European Flexible Heat Shields: Advanced TPS Design and Tests for Future In-Orbit Demonstration - 2

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EFESTO-2: European Flexible Heat Shields Advanced TPS Design and Tests for Future In-Orbit Demonstration - 2

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Abstract

EFESTO-2 is an EU-funded project under Horizon Europe that aims to enhance European expertise in Inflatable Heat Shields (IHS). Building on the achievements of the previous EFESTO project (H2020 funds No 821801), EFESTO-2 focuses on advancing key IHS technologies to increase their Technology Readiness Level (TRL). The project pillars include analyzing the business case for IHS applications, exploring additional aspects of IHS, improving tools and models, and establishing a development roadmap for IHS systems. This paper outlines the project objectives and plan, highlighting ongoing and future activities for the next two years, positioning it within the European re-entry technology roadmap. Funding was provided by the European Union's Horizon Europe program (grant agreement No 1010811041).

1. Introduction

Current planetary entry systems rely on rigid heavy heat shields to decelerate and protect themselves from aerothermal loads during atmospheric flight. However, rigid heat shields are also constrained in size and mass to fit within the launcher fairing volume (see Figure *1*, [1]).

Figure 1: Rigid heatshield (MSL) and inflatable heatshield concept (HEART, NASA)

In that perspective, state-of-art rigid heat shields introduce non-negligible design constraints to space missions, heavily limiting the capability of re-entering a payload in atmosphere for current and future Earth re-entry applications as well as for Mars exploration missions.

In turn, innovative heat shield are needed to break the current design limits, and extend the applicability range. This relies to Flexible Thermal Protection System (**F-TPS**) and Inflatable Structure (**IS**) solutions (or Inflatable Heat Shields

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- **IHS**) because of their capability of having a packed heat shield during the launch phase with a reduced mass/volume impact on the launcher.
European experiences in the field of IHSs date back to mid-2000s [2], however the TRL achieved was not that significant. Recently interest in this field has revamped worldwide also thanks to NASA LOFTID mission [3], [4].
In EU, the EFESTO project, funded by European Union's Horizon 2020 programme and run from 2019 to 2022, contributed to the increase of the TRL from 3 to 4/5 [5][6][7], with a broad scope of activities ranging from mission and system level design, in order to design, manufacturing and testing of breadboards of the two key technologies of an Inflatable Heat shield system (i.e. Flexible TPS and Inflatable Structure). Significant achievements were obtained in the frame of the EFESTO project, however, much more shall be done to further increase the TRL to a maturation such to allow for an operational use of that technology in the field of space applications.
In view of the above context, the present EFESTO-2 initiative aims at implementing the needed forward advance to improve the current TRL 4-5 reached in the father project 'EFESTO' towards a TRL 5-6 level, as the necessary intermediate step between modern design capabilities and future operational IOD re-entry missions.
In November 2022, the EFESTO-2 project received funds from the European Union's Horizon Europe program under grant agreement No.1010811041 and a kick-off was carried out to address the following four macro tasks:

i. consolidate the use-case applicability of IHSs through a business case analysis for a meaningful space application.
ii. extend the investigation spectrum to other critical aspects of the field through an extensive test effort focused in parallel on aerodynamics and mechanical aspects in complementary way to what was done in the frame of EFESTO father project.
iii. increase the confidence-level and robustness of tools/models developed in the frame of the previous project EFESTO by feeding them with the test data.
iv. finally, consolidate the definition of the roadmap toward a near-future development up to TRL7.

Figure *2* represents the study-logic applicable within the EFESTO-2 initiative for implementation of the planned effort.

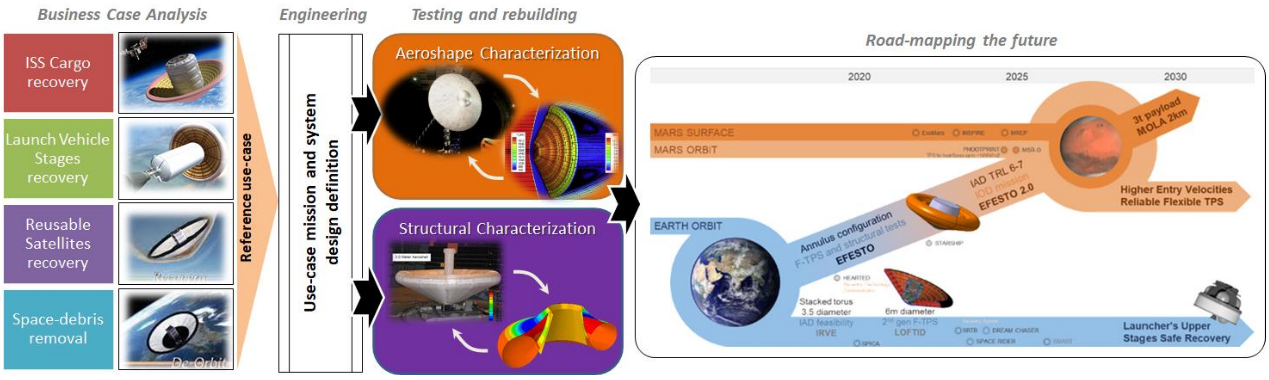

Figure 2 EFESTO-2 project study-logic

2. Business Case Analysis

2.1 BCA rational

With the objective to identify the most promising use-case application for inflatable heat shields and guide the subsequent design-study for a reference mission/system, a Business Case Analysis (BCA) has been the very first task appointed in the early stage of the EFESTO-2 project. The BCA focused on the possible range of applications potentially making use of IHSs and oriented toward re-entry and recovery of space systems meant to be reused or potentially reusable.
State of the art examples of missions potentially enabled by advanced IHSs inspiring EFESTO-2 are (Figure *3*):

- **Recovery of Launch System stages [8]**
- **Recovery of ISS cargo systems**
- **De-orbiting and recovery of Reusable satellites [9][10]**

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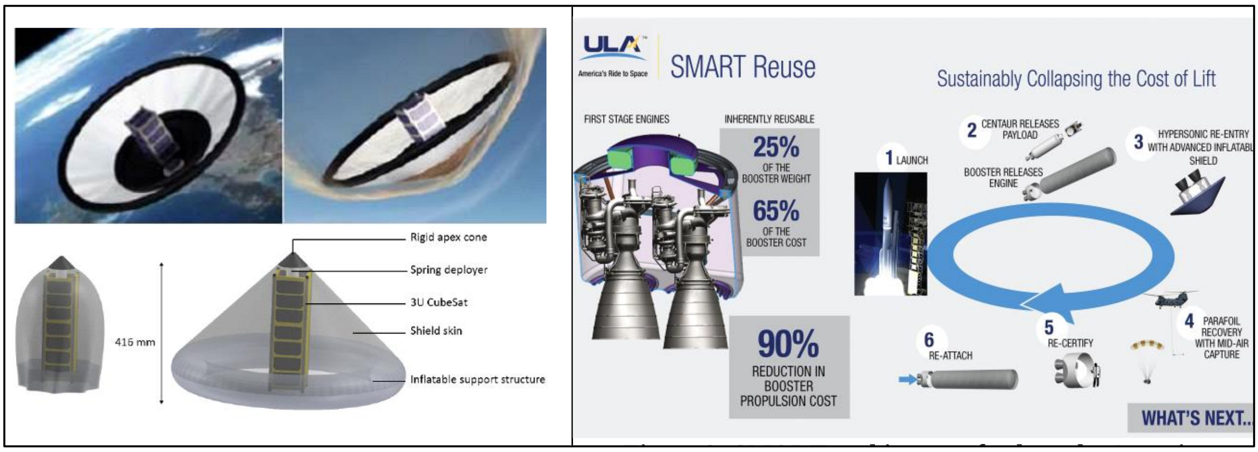

Figure 3 Potential applications with IHSs for the BCA trade-space investigation

A literature review of the advancements in space technology and exploration was appointed as preparation to the BCA, including: exploration of the socio political environment regarding the enhancement of reusability for space hardware; review of regulations for Clean Space and examination of the "Green Deal" for the space industry; study of the new space market and trends; discussion of the European Space Agency's (ESA) Agenda 2025, including its vision for the future of space activities in Europe and the importance of maintaining and expanding Europe's excellence in space.

2.2 BCA workflow and process

As depicted in Figure 4, the BCA came across an articulated workflow with different stages through implementation of an iterative process fed by evaluation of the IHSs key features on the one hand, and on the other the execution of both a quantitative and qualitative evaluation of the problem.
The iterative segment of the workflow was executed through the following steps:

- Overview of reference target markets for IHSs technology for re-entry purposes and definition of application scenarios.
- Identification of most promising commercial applications using a trade-off analysis based on market interest, market timeline, IHS complexity, and technological fit.
- Qualitative evaluation of IHSs marketable applications using SWOT (Strengths, Weaknesses, Opportunities, and Threats) and PESTEL (Political, Economic, Socio-cultural, Technological, Environmental, and Legal) frameworks, and consideration of market trends, substitutes, competing solutions, and possible customers.
- Cost-oriented assessment of the reference use-case in view of adoption of an IHS as device to perform re-entry and recovery.

The outcome of the whole process ended up with freezing a unique use-case to be referred to for the subsequent project stage (i.e. mission and system engineering).

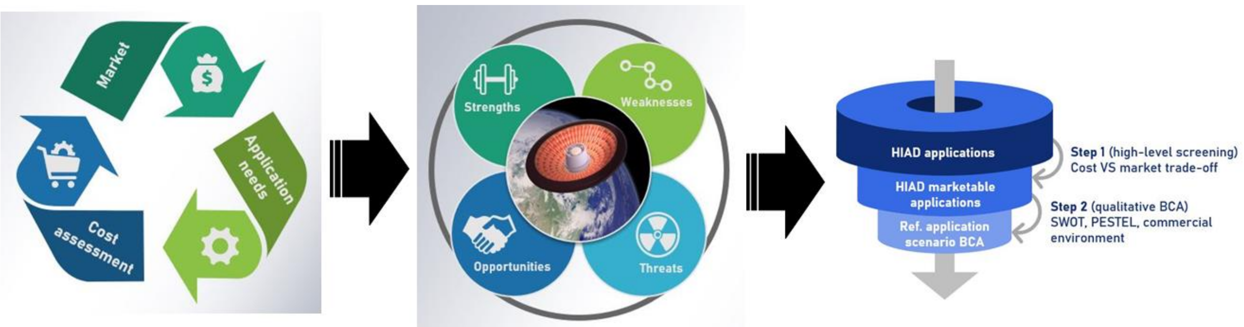

Figure 4 BCA workflow

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2.3 IHSs application scenarios under evaluation

Figure 5 displays the potential IHSs application scenarios on the estimated commercialization timeline vs. system scale domain. In particular, the X-axis variable gives the order of magnitude of the time for the IHSs product to be sold and employed, in consideration of the maturity of the scenario and the foreseen development challenges. As expected, direct correlation exists between these two aspects.
The applications have first been linked to the specific planetary re-entry scenario, clearly including Earth, Mars and Others (namely: E, M and O), and have been numbered to ease their identification along the trade-off as follows:

- **Earth scenario cases**: LV stage reusability (A1), satellite recovery (A2), small payload recovery (A3), high-speed cargo re-entry (A4), crew-return from LEO and beyond (A5), space mining cargo recovery (A6).

- **Mars/Venus scenarios cases**: Mars micro-lander (A7), Venus robotic missions (A8), Mars robotic missions (A9), Mars cargo delivery (A10), Crew delivery to Mars (11).

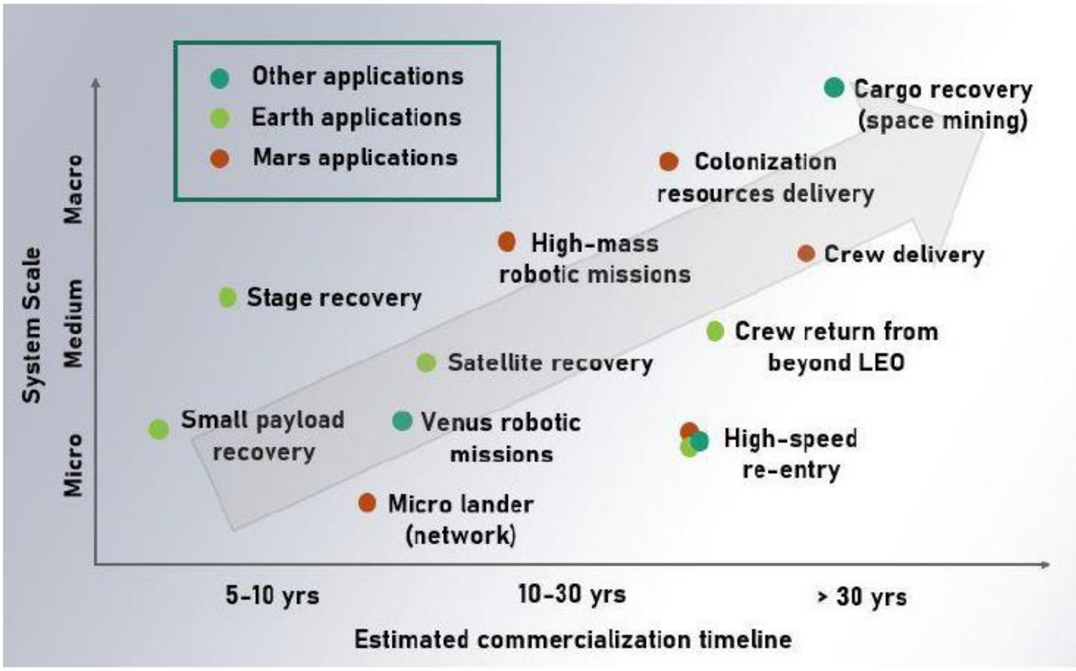

Figure 5 HIAD application scenarios overview

2.4 High-level trade-off of different potential mission scenarios

Based on the application scenario listed above, a quantitative trade-off was carried out to down-select those that are more interesting from a commercial point of view to be investigated afterwards and in more detail in the frame of a qualitative SWOT/PESTEL analysis.
The possible application scenarios have been evaluated from the point of view of technological fit of the solutions in terms of complexity compared to competitors and in terms of interest of the target market specified by the expected size and estimated profitability timeline.
A total of 4 criteria, summarised in Figure 6, were used to evaluate each alternative: Market Size (MS) identifies the rough order of magnitude in M€ of the reference market where the HIAD technology will be employed, independently of the specific use niche of the HIAD within it; Market Timeline (MT) instead estimates an investment horizon when the corresponding market shall start to be profitable; Complexity (IC) score serves as an indication of the development and production cost of the solution ; Technological Score (TS) gives an indication of how useful or necessary the IHSs solution is expected to be for that specific market applications, also in consideration of existing alternatives.
Criteria were given a relative weight of importance according to the Table 1, while alternative application scenarios were judged against criteria in a scale 1:5 as illustrated in Figure 6. Each application scenario was assessed with respect to the criteria, and it was assigned a single “commercial interest score” as combination of both technologic and market scores.

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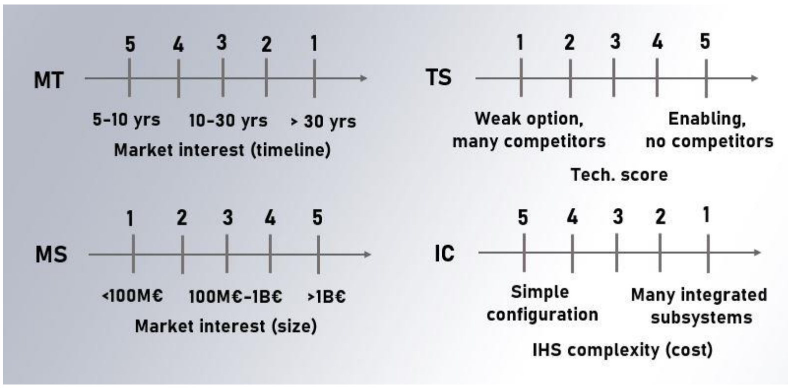

Figure 6 Trade-off criteria and satisfaction grade scale for the trade-off of alternatives

Table 1 Criteria weights of importance with respect to technology and market aspects

Technology prediction confidence		Market prediction confidence	
0.5		0.5	
K_{TS}	K_{IC}	K_{MS}	K_{MT}
0.4	0.1	0.3	0.2

The Table 2 and Table 3 collect the evaluation of each alternative with respect to the given set of criteria, while Table 4 lists the outcome of the whole trade-off. The results highlight that the stage reusability (A1), the small payload recovery (A3) and the space mining cargo recovery (A6), seem to be the promising applications where adoption of IHSs can introduce a commercially advantage. In particular, while for the A1 and A3 cases the strong point is the good market size coupled with an estimated short market timeline, for A6 the potentially huge market guarantees the high interest despite the uncertain and far in time profitability.

Also for the Mars scenario the outcome confirms the expectations, with the micro-lander (A7) and large cargo delivery (A10) resulting to be the most commercially interesting cases for the use of HIAD. Again, while for A7 the high overall score is pushed by the low complexity and the high packability advantage, for A10 it is a combination of the promising Mars colonization market size and the expected technological fit.

As conclusive remark, it is reminded that being the Horizon Europe program exclusively focused on Earth re-entry applications, then the EFESTO-2 project team decided to retain only the Earth scenario cases for the subsequent stage of the BCA. In turn, stage reusability (A1), small payload recovery (A3) and space mining cargo recovery (A6) will be analysed using a dedicated framework while instead the Mars winning applications as micro-lander (A7) and large cargo delivery (A10), despite relevant from a commercial point of view will not be discussed any further. These cases might be considered only for future possible technology development synergies.

Table 2 Earth recovery and reusability applications evaluation

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

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Table 3 Mars recovery and reusability applications evaluation

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

Table 4 Final trade-off outcome

App.	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
Score	3.85	2.05	3.65	2.90	2.50	3.50	3.70	3.05	3.00	3.55	2.65
Scena	E	E	E	O	E	E	M	O	M	M	M

2.5 SWOT/PESTEL-based selection of the best candidates among Earth re-entry applications

The preliminary trade-off analysis presented above has identified three Earth re-entry use-cases potentially characterized by a high commercial interest in view of adoption of Inflatable Heat Shields device as solution for implementation of re-entry and recovery of a space system element. Specifically, the selected use-cases are LV stage recovery (A1), small payload recovery (A3) and space mining cargo recovery (A6).
Pros and cons of these three use cases have been further assessed within the frameworks of SWOT (Strengths – Weaknesses – Opportunities - Threats) and PESTEL (Political – Economic – Social – Technological – Environmental - Legal) with the goal to support the selection of a unique reference use-case for the final step of the BCA (i.e.: profitability evaluation in consideration of the estimated costs of development and realization).
Information regarding market trends, competitors and substitute solutions were injected to support the analysis.

The PESTEL framework embedded the following assessment factors:

- **Political**: EU strategy strictly related to access-to-space autonomy and space technology independence
- **Economic**: sustainability and affordability of access to space
- **Social**: public interest for innovative technology and EU self-reliability
- **Technological**: contribution to scientific community know-how and promotion of technology grow-up
- **Environmental**: reusability vis-à-vis the green deal philosophy
- **Legal**: near-future regulations regarding disposal, re-entry and reuse of space transportation systems

The SWOT framework embedded the following assessment factors: mass and volume impact on the launch system; required increase of TRL and IRL vis-à-vis a prompt marketability; capability to trigger new solutions and services in the space transportation realm; cost penalties.

According to the SWOT/PESTEL assessment, whose details are omitted here, the best candidate use-case in the frame of Earth re-entry is the '*LV stage recovery*' because it is a sample of average size and can show characteristics relevant for both micro and macro IHSs. Also, it is something achievable and marketable in a short time with possibly fairly good profitability opportunities. Hence, the recovery of a "LV stage" will be the reference use-case for the work presented in the following section.

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2.6 Engineering-based selection of the best alternative within the LV-stage recovery use-case

Once the recovery of a 'reusable LV stage' is identified as the most promising commercially profitable scenario for an Inflatable Heat Shield, the aim is to identify a range of launch vehicle to determine the most promising class size for applying the IHS technology. In this regard, a review of potential candidates was performed in order to clarify the bandwidth of size and mass of the application.
Launch systems for which a minimum level of information available, either by literature research or by in-house crosscheck analysis, were taken into account for further review. From over 70 cases around the world identified 20 were down-selected depending on their potential, specifically commercially available launch systems in the United States or Europe at a time horizon compatible with the development time of the IHS technology.
It shall be highlighted that this selection is only motivated to obtain a higher degree of analysis depth but does not aim to exclude any launch system as potential future application of the IHS technology. Furthermore, the selected launch systems are to be understood only as a study case and definitely not as a preselection for the IHSs.
Key parameters and indicators (KPI) as length and diameter of the LV stages as well as their mass at re-entry have been considered to organize the different cases within 'classes' in order to ease the further down-selection. Analysing the KPIs it can be seen that the launch systems can roughly be classified in four clusters as summarized in Table 5.
Again, it shall be highlighted that this categorization is based only on candidates for which sufficient data was available to perform this analysis.
Based on these results, for application of the EFESTO technology, the Cluster II was selected as the most promising one because of two reasons: it exhibits the greater number of potential LV systems to which the IHS may be applied; and, in terms of size and mass, it includes cases comparatively close to that for which a significant technology development step was already taken during the EFESTO project.
In turn, the identified reference study-case for the subsequent stage of the EFESTO-2 project is the recovery of a medium-size LV stage in the range [500÷2000] kg.

Table 5 Clusters of classification for the launch systems considered

Cluster	Stage category	Re-entry mass range
I	Very small stage	Below or equal to 500 kg
II	Medium-sized stage	Above 500 kg and below or equal to 2000 kg
III	Large stage	Above 2000 kg and below or equal to 5000 kg
IV	Very large stage	Above 5000 kg

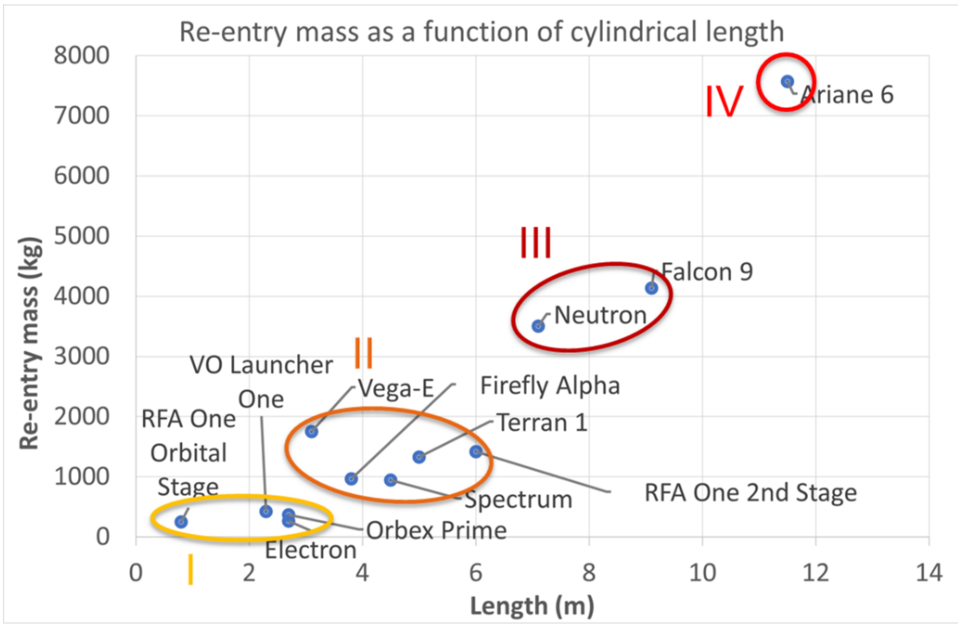

Figure 7 Re-entry mass of LVs stages as function of stage length

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3. Reference mission and system design

3.1 ConOps

Based on the Business Case Analysis investigation, the reference use-case for the Inflatable Heat Shield exploitation is the recovery of a launch vehicle upper stage. In this context, the ConOps (concept of operations) for the Inflatable Heat Shield exploitation is based on the recovery of a launch vehicle upper stage, as for Figure 8.
Basically, the ConOps is divided into two main phases:

A. The LEOP/ORBITAL, during which the launcher is meant to execute the typical tasks of the Launch and Early Operation Phase and orbit injection of the main payload (i.e.: the satellite);
B. The RECOVERY phase, during which the LV stage is recovered;

Regarding Phase 1 (LEOP/ORBITAL), after having reached a certain altitude above the ground level and having passed the ascent heat-flux peak, the separation of some masses is executed (i.e.: the LV fairing and the IHS cover) and subsequently the satellite is placed into its final orbit. Afterwards, the LV stage executes a de-orbit burn in order to decelerate and allow to place itself on a re-entry path. Before the re-entry interface point (namely an altitude of about 120km) the P/L adapter is also separated and the shield is inflated.

As for Phase 2 (RECOVERY), it is remarked that the baseline strategy for EFESTO-2 is to execute the recovery via 'Mid-Air Retrieval' by helicopter at the end of the descent sub-phase. Therefore, the very first section of the RECEOVERY phase is the hypersonic re-entry executed thanks to the inflatable heat shield itself. Then, once reached the proper conditions, a descent section is initiated by extraction of a supersonic parachute meant to decelerate passively the system trajectory. Prior to trigger the parachute extraction, the IHS is ejected since it will be no longer useful. The parachute will act down to the subsonic velocity to allow for a parafoil to be extracted and then to obtain the controlled flight toward a target area where a helicopter is expected to complete the recovery of the system.

It should be noted that the engineering effort addressed during the project focused exclusively on the re-entry part of the recovery up until the parachute triggering. This is because the key aspects for the design of the IHS and its key elements are strictly related with the re-entry only. All is about the missions' sections of descent and MAR is out-of-the-scope of the EFESTO-2 project objectives.

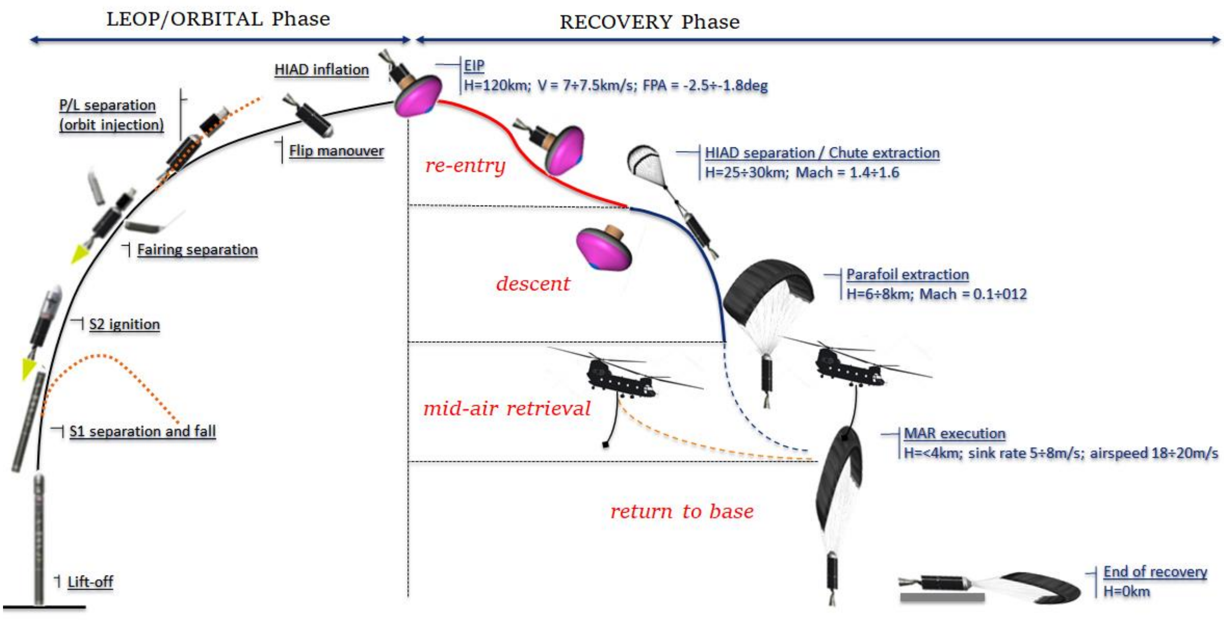

Figure 8 EFESTO-2 baseline ConOps

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3.2 Mission analysis

Based on ConOps, a parametric analysis was conducted to determine which combination of boundary conditions (BC) could offer both a good initial FPA range and compliance with system constraint. Reference and sizing trajectories were also calculated for a entry flight path angle range between -2.56° and -1.70 and ballistic coefficient of 57 kg/m². A Monte Carlo analysis was conducted to confirm that the expected peak conditions fall within the limits identified by the Local Entry Corridor (LEC) analysis for all the constraints. (Figure 9 to Figure 11),

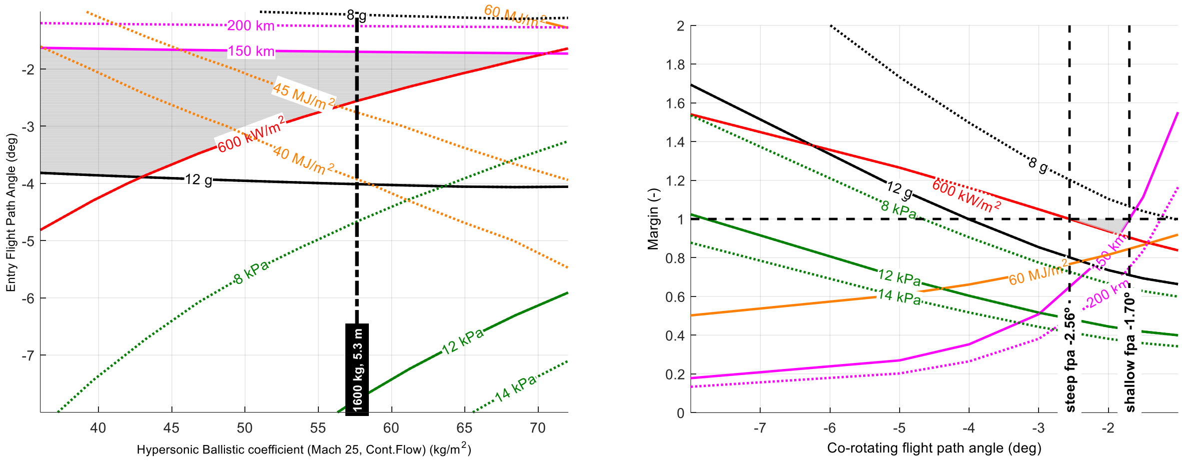

Figure 9 EFESTO-2 Local Entry Corridor (left) and flight-path-angle margin (right)

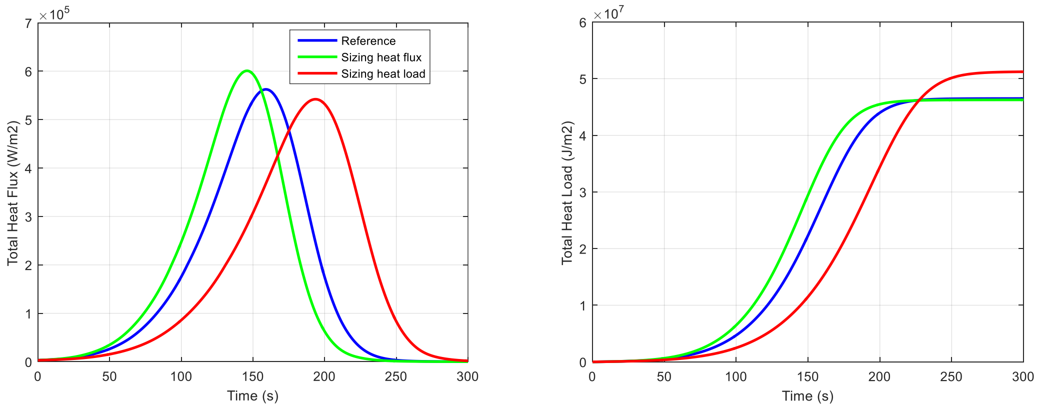

Figure 10 EFESTO-2 reference trajectories time-history: heat flux (left), heat load (right)

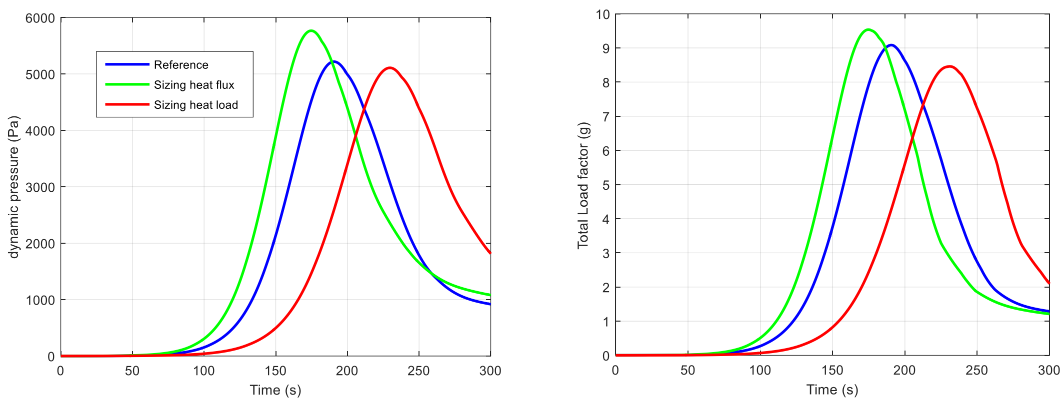

Figure 11 EFESTO-2 reference trajectories time-history: dynamic pressure (left), g-load (right)

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3.3 Aerodynamics and Aerothermodynamics

Based on EFESTO heritage, different variants of a reference aero-shape have been investigated varying key parameters as cone-angle and diameter (Figure 12). For each of aero-shape under investigation, the aerodynamics and aerothermodynamics studies are carried-out in two stages: 1) the development of an aerodynamic database for Mach number between 1.5 and 30 and angle of attack of ± 20° using engineering tools; 2) the investigation of aerodynamics and aerothermodynamics physical phenomena for selected flight point of the trajectory using CFD.
Based on the project objectives, the flight domain investigated is limited to hypersonic and supersonic flow in continuum regime where the boundary layer can be laminar or turbulent according to the Reynolds number experienced during the flight.
The aerodynamic database allows performance evaluation including trajectory envelope and flying qualities. A trade-off was performed with the 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). The baseline aero-shape chosen (option #1.1 which is a variant of option #1) for the project is the one featuring: a diameter of 5.32 m, an half cone angle of 60°, and a nose radius of 1.3 m.
CFD simulations have been also conducted, focusing on the critical flight points as maximum heat flux and maximum pressure flight points (Figure 13). The objectives were an in-depth evaluation of the aerodynamic and aerothermodynamic behaviour, as well as to get distributions of loads (pressure and heat flux) along the body in support of the system design loop, sizing of the thermal protection system (TPS) and of the inflatable structure (IS), as illustrated in Figure 14.

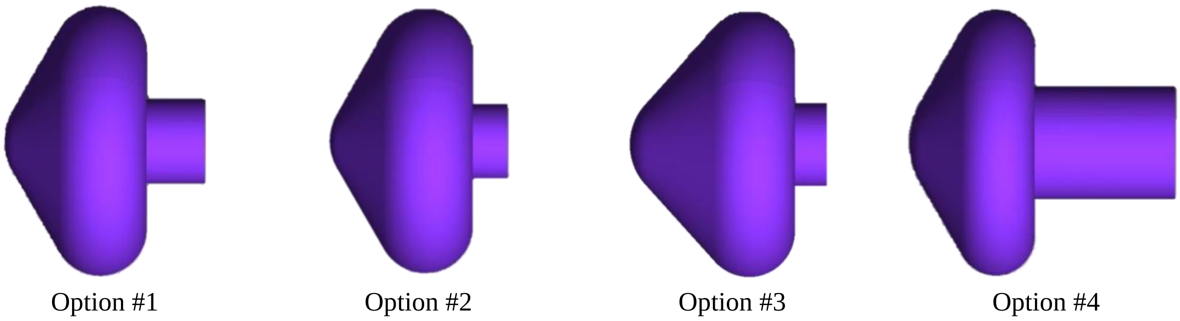

Figure 12: Various aero-shape investigated during the preliminary phase of EFESTO 2 project.

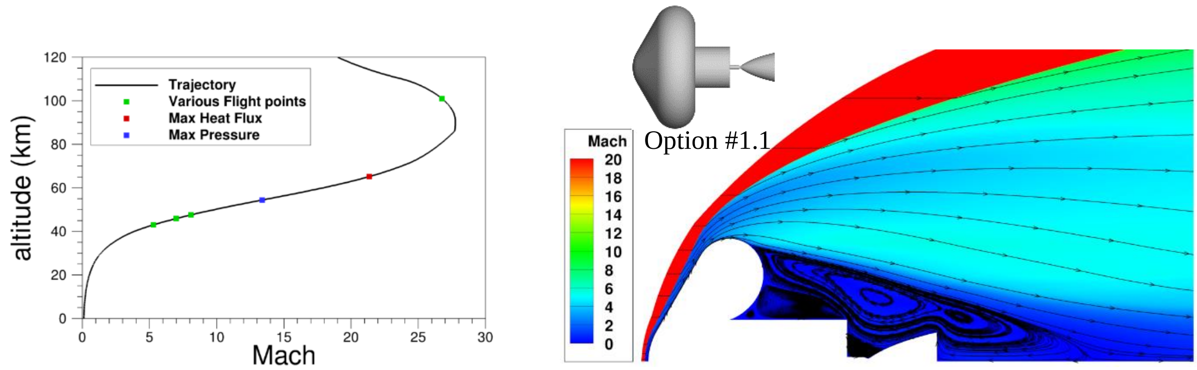

Figure 13: flight point under investigation for the CFD simulations for the reference shape (option #1.1) (left), Flow topology for the Mach 21 flight point (right).

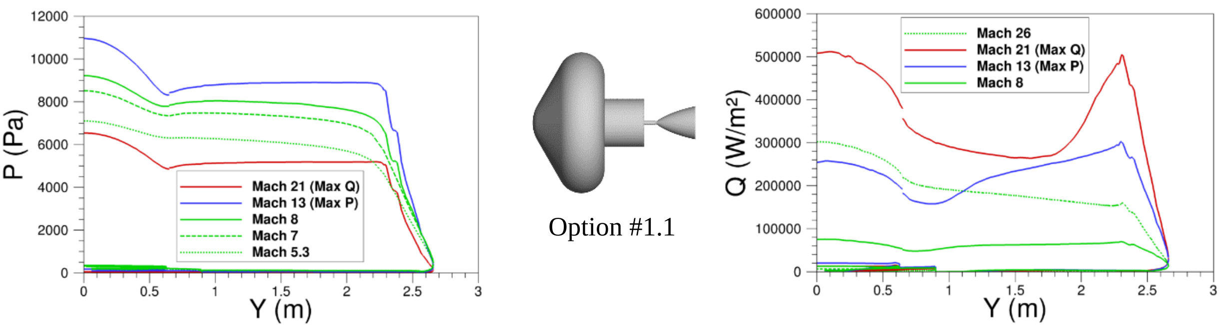

Figure 14: CFD results for the reference shape (option #1.1): pressure distribution (left), heat flux distribution (right).

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3.4 System Design

A system design loop was performed in order to obtain a coherent layout for the IHS and its subsystem integrated to the use case of the Firefly Alpha upper stage with the objective to obtain a suitable architecture, geometry and a mass estimation. The loop was initiated by performing a trade-off of the maximum diameter of the inflated heat shield. Four shapes were identified as potential candidates:

- Option 1: Diameter 5.79 m, half cone angle 60°
- Option 2: Diameter 6.40 m, half cone angle 60°
- Option 3: Diameter 5.79 m, half cone angle 48°
- Option 4: Diameter 4.29 m, half cone angle 60°

A qualitative assessment supported by an evaluation of the aerodynamic performance (see section 3.3) led to a down selection of Option 1 and 2 and finally to retain Option 1 due the estimation with a more favorable mass. This geometry was then elaborated to higher detail involving aerothermodynamics simulations (section 3.3) and mission analysis (section 3.2). These results were used for F-TPS sizing (section 3.4) and mass estimation of the inflation system and the inflatable structure complemented by a mass estimation for secondary subsystems. Further effort to reduce system mass resulted in a minor reduction in the diameter of the inflated IHS to 5.32 m. Figure 15 presents major key dimensions and an external view of the retained configuration. It shall be noted that the shape of the anulus volume is simplified to a circular cross section while it is actually tear-shaped.

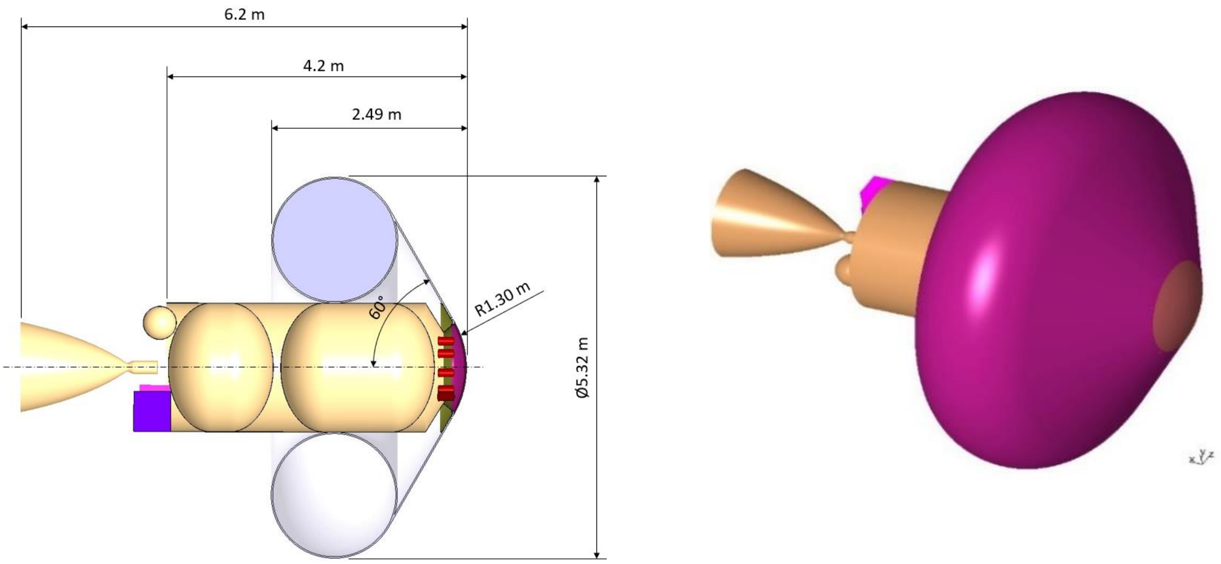

Figure 15: Key dimensions (left) and exterior view (right) of the retained configuration during re-entry.

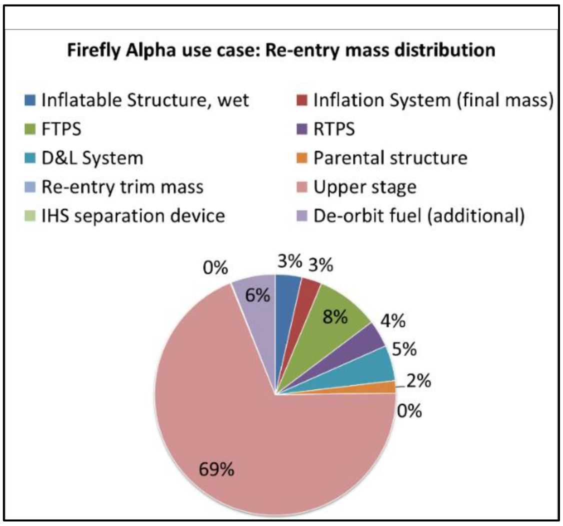

Figure 16: Mass distribution of the reference configuration during re-entry.

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The mass distribution for the re-entry configuration can be consulted in Figure 16. As can be seen the additions to the system in re-entry configuration sum up to no more than 31% of the total re-entry mass. It shall be highlighted however that all masses, including the mass of the stage itself were subjected to a 15% system margin. Furthermore, some mass additions are not included in the mass distribution when not present during re-entry such as the external HIAD cover or the dedicated payload adapter which are separated prior to re-entry.

3.4 Flexible TPS and Inflatable Structure design

The system design loop involved mainly the two key sub-systems of the Inflatable Heat Shield (i.e.: Flexible TPS and Inflatable Structure) that that underwent modeling and analysis through a dedicated effort covering thermal and structural investigation adopting design approaches, models and material databases inherited from the previous project, EFESTO.
The numerical investigation allowed to evaluate different architectural solutions and to identify the optimal ones as well as to obtain system budgets in terms of mass and volumes.
Figure 17 and Figure 18 depict the design outcomes for the two subsystems along with key elements.

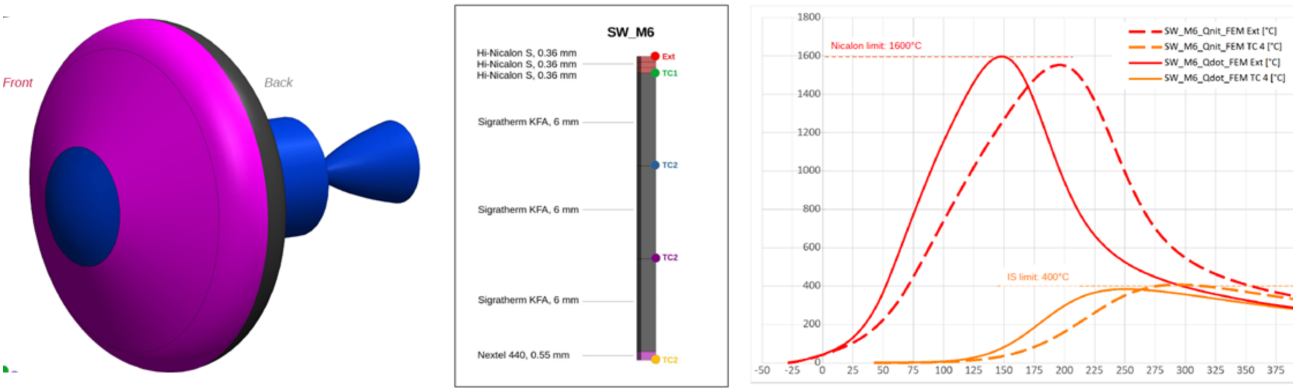

Figure 17 LV-stage and Inflatable Heat Shield integration (left), F-TPS layers and temperatures (center/right)

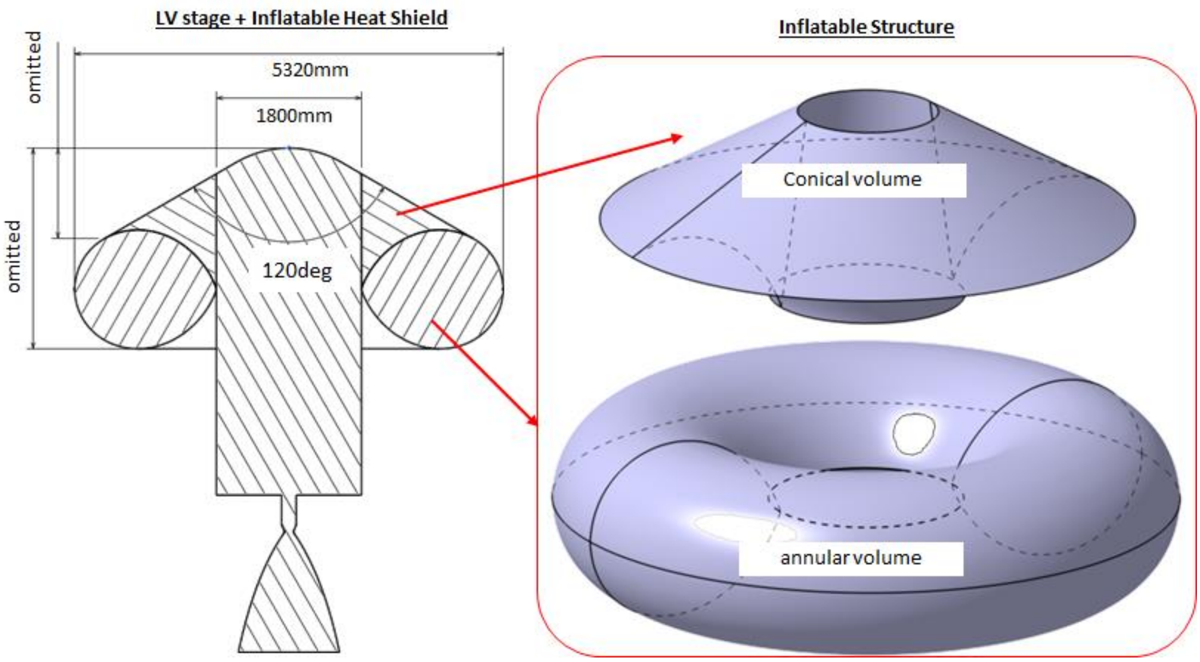

Figure 18 LV-stage and Inflatable Heat Shield integration (left), Inflatable Structure model (right)

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4. Future work: tests effort implementation and exploitation

In the near future, the project will focus on conducting ground tests, consisting of two parallel efforts:

- The first effort involves the investigation of aerodynamics and flying qualities. It will be conducted through cold-flow wind tunnel testing of subscale models at DLR-Cologne facilities (H2K, TMK). The goal is to study the dynamic and static stability of capsule-like bodies, particularly focusing on deformed shapes at relevant flow regimes.
- The second effort focuses on the mechanical characterization of the Inflatable Structure. It aims to further explore the structural behaviour of these unique structures, with a focus on modal survey, stiffness, deformation measurements, and morphing observation.

The aerodynamics and flying qualities investigation will involve the design and manufacturing of wind tunnel models that replicate the deformed shape of the Inflatable Heat Shields at critical points of the trajectory (Figure 19).
Two wind tunnel test (WTT) campaigns are planned: one at the H2K facility to cover static stability tests in the Mach number range of 5.3 to 7, and another at the TMK facility to cover both static and dynamic stability tests in the Mach number range of 1.4 to 4, with variations in Reynolds number. The WTT tasks will include the characterization of surface properties, calibration, integration of strain gauge balances for static tests, and free oscillation devices for dynamic stability tests. The collected experimental data will be used to update the Aerodynamic Database and cross-correlate with computational fluid dynamics (CFD) simulations to reassess trajectory and flying quality.

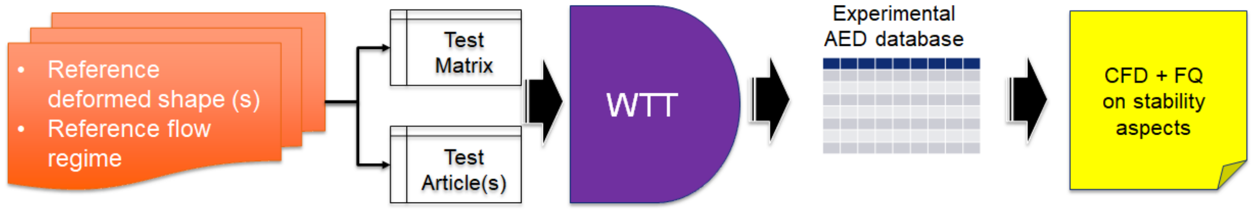

Figure 19 Reference flow of wind-tunnel testing for the EFESTO-2 tasks

Regarding the mechanical characterization of the Inflatable Structure, a ground demonstrator with a diameter of 2.4m will be utilized, along with a dedicated test rig developed in the previous EFESTO project (Figure 20). This extended test campaign aims to improve the correlation between numerical and experimental results, including dynamic tests to evaluate the system's behavior under dynamic loading by means of hammers (tuned for low frequency search) and with specific shakers (to apply localized periodical solicitation at controlled frequency). The demonstrator will be instrumented with accelerometers (monoaxial and triaxial) to identify the modal behavior, and photogrammetric reconstruction will be employed to analyze the deformed shape under load and calculate the applied axial force.

Figure 20 Static-load testing of the EFESTO inflatable heat shield ground demonstrator

After the completion of the test effort, a numerical-experimental cross-correlation will be performed to compare the results with numerical models and enhance the predictive capability at the material, structural, and aerothermodynamics levels. Successful testing and model revision will improve the confidence level in design and simulation tools, increase knowledge about inflatable heat shield technology, and lead to enhanced performance in the design, manufacturing, and testing of these complex systems. The project will conclude with the development of a roadmap towards technology consolidation up to TRL7.

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5. Conclusive remarks

Building upon the achievements of the previous EFESTO project, the EFESTO-2 project aims to further advance European expertise in the field of Inflatable Heat Shields (IHS). The project, initiated in November 2022, has completed its initial stage, which involved conducting a Business Case Analysis and engineering a reference mission/system design for an IHS solution tailored to a specific use-case in Earth re-entry and reusable space transportation systems.

This paper provided an overview of the project's objectives, scope, and ongoing activities, as well as a glimpse of the planned work for the next two years. The Business Case Analysis revealed that the recovery of LV stages in the small launcher mass class/size range (500-2000 kg) appears to be the most promising application for IHS. Despite the mass penalty associated with employing an IHS-based solution for stage recovery, the cost reduction enabled by stage reuse continues to make it commercially viable and environmentally beneficial.

Additionally, the project successfully developed a conceptual engineered adaptation of an IHS for the re-entry and recovery of a generic LV stage within the specified mass/size class. This conceptual adaptation was translated into a reference design baseline, including the mission and system requirements, which will serve as a foundation for the extensive test effort planned in the second phase of the project.

The project is currently progressing according to plan, aiming to achieve an important milestone before the summer of 2023. The next step involves organizing and conducting the test campaigns, which will provide valuable data to improve the confidence level of numerical models and enhance the consortium's knowledge in this strategic field. Additional papers will be produced to document the second half of the project and disseminate the findings.

Acknowledgement

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