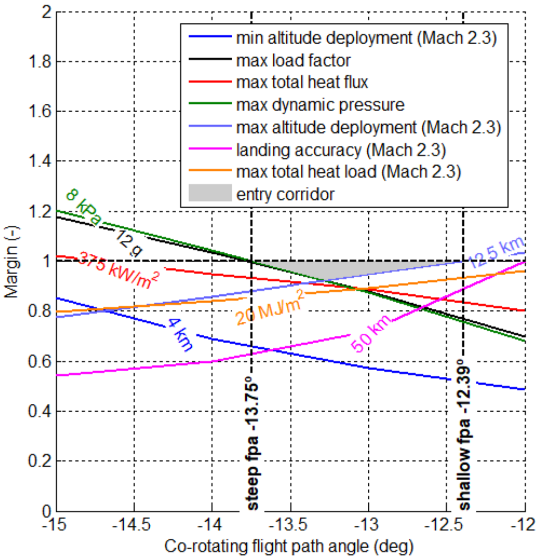

Figure 10: Mars, entry corridor. Variability of trajectory margins with respect to constraints as a function of the flight path angle at the EIP.

The desired aeroshape is obtained by a dedicated inflatable structure and is protected by a specific flexible TPS membrane solution. This morphing heatshield solution overcomes the limitation imposed by the fairing geometry limits and achieves an efficient protection of the payload stage, inflating few minutes before the Entry Interface Point (EIP) and after the separation from the carrier spacecraft.

The TPS membrane has similar functions needs as per the Earth application, therefore a similar design and trade-off approach is followed. Remarkably, heat fluxes on the Flexible TPS will reach peak values of up to 600 kW/m2. This value has been established thanks to ATD 2D/3D simulations, considering the influence of the turbulence, wall catalysis and radiative heat transfer mechanism. While in general the design will be different from the Earth application, in particular for the thickness of the insulation layer, the overall combination of multi-layer membrane is maintained and similar materials have been selected.

The diameter of the inflatable structure for the Mars scenario is twice the size compared to the one developed for the Earth scenario. However, the inflatable structure is designed under the same general solution adopted for the Earth scenario (Annular torus plus secondary conical volume), demonstrating good capability of this concept to adapt to the specific design problem. The main difference to highlight is that in this case the Annular Torus in not directly in contact with the main body to avoid an excessive size of the Annular Torus as shown in Figure 22. Also, in this configuration the conical volume is used to maintain the desired shape along the re-entry trajectory. The two inflatable volumes have different values of pressurization for each configuration that have been designed ad-hoc for the reference missions

4. Technology roadmap: ground tests, IOD mission and the long-term way forward

Within the EFESTO project, the objective is to increase the TRL from 3 up to 4/5. This is achieved with dedicated ground test campaigns. Beyond them, an In-Orbit Demonstration flight is foreseen; this IOD mission will be designed but nor realized within the scope of the EFESTO activities.

More in details, for what concerns the ground tests, samples of the F-TPS membranes designed will be tested in Plasma Wind Tunnel and a 1:2 test article will be built to test the inflatable structure during the morphing and under static loads.

The development of the proposed inflatable TPS solutions will be supported by thermal characterization in ground test facilities. Two test campaigns are foreseen in DLR’s arc-heated facilities LBK, see Figure 11.

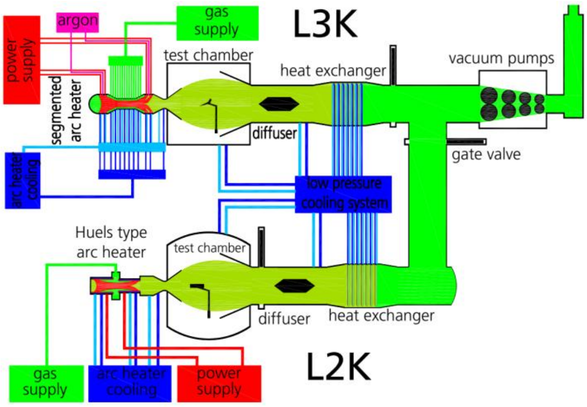

Figure 11: DLR’s arc-heated facilities LBK.

In the first arcjet loop, selected candidate TPS designs will comparatively be tested on sample basis at mission relevant conditions. The candidates are being identified during the detailed HIAD design. The results of the arcjet tests will support the selection of the most suitable TPS layups for both applications, Mars as well as Earth. The second arcjet loop will then be objected to the final TPS design. Beyond the flexible TPS membrane, the specimens for this series of tests will also include elements of the inflatable structure.

Investigation of mechanical behavior of Inflatable Structure as a sub-system will be achieved through design, manufacturing and testing of a 1:2 Demonstrator (2.4 m diameter) with particular focus on key aspects as folding and stowing, inflation process and capability to withstand static load patterns (see Figure 13).

The Demonstrator will replicate 1:1 the Inflatable structure architecture, materials and design solution. On the contrary, a simulacrum of the F-TPS skirt will be manufactured to replicate packing density and mechanical strength (see Figure 12).

Two specific dedicated tests will be carried out:

- Inflation and Deployment Test: to provide a feedback about critical aspects as folding and packing method, inflation phase and deployment sequence (see Figure 28).
- Static Load Test: to characterize the structural deformation of IAD model under a symmetrical and asymmetrical load distribution (see Figure 14).

Figure 12: EFESTO 1:2 Ground Demonstrator – simulacra of the F-TPS.

On a long-term perspective, a technology roadmap will place the project in the worldwide context suggesting the step by step development for the European effort in the field. More details are presented in a parallel IAC paper (see [4]). In brief, the project culminates with the design of an In-Orbit Demonstration (IOD) mission, setting the basis for a technology development programme. Within EFESTO, the technology roadmap, planning the necessary development activities, is generated to support the European strategic decisions in this field. A rational and logical methodology is proposed for the technology roadmap generation, considering the robustness of the result and the influence of the chosen parameters through sensitivity analysis. Multi-attribute theories are considered and implemented to include features of different nature and the preference among them. An ad hoc database of the past, present, and planned efforts in the field of atmospheric entry systems is developed and implemented in the process.

The technology roadmap defined responds to the multiple technical challenges identified in the different disciplines involved: system aspects, addressing geometric and functional integration of critical uncommon sub-systems as the F-TPS and the inflatable structure in folded state, concerning the available volume and cross-section, and during re-entry conditions in consideration of the centre of gravity position and related impact on flight stability and control; aerothermodynamic aspects, strong fluid-structure interactions along the atmospheric entry which are critical for the TPS design; materials and structures aspects related with not yet matured technologies including the design of a flexible thermal protection sheet able to withstand the peak heat fluxes experienced during entry, as well as a suitable underlying inflatable structure that allows maintaining the optimal aerodynamic shape during the entirety of the mission; mission and GNC aspects, controlled entry on Earth combined with parafoil descent and Mid-Air Retrieval and ballistic entry combined with supersonic retro propulsion for Mars.

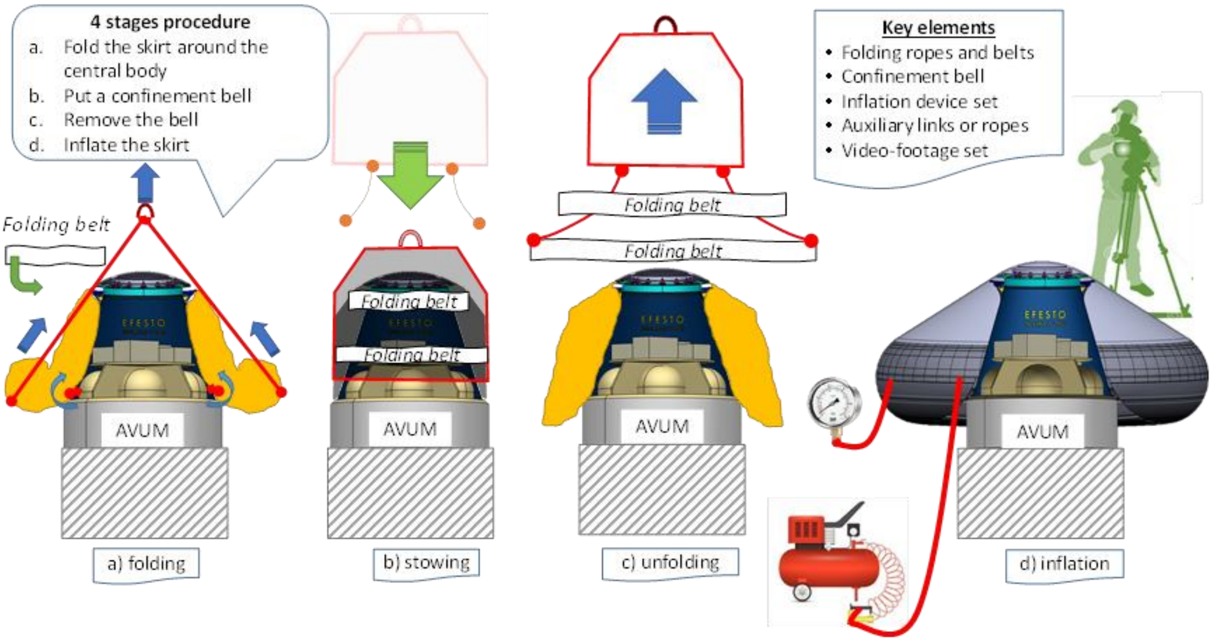

Figure 13: EFESTO Ground Demonstrator – Inflation and Deployment test.

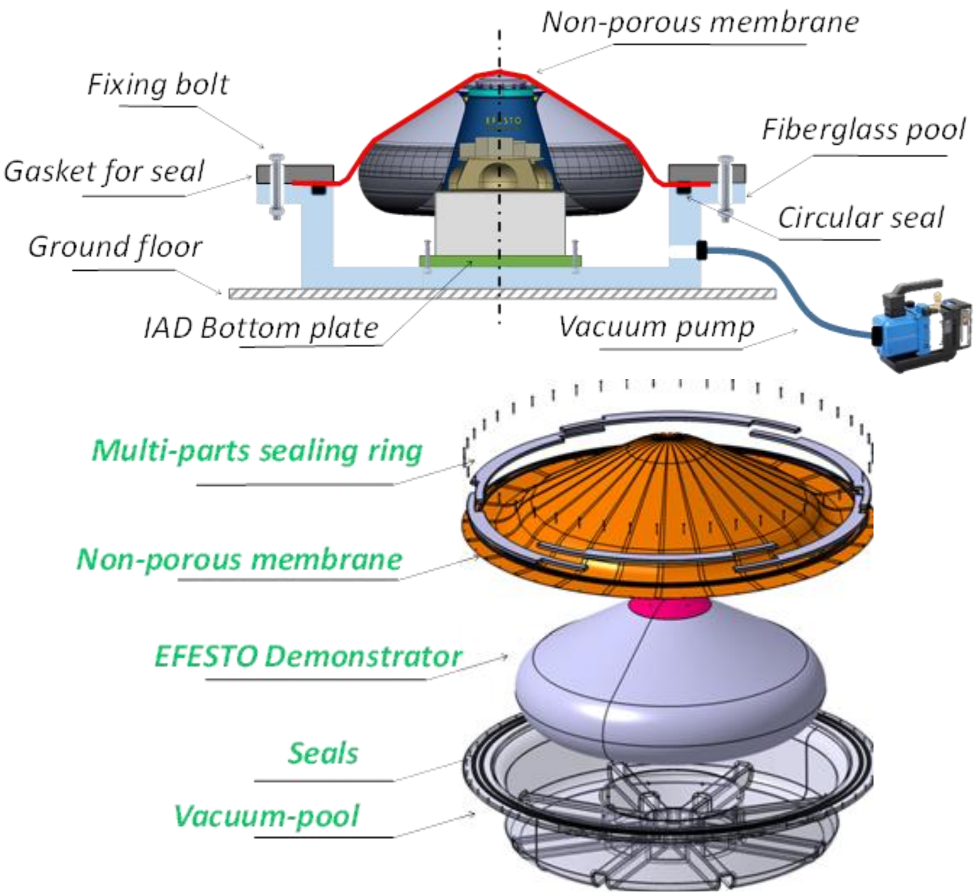

Figure 14: EFESTO Ground Demonstrator– Static Load test.

5. Conclusions

EFESTO objectives, motivation and a general overview of the activities have been presented.

Concepts design for Earth and Mars inflatable heatshields applications have been briefly presented: the technologies explored in EFESTO are expected to have a promising impact on future missions, including breakthrough performance improvements in Mars exploration and real possibility of applications for future reusable launcher concepts, notably for the European VEGA launcher upper stage AVUM.

Beyond space missions, the innovation introduced in flexible TPS and inflatable structures can find applications on multiple other fields, in particular in fire protection solutions.

The next steps following the concept design will include the completion of the detailed design, laboratory tests and preparatory activities for a future in-orbit demonstration mission.

Placing this future mission in the context of a broader and longer term technology roadmap is also one of the project goals, open and willing to find synergies with ongoing and future efforts in the European context.

In the worldwide context, strong commonalities with the LOFTID demonstration mission by ULA and NASA are identified, see [1] and [6].

Two workshops will be organized and hosted by Politecnico di Torino as dissemination and outreach activities to both technical and non technical public (target dates: Q1 2021 and Q1 2022).

Acknowledgements

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 https://cordis.europa.eu/project/id/821801

The EFESTO consortium acknowledges essential contributions of TRLA Aerospace Canada and ALI Scarl Italia.

References

[1] Dillman, R. A., DiNonno, J. M., Bodkin, R. J., and Hughes, S. J., “Planned Orbital Flight Test of a 6m HIAD,” 15th International Planetary Probe Workshop, June 2018.

[2] “Vega User’s Manual Issue 4 Revision 0,” Arianespace, April 2014.

[3] “In-Space Propulsion Data Sheets, Monopropellant and Bipropellant Engines,” Aerojet Rocketdyne, September 1019.

[4] G. Governale, D. Bonetti, I. Dietlein, G. Gambacciani, G. Guidotti, Y. Prevereaudf N. Viola, “Advanced European Re-Entry System Based on Inflatable Heat Shields - Technology Roadmap and Technical challenges (EFESTO project)” 71st International Astronautical Congress (IAC) – The CyberSpace Edition, 12-14 October 2020. IAC-20-D1.1.1

[5] Hughes, S., Dillman, R., Starr, B., Stephan, R., Lindell, M., Player, C., and Cheatwood, F., “Inflatable Re-entry Vehicle Experiment (IRVE) Design Overview,” 18th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, AIAA Paper 2005-1636, 2005.

[6] Hughes, S., Cheatwood, N, Swanson, G, Kazemba, C, Lindell, M, Tobin, S, Bodkin, RJ, Dillman, R, DiNonno, J, Johnson, K, “Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) – Aeroshell System Overview”. 16th International Planetary Probe Workshop, 11 July 2019.

[7] D. Bonetti, G. De Zaiacomo, I. Dietlein, B. Esser, G. Guidotti, A. Fedele, J-L. Verant, Y. Prevereaud, G. Gambacciani, G. Bimbi, G. Governale, N. Viola, “EUROPEAN FLEXIBLE HEAT SHIELDS: ADVANCED TPS DESIGN AND TESTS FOR FUTURE IN-ORBIT DEMONSTRATION“, FAR 2019, International Conference on Flight Vehicles, Aerothermodynamics and Re-entry Missions & Engineering, 30 September-03 October, 2019, Monopoly, Italy.

[8] D. Bonetti et al. “OPTIMUM SIZING FOR DESIGN OF MARS PROBES”, 9th International Planetary Probe Workshop, June 2012.

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

This project has received funding from the European Union’s Horizon 2020
research and innovation programme under grant agreement No 821801