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EUROPEAN FLEXIBLE HEAT SHIELDS: ADVANCED TPS DESIGN AND TESTS FOR FUTURE IN-ORBIT DEMONSTRATION

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ABSTRACT

The European Union H2020 EFESTO project is coordinated by DEIMOS Space with the end goals of improving the 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).

This paper presents the project objectives and provides with a general overview of the activities ongoing and planned for the next three years, promoting its position in the frame of a European re-entry technology roadmap.

Index Terms— heat shields, TPS, materials and structures, mission and system design, technology roadmap

1. INTRODUCTION

EFESTO aims at (1) the definition of critical space mission scenarios (Earth and Mars applications) enabled by the use of advanced inflatable Thermal Protection Systems (TPS), (2) characterization of the operative environment and (3) validation by tests of both the flexible materials needed for the thermal protection (flexible thermal blanket will be tested in arcjet facility in both Earth and Martian environments) and the inflatable structure at 1:1 scale (exploring the morphing dynamics and materials response from packed to fully inflated configuration). These results will be injected into the consolidated design of a future In-Orbit Demonstrator (IOD) mission.

Fully in line with the European Union H2020 call SPACE-11-TEC-2018, 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 payload 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.

2. MOTIVATION

Re-entry vehicles are critical elements in space missions that require bringing a payload from space to ground on a planetary body with an atmosphere. The hypersonic conditions in a dense atmosphere generate a plasma flowfield around the entry vehicle resulting in extreme thermal heat fluxes and thermal heat loads. This is the most important challenge for the thermal control of a re-entry vehicle: the payload must be protected from this harsh environment by a Thermal Protection System (TPS) in order to keep it within a range of safe conditions.

Europe has demonstrated its excellence in the design and flight of re-entry vehicles in multiple environments like Earth (ARD, 1998, and IXV, 2015), Mars (Beagle2, 2003, and ExoMars, 2016) or Titan (Cassini-Huygens, 2005). These missions performed successful entry phases protecting their payloads with rigid heat shields, which currently represent the state of the art in re-entry TPS and still are the baseline solutions for current or short term next

exploration missions: ESA's ExoMars 2020, NASA's InSight and Mars2020, and the international Mars Sample Return. Rigid, heavy heat shields are designed to provide re-entry vehicles with enough drag and stability while keeping the heat fluxes within the available materials limits. However, they are constrained in size and mass to fit within the launcher payload fairing volume. For these reasons, rigid TPSs introduce important design constraints to space missions, heavily limiting the capability of re-entering a payload in atmosphere, and represent a limiting factor in particular for current and future Mars exploration missions and Earth re-entry applications

The requirements of next generation Mars exploration missions, that aim at more advanced scientific goals, will call for the capability of considerably increasing the mass landed, or land payloads at higher altitude regions on Mars: only 30-40% of the planetary surface is currently accessible because it is required to land below "sea level" due to the lack of large enough heat shields for a thin and low density atmosphere such as the Martian one (Figure 1 shows the location of the landing sites of past and current exploration missions). This is even more essential for the planned Mars human exploration that would imply the necessity of landing 10+ times bigger payloads (astronauts, Mars ascent vehicles, water, food, air, power, etc...).

On Earth, the trend in the space transportation market is to achieve long term sustainability: in the modern "access to space" market worldwide context, the capability of performing the recovery of launchers' stages is considered critical and is revolutionizing the classic expendable launcher approach. This capability is not yet available in Europe, while only partial reusability, for lower stages, is now a reality in the USA. Protecting a launcher's upper stage from entry thermal loads is mandatory to achieve full reusability. State of the art operational TPS technology, based on rigid heat shields, is a blocking factor for full reusability, due to multiple constraints mainly imposed by mass and cost but also by geometrical, mechanical and structural aspects. Higher performance TPS are needed to break the current design limits, and extend the applicability range of thermal protection systems.

Despite of the very different environments, Mars and Earth re-entry applications are driven by the same basic physics. One of the key design parameters driving the thermal conditions experienced by re-entry vehicles is the ballistic coefficient (BC):

$$BC = m / (S * C_D)$$

($m = \text{mass}$, $C_D = \text{drag coefficient}$, $S = \text{reference surface}$).

For a given entry vehicle, the bigger the heat shield area, the lower the BC. Reducing the BC is mandatory to produce enough drag to decelerate larger entry masses at higher altitudes and to reduce the thermal loads during the re-entry phase. To break the size limit imposed by the

launcher fairing, new morphing TPS solutions emerged in recent years: they allow having a densely packed heat shield during the launch phase that deploys or inflates in space before the entry phase. In this way, flexible heat shields with larger diameters than the launcher fairing's can be achieved, leading to a **radical reduction of the re-entry BC**. This will enable space missions that will require landing heavier and larger payloads (on Earth or Mars) or reaching higher-altitude landing sites on Mars that have never been explored. Moreover, inflatable heat shields could be assembled, packed and deployed to allow the re-entry and the recovery of launchers' upper stages for multiple reuses.

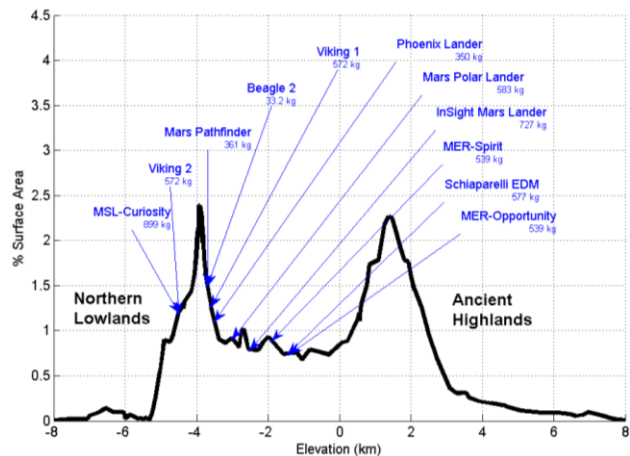


Figure 1: Missions to Mars, elevation and mass

Europe has got significant past experience in inflatable heat shields. Under the European Space Agency (ESA) coordination, flexible materials and inflatable subscale designs were indeed tested in the mid 2000s in arcjet facilities (IRT and SPEM projects) and In-Orbit Demonstrator (IOD) missions were also attempted even earlier, enabled by cooperation with Russian companies and making use of Russian technology (IRDT), but with multiple failures and with a partial success (putting also on evidence how important is to follow the TRL steps to successfully develop a technology).

More than 10 years have passed since these activities, and meanwhile new materials emerged and numerical modelling capabilities dramatically improved, enabling a better understanding of the physics of the morphing process and of the increased TPS materials performance. The current **TRL** has lowered to a value of 3 (on modern, advanced materials and structure solutions) indicating that the present tendency is to start back from basic design: this is confirmed by the most recent activities at European level: the potential benefits of Inflatable and Deployable Aerodynamics Decelerators (IAD & DAD) concepts have been studied and confirmed at conceptual design level through an ESA TRP completed in 2017.

Starting from this point, Europe today needs to keep improving the knowledge and the design and test capabilities of inflatable TPS by following a structured technology development roadmap. EFESTO will keep pushing the European TRL, aiming at reducing the gap with respect to NASA that is keeping a high pace in research and innovation in this field, see Figure 2.

One of the EFESTO outcomes will be the definition of an **IOD mission** demonstrating in flight the inflatable TPS solution. This demonstration mission will rely on a robust design methodology, modern TPS materials and validated design models. Once flown (beyond the EFESTO scope), such mission will represent a step forward with respect to the ESA IRDT (partially successful mission flown in 2000)

and it will also act as a bridge in the gap with NASA state-of-art in the field, represented by the NASA IRVE-3 (fully successful mission tested in 2013). The IOD mission will be necessary in the future to bring the inflatable heatshield concepts towards a TRL of 6 and would be the natural continuation of the EFESTO project.

2. STUDY LOGIC

EFESTO is built on four key technical elements (red bullets in Figure 3 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.

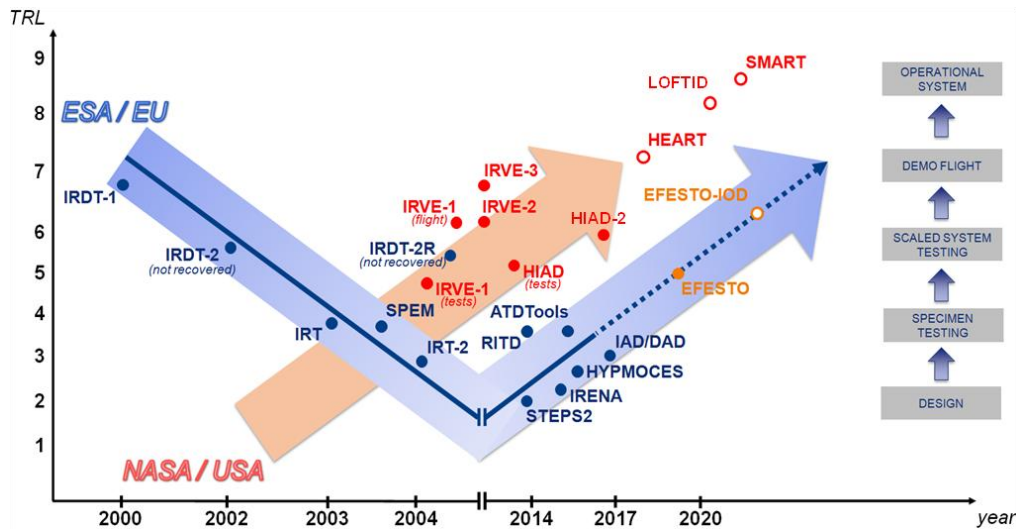


Figure 2: TRL evolution in inflatable heatshields technology: comparison of ESA/EU and NASA/USA trends.

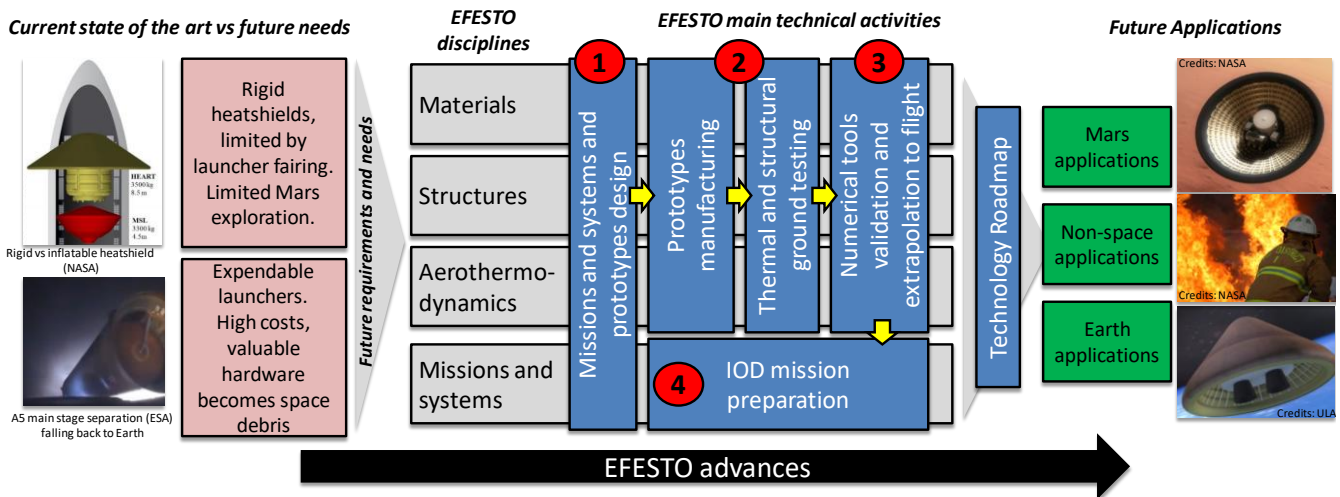


Figure 3: EFESTO study logic and key elements (red circles)

2.1. Element #1: Missions and system design

Given the multi-disciplinary nature of inflatable heat shields design, expertise in the fields of materials, structures, aerothermodynamics, mission engineering and system design is needed. Expertise and modern numerical tools are available in the consortium to support the engineers in the detailed assessment of performance in each of the above mentioned areas; moreover, concurrent engineering design and multi-disciplinary optimisation techniques are mastered by the team to support the trade-off and conceptual design phases in a coherent and structured way.

Efforts are concentrated on the design of inflatable heat shields as the novel element of a re-entry vehicle to enable future missions beyond current capabilities. The design phase runs from conceptual design to detailed design and covers two mission applications: Mars exploration missions and applications for reusable launch vehicles on Earth.

2.2. Element #2: Prototypes manufacturing, development and ground tests

Tests in representative environment are needed to increase the knowledge of the materials and structural assembly in order to perform the critical assessment and support the development of the proposed inflatable TPS solutions. Laboratory tests will be performed on the two building elements of inflatable heat shields: the flexible TPS membrane in arcjet (Figure 4) and the large inflatable structure in ground test facilities. Successful testing will eventually increase the TRL of the inflatable heatshields technology to TRL 4 and the TRL of multi-layer flexible TPS (thermal blanket) to TRL 5. Prototypes (several multi-layer flexible TPS samples and a 1:1 scale inflatable structure) will be manufactured under the technical specifications resulting from the mission design and operational environment definitions.

2.3. Element #3: Numerical models validation

Validation of the numerical models is another objective of the test campaign, and it is a critical aspect to increase robustness of the inflatable heat shield design process and the extrapolation of results to flight. Within EFESTO, three areas will be covered:

- **Materials:** thermal characterization of flexible TPS membranes is the starting point for the definition of a suitable solution. Aerothermodynamic (ATD) assessment of FTSPS layups requires knowledge of the thermal properties of all materials, i.e. outer layer, insulation, gas barrier.

- **Aerothermodynamics:** aerothermodynamics will define for the aeroshell and the payload the integrity and feasibility conditions for both Mars and Earth missions. Validation of wall temperature and heat flux distribution based on ground test results is a target for a thermal balance assessment. Extrapolations to flight, based on ground tests

validation, are a key point aiming at increasing the TRL of inflatable heat shields in Europe. Moreover, experience gained in Europe gave important lessons learned for payload design/housing improvement at the back of the aeroshell to prevent/mitigate any over-heating on payload involving wake flow Radiative Heat Transfer: radiative heating effects on the payload due to the heatshield ATD behavior should be correctly included in the numerical model and validated.

- **Structural morphing process:** validation of the inflation process can be achieved by a hybrid analysis-test method, which foresees the implementation of virtual (i.e. CAE/FEM based) models of the inflatable structure, both for the relevant flight applications and for the ground test model. In the case of the ground model, validation will be sought via correlation between test data and analytical data.

2.4. Element #4: In-Orbit Demonstration (IOD) mission preparation

In the development process for operational space applications, an In-Orbit Demonstrator mission is a key milestone to demonstrate the performance of the system in operational scenario and bring a technology to TRL 6. In EFESTO, leveraging on validated numerical tools, a consolidated design of an inflatable heatshield for a specific IOD mission will be performed. The goal is to prepare the terrain to demonstrate the feasibility of using this new technology with significant re-entry heating in a future flight (not performed within the project activities planned for this call). In line with the technology roadmap drawn for the project, the flight target will be to test in hypersonic conditions the TPS solution and validate it for future space mission applications. In Europe, a possible candidate launcher could be the MAXUS sounding rocket operated from the Esrange Space Centre (Kiruna, Sweden), which allows reaching apogee altitudes of up to 700km with payloads of ~500kg (suborbital conditions, with peak re-entry velocity about 5.4km/s).

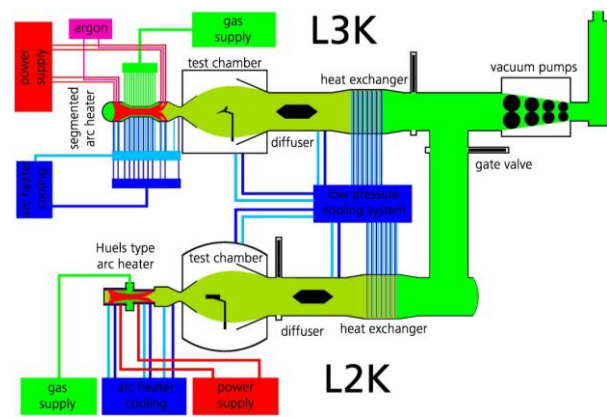


Figure 4: DLR arcjet facilities

3. EFESTO TEAM AND EXPERTISE

Figure 5 presents the EFESTO Project Consortium. It combines 6 European partners including world renowned research institutes (DLR, ONERA and CIRA), space industry with a unique and internationally recognized expertise in atmospheric flight (DEIMOS Space), flexible TPS materials and morphing structures (AVIOSPACE) and leading university with large expertise in Space and an active role in re-entry technology roadmaps (POLITO).

The consortium represents a balance over the full R&D cycle, from research institutes to industry and university, including excellent numerical simulation capabilities of complex multi-physics phenomena, unique samples manufacturing skills and world class testing facilities. The partners put together the competencies required to fulfill the objectives of the project covering the full chain of (1) design, (2) test and (3) validation through numerical rebuilding in the areas of advanced materials, structures and thermal control for high temperature applications.

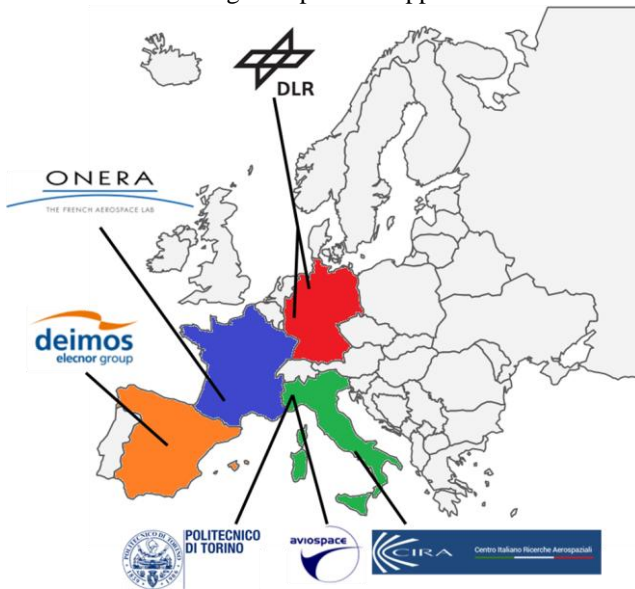


Figure 5: EFESTO project consortium

4. EFESTO ACTIVITIES OVERVIEW

The project has a duration of 36 months and has received funding of about 3M€ from the European Union’s Horizon 2020 research and innovation programme. Overall the activities are organized in 9 different work packages (WP).

The project management (WP1) and the dissemination and exploitation (WP9) activities run in parallel to all others, throughout the three years. The project technical work packages run sequentially, with some overlapping to maximize the efficiency of the project. First, the identification of future applications, study cases

scenarios and the associated Mission and System Requirements has been performed in WP2, including the preliminary trade off for the IAD concept. The preliminary and the detailed designs of the innovative missions and systems are carried out in WP 3 and WP4, respectively, serving as the basis for the latter technical activities.

In parallel the basic inflatable FTPS technological solution candidates will be defined, modeled and analyzed. Then the technological solutions for the flexible TPS material and inflatable structure will each be developed and tested in a representative laboratory environment in WP5 and WP6, providing solutions for each of the technological challenges of the EFESTO project. At the end of WP7, the technological solutions will be available as a project output, and the models developed will be validated. In WP8 these consolidated solutions will be integrated to design an In-Orbit Demonstrator mission for a future validation of the technology developed in operational environment.

As part of WP9 activities, 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).

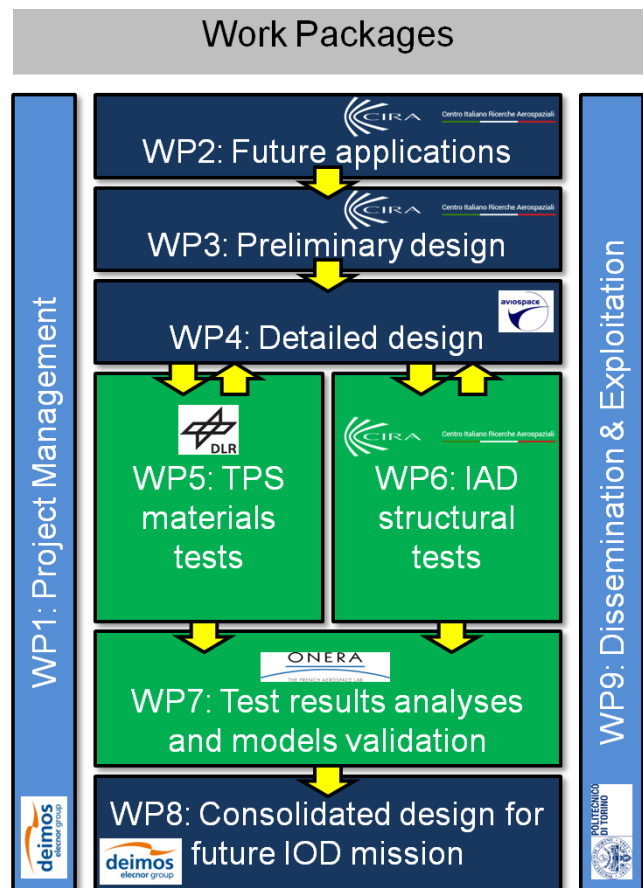


Figure 6: EFESTO Work Packages

5. INFLATABLE AERODYNAMIC DECELERATORS (IAD) APPLICATIONS

As part of the WP2 activities, an exhaustive worldwide state of the art review has been performed to identify future applications and missions that would most benefit from advances in inflatable heatshields technology.

This technology will open mission scenarios precluded so far by technological limitations. The review of state-of-art and the identification of the key performance affected by the proposed technology leads to the identification of candidate scenarios for which relevant Mission and System requirements can be drawn.

Candidate scenarios can be identified in the field of space exploration, in particular to develop critical technologies for future larger scale robotic and human Mars exploration, and space transportation, in which the possibility of recovering and reusing launchers' stages could significantly reduce the costs for access to space.

Tens of relevant studies, projects or missions have been reviewed and analyzed, key performance indicators have been extracted and general categories of applications have been defined. In brief, four different classes of missions have been identified (see Table 1):

- LEO return (selected)
- Suborbital return
- Robotic Exploration of Mars (selected)
- Human Exploration of Mars

Two classes been selected for design in EFESTO and are described in the following sub-chapters.

Table 1: Classes of missions with IAD applications

Performance	LEO Return	Suborbital return	Robotic Exploration of Mars	Human Exploration of Mars
IAD Diameter (m)	<6	12	~10	23
IAD Cone angle (deg)	60-70	60-70	60-70	70
Entry Mass (kg)	<1500	12000	6000 (<10000)	80000
Entry Velocity (km/s)	7-7.5	4-6.5	3.3-6	3.35
Peak Heat Rate (kW/m ²)	<500	<300	300-400	400
Approx. BC (kg/m ²)	30	60	45	35

5.1. Earth mission scenario: LEO return

Among the possible LEO return scenarios, which are all technologically appealing, there is one which is relevant as far as innovation is concerned: recovery of launcher upper stages.

In general, recovery and reuse of dropped launchers elements becomes the optimum solution if the extra costs of design, manufacturing, operations and refurbishment are compensated by the value of the recovered element. The economics could become beneficial after a number of launches, re-entry, recoveries and refurbishments, implying that the risk of a failure in any of these phases could result

in a negative net value in comparison to the non-reusable design. Given the fact that extra costs and risks could be relatively high, compared with expendable launcher solutions, the interest in recovery and reuse of launcher elements is limited to the most valuable and easier to recover and refurbish ones.

For these reasons, the market is currently focused on the recovery of liquid first stages, or their most valuable parts, such as the engines and the avionics. State of the art launchers (e.g. Falcon Heavy, SpaceX) are capable of re-using (by landing on pads or on a drone ship as part of routine launch operations) the main engine and the two boosters with the use of supersonic retro propulsion. Other actors, like ULA, are also interested in the reuse of the launcher first stage and plan the use of IAD systems. ULA and NASA defined a demonstration mission (LOFTID) that recently (May 2019) achieved funding for testing the IAD in an In-Orbit Demonstrator mission (IOD) [1]. This is perfectly in line with the right technology roadmap steps that EFESTO aims at defining for an equivalent European application.

Overall, within EFESTO, applications of IAD solutions for the recovery and re-use of micro-launchers and small-launchers stages are considered appealing, both at commercial level and at technological research level. While the technical research is of absolute interest for the goals of the EFESTO project, the commercial aspects will require further dedicated research and analyses (out of scope of EFESTO). From a preliminary assessment done, a satisfactory business case (costs savings) can be achieved if:

- CAPEX: Capital Expenditures (e.g. development and production costs) are 100% (or less) of one expendable launch cost
- OPEX: Operational Expenditures (e.g. recovery operations and refurbishment costs) are around 5-10% (or less) of one expendable launch cost
- The recovered element performs 5-10 re-flights
- Element recovered value is 15-20% (or more) of one expendable launch cost

Based on these results, it is found that an upper stage of at least a small launcher class is an interesting candidate with a business case that works for example for the European VEGA upper stage (AVUM).

Within EFESTO, both micro-launcher (a representative one from past ESA/DLR studies) and small launcher upper stages (VEGA AVUM) have been considered as possible candidates: preliminary IAD concepts have been designed for both classes and are briefly presented in section 6.

5.2. Mars mission scenario: Robotic Exploration

Mars exploration began in the 1960s and more than 40 missions have attempted to reach the Red Planet, with varying degrees of success. Among the successful missions

that survived the Entry, Descent and Landing (EDL) phases, the biggest and heaviest system successfully landed on Mars to date has been the NASA Mars Science Laboratory (MSL) with a landed mass of about 900 kg. All these successful missions relied on the use of rigid heatshields, supersonic parachutes and (in most of the cases) subsonic powered descents, as heritage of the first pioneering Viking missions of the 1970s. For the landing phase, soft touchdown has been achieved in multiple ways, with solutions ranging from crushable structures, to landing legs, to airbags or sky crane (MSL). Short term future missions to Mars include the ESA ExoMars2020 Rosalind Franklin rover and the NASA Mars2020 rover, both based on classic EDL key elements.

Future missions to Mars that want to exceed the current limits in terms of landed mass (> 900 kg) or topographic altitude of the landing site (MOLA > -1.4 km) will need to introduce novel EDL solutions. Increasing the TRL of structures and materials solutions enabling new missions is one of the key objectives of EFESTO: they find a direct application to Mars exploration, in particular for the entry phase.

NASA is working on two critical “game changer” solutions to enable future missions: **morphing heatshields** (inflatable, HIAD; deployable: ADEPT) and **supersonic retro-propulsion** (SRP). The first is the technology of interest of EFESTO, in particular for what concerns inflatable heatshields (HIAD, Hypersonic Inflatable Aerodynamic Decelerators). The second, SRP, has been identified as a clear enabler also in Europe for future Mars explorations and, even if it is not the core activity of EFESTO, it is recognized as a necessary building block for an end-to-end EDL mission, in combination with a HIAD.

Worldwide the SRP has not yet been tested on Mars, but it has been successfully implemented on Earth by SpaceX and Blue Origin for a successful recovery of their launcher stages. Europe has a lower TRL on this field but is recently investing on it for Earth applications: the state of the art is represented by the projects CALLISTO, Prometheus, THEMIS and RETALT, whose research is lead in Europe by DLR and/or CNES.

A hypersonic inflatable aerodynamic decelerator (HIAD) composed of an Inflatable Structure and a Flexible TPS would address most of the afore-mentioned limitation, widening considerably the possible design solutions of the entry phase. Given that the European TRL on inflatable technology is rather low nowadays, HIAD applications of Robotic Exploration of Mars are more realistic to consider for EFESTO; the Humans Mars Exploration is considered within the project as a long term goal in the technology roadmap but not as a study case for the design phases.

A target for the Robotic Exploration of Mars mission is set in term of lander mass and landing site altitude (above the Mars MOLA): 3000 kg at MOLA +2km (very challenging compared to the state of art, see Figure 1).

6. CONCEPT DESIGN

This section briefly presents the results of the first design step: concurrent design sessions at DLR Bremen have been performed for Earth and Mars mission scenarios involving the full team to discuss, explore and define the system and mission design concepts for the applications of interest presented above. A multidisciplinary design approach is followed, focused on the IAD subsystem and including full iterations of geometry, mission (trajectory), aerodynamics, flying qualities, aero-thermo-dynamics, structures and materials (for the IAD) and system budgets. An overall comparison of the concepts design is shown in Figure 9.

6.1. Earth mission scenario: LEO return

As introduced in section 5, micro-launcher (a representative one from past ESA/DLR studies) and small launcher upper stages (VEGA AVUM) have been considered in EFESTO.

For the micro-launcher class, two options have been considered (see Figure 7): a partial reuse of the upper stage (recovering only the engine and the avionics, about 900 kg) and a full reuse of the upper stage (about 1800 kg, including ad-hoc modification of the system design with respect to the original expendable configuration to achieve satisfactory flying qualities during the re-entry phase).

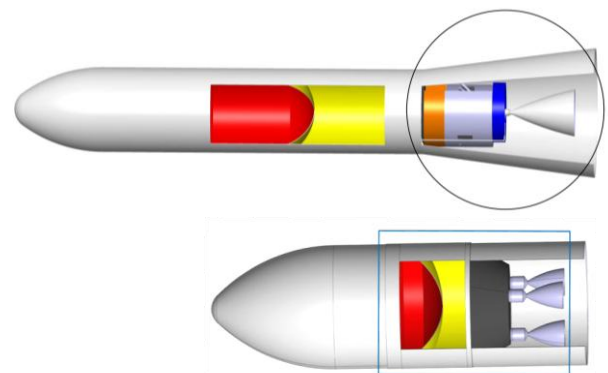


Figure 7: Micro-launcher second stage. Expendable (original, top) and reusable re-design (bottom)

The IAD design of these micro-launcher class configurations ended in the selection of a BC around 20 kg/m², with corresponding IAD diameters in the range of 6 and 10 m (partial and full reuse).

For the VEGA upper stage (AVUM), the BC is set around 70 kg/m² and the IAD is about 4m in diameter. No re-design was needed for AVUM: the overall geometry showed satisfactory flying qualities during the re-entry phase, making it an appealing business case for IAD applications. Of course, ad-hoc local modifications have been identified and are needed for a proper installation and deployment of the inflatable heatshield, in particular in the area of the payload adapter (an ad-hoc adapter is foreseen).

6.2. Mars mission scenario: Robotic Exploration

For the Mars Application, the robotic exploration mission class resulted in a 10 m diameter IAD class, with about 6600 kg of entry mass, and a BC of about 50 kg/m², see Figure 8. The current mission foresees a direct Mars entry and combines the use of hypersonic IAD (HIAD) with Supersonic Retro-Propulsion (SRP, activated about Mach 2.3) to deliver about 3000 kg of payload at MOLA +2 km.

This mission promises a real breakthrough in performance with respect to current state of art missions, based on rigid heatshield and parachute technology. It is also requiring materials performance beyond the limit of common flexible TPS materials available on the market (e.g. Nextel), in particular for what concerns the first, most external layer exposed to the plasma flowfield. A new generation of more advanced FTPS materials is needed for this mission: the consortium has explored and already identified preliminary solutions with properties compatible with this mission needs, beyond what has been tested so far in European facilities and fully in line with the research and innovation nature of EFESTO.

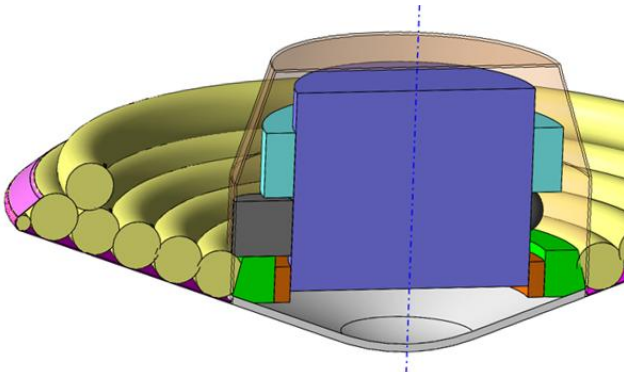


Figure 8: Mars Exploration mission, concept design

7. CONCLUSIONS AND WAY FORWARD

This paper presents the EFESTO objectives and gives a general overview of the activities ongoing (including concept design for Earth and Mars inflatable heatshields applications) and planned for the next three years, promoting its position in the frame of a European re-entry technology roadmap. 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 project EFESTO started in 2019 and will continue over 36 months. The next steps following the concept design will include 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 context is also one of the project goals, open and willing to find synergies with ongoing and future efforts in the European context.

10. ACKNOWLEDGMENTS

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

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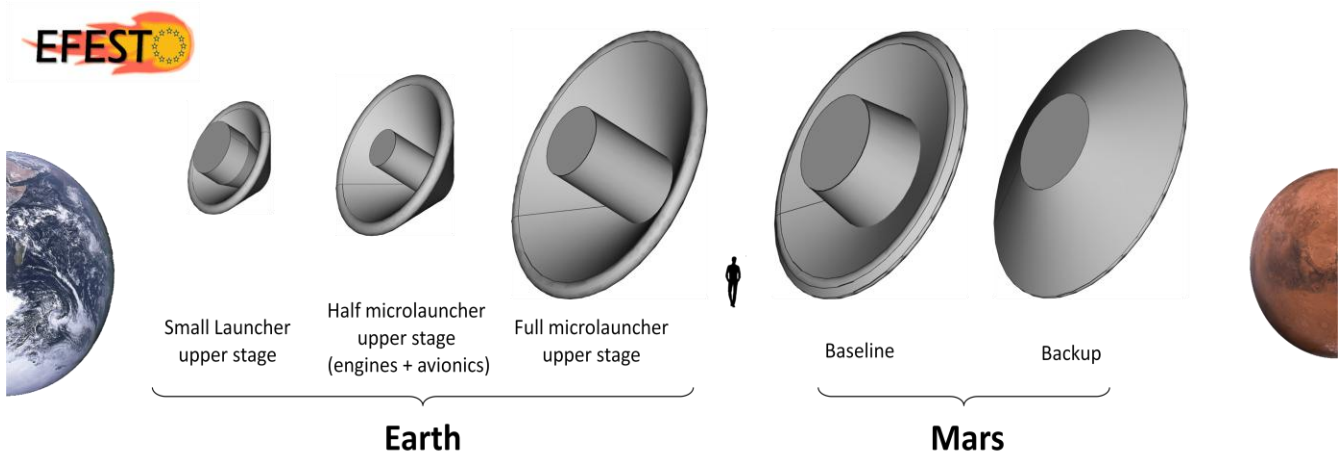


Figure 9: Inflatable heatshields applications and configurations considered during the concurrent design phase