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ORIGINAL ARTICLE

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 analysing 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 2 years, positioning it within the European re-entry technology roadmap. This project has received funding from the European Union's Horizon Europe program (grant agreement No 1010811041).

Keywords Inflatable heat shields · Re-entry · Reusability · Reusable launchers

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 Fig. 1, [1]).

In that perspective, state-of-the-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 shields are needed to overcome the current design limits and extend the applicability range. The innovation relies on Flexible Thermal Protection System (**F-TPS**) and Inflatable Structure (**IS**) solutions (or Inflatable Heat Shields—**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 in the TRL from 3 to 4/5 [5–7], with a broad scope of activities ranging from mission and system level design to 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

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Fig. 1 Rigid heat shield (MSL) and inflatable heat shield concept (HEART, NASA)

further increase the TRL to a maturation such as to allow 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 focussed 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 towards 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.

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 focussed on the possible range of applications potentially making use of IHSs and oriented towards 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 shown in Fig. 3:

- Recovery of Launch System stages [8]

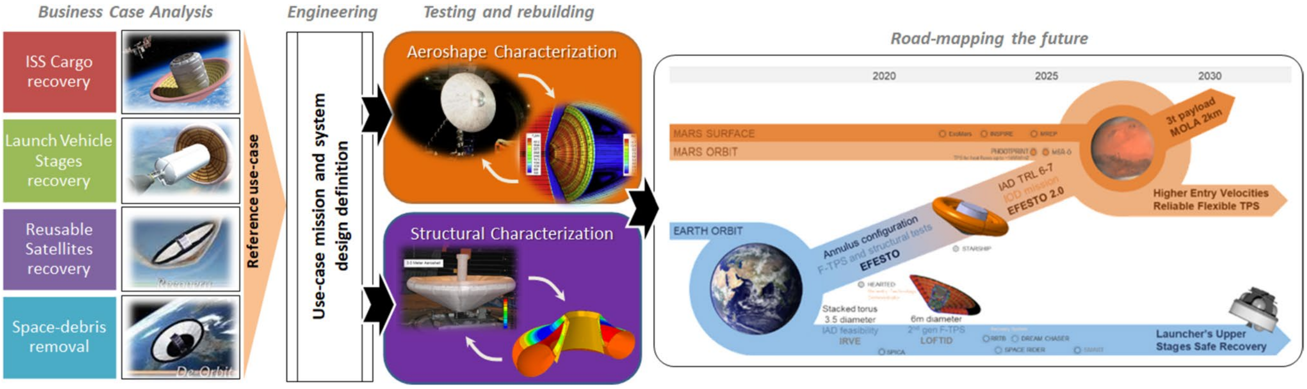


Fig. 2 EFESTO-2 project study logic

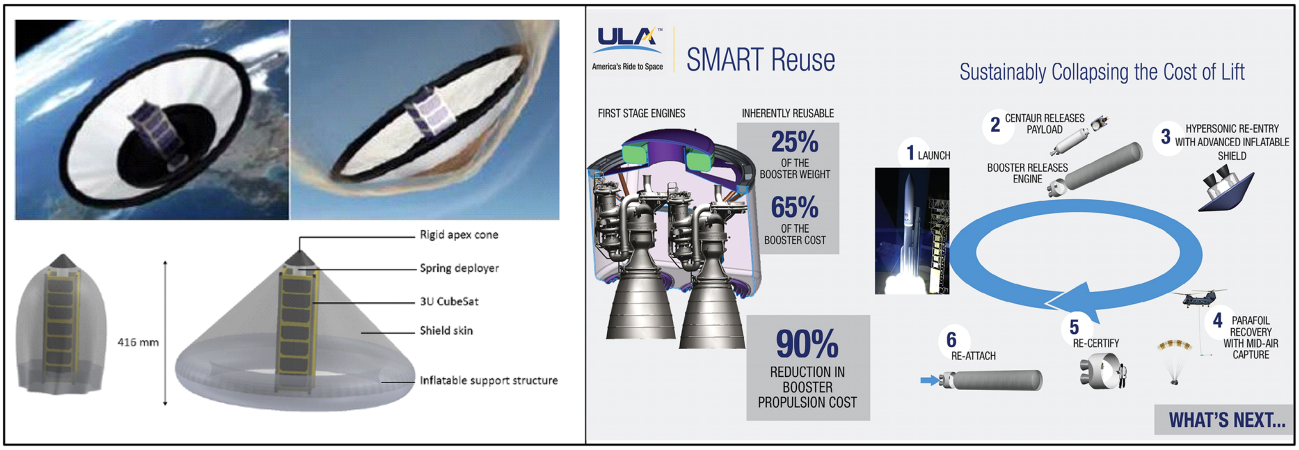


Fig. 3 Potential applications with IHSs for the BCA trade-space investigation

- Recovery of ISS cargo systems
- De-orbiting and recovery of Reusable satellites [9, 10]

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 Fig. 4, the BCA came across an articulated workflow with different stages through implementation of an iterative process fed by evaluation of the IHS 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 the most promising commercial applications using a trade-off analysis based on market interest, market timeline, IHS complexity and technological fit.
- Qualitative evaluation of IHS 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).

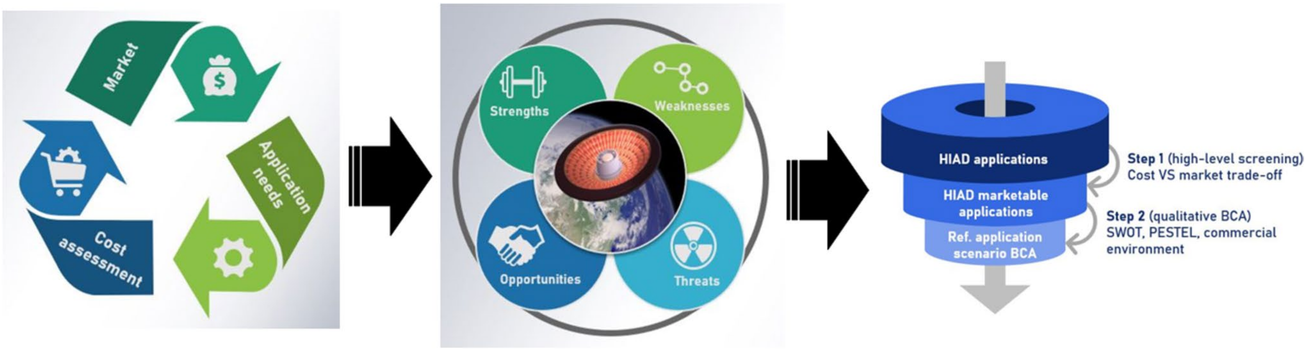


Fig. 4 BCA workflow

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)

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 (TS, IC, MS, MT), summarised in Fig. 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.

The assumed weight of importance of the criteria is obtained by a combination of 4 gains (KXY) or factors, each factor being assigned a value as reported in Table 1.

The relative importance between the market and the technological aspects is assumed to be fairly equivalent (0.5, 0.5), whilst sort of "rule-of-thumb perception" is applied with respect to identification of "criteria relative weight of importance" for the single factors. (e.g.: KTS is considered more important than KIC).

Afterwards, any HIAD application was judged vis-à-vis each criterion based on a "5-value grade scale", with a simple logic as: the lower bound value is assigned when the alternative is considered to be "very poorly satisfactory"

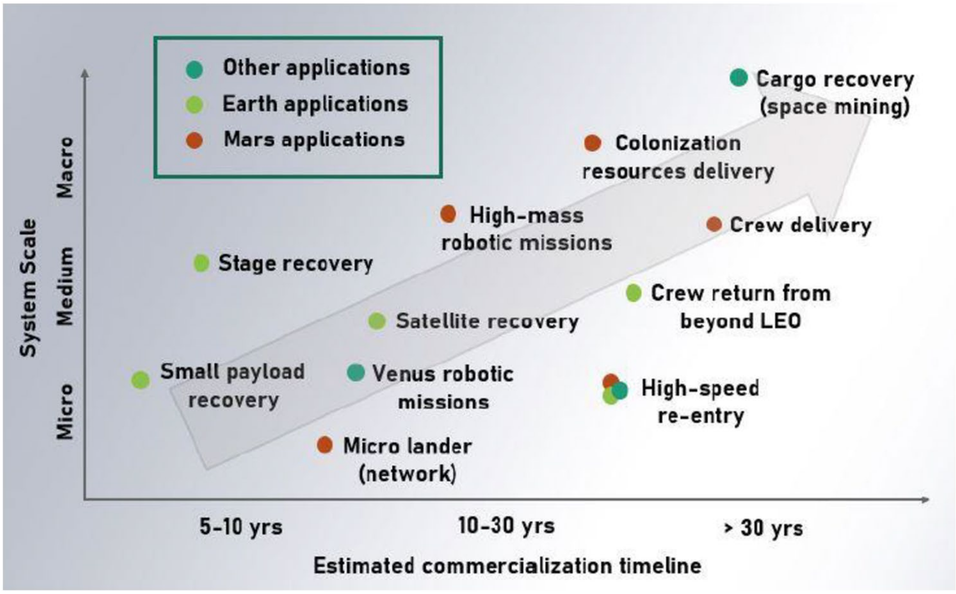


Fig. 5 HIAD application scenarios overview

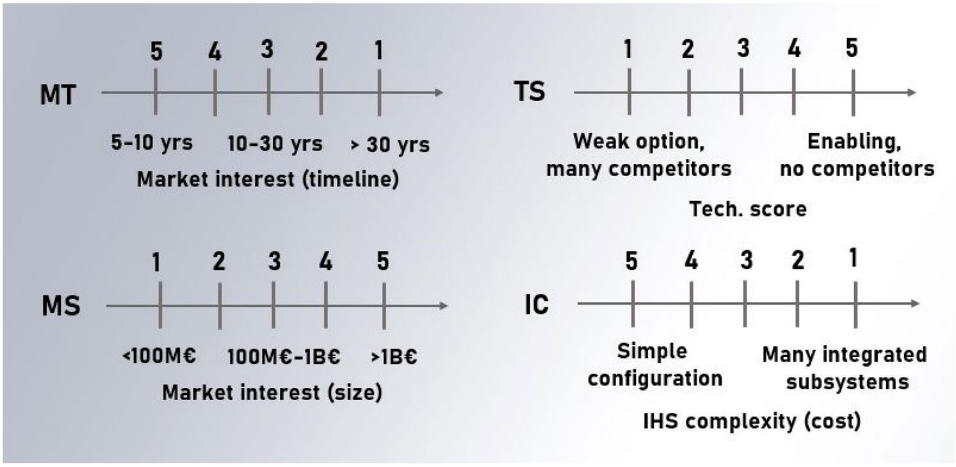
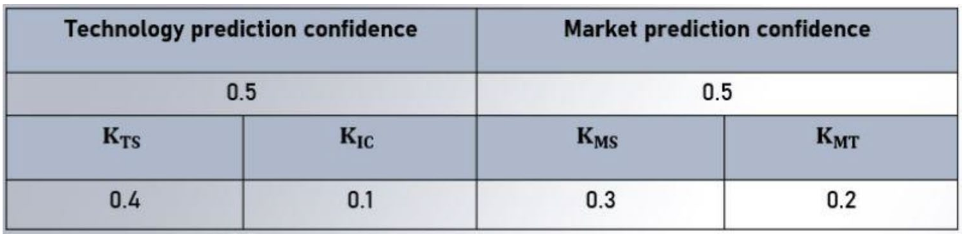


Fig. 6 Trade-off criteria and satisfaction grade scale for the trade-off of alternatives

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

towards the criterion; and, on the contrary, the upper bound value is assigned when the satisfaction grade is deemed very high.

The 5-value scale for each criterion is reported in Fig. 6.

Based on the above, each alternative is first assigned a set of two couple-score, one couple related to the technical evaluation [TS, IC]; and the second related to the market evaluation [MS, MT]. Any single score is assigned based on the self-evaluation the project team was able to produce based either on project perception or coarse analysis of public available data or a combination thereof.

Second, for each alternative, a total score is derived to obtain the eventual commercial interest associate to that alterative. For this to be done, the following formula is applied:

$$\mathrm{APPLICATIONscore} = \mathrm{TSvalue} * \mathrm{KTS} + \mathrm{ICvalue} * \mathrm{KIC} + \mathrm{MSvalue} * \mathrm{KMS} + \mathrm{MTvalue} * \mathrm{KMT}.$$

For the sake of clarity, the alternative A1 (Launcher stage recovery) is evaluated as worth as:

- 3.5 w.r.t. technology; and 3.5 w.r.t. complexity; hence it is [TS = 3.5, IC = 3.5]
- 4.0 w.r.t. market size; and 4.5 w.r.t. market timeline; hence it is [MS = 4.0, MT = 4.5]

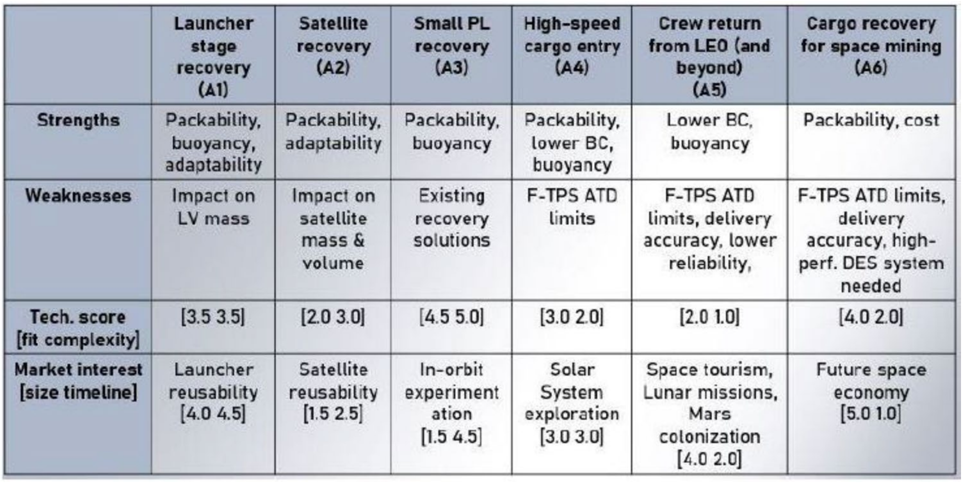
Table 2 and Table 3 collect the evaluation scores of each alternative in terms of gains, whilst Table 4 lists the outcome of the whole trade-off as result of the formula above. In particular, Table 2 refers to Earth-oriented applications, whilst Table 3 refers to Mars-oriented applications.

The results in Table 4 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, whilst for the A1 and A3 cases, the strong point is the good market size coupled with an estimated short market timeline, and 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, whilst 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 colonisation market size and the expected technological fit.

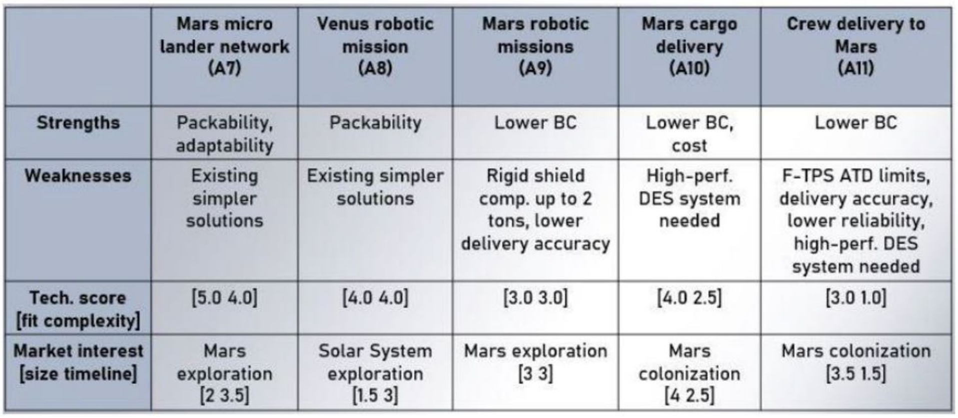
As conclusive remark, it is reminded that being the Horizon Europe program exclusively focussed on Earth re-entry applications, then the EFESTO-2 project team decided to retain only the Earth scenario cases for the subsequent stage of the BCA. In turn, stage reusability (A1), small payload recovery (A3) and space mining cargo recovery (A6) will be analysed using a dedicated framework whilst instead the Mars winning applications as micro-lander (A7) and large cargo delivery (A10), despite relevant from a commercial

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 experiment ation [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]

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

point of view will not be discussed any further. These cases might be considered only for future possible technology development synergies.

2.5 SWOT-/PESTEL-Based Selection of the Best Candidates Amongst Earth Re-Entry Applications

The preliminary trade-off analysis presented above has identified three Earth re-entry use cases potentially characterised 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 realisation).

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

In the frame of the PESTEL assessment, a solution is evaluated as “preferable” when: minimises mass and volume impact on the launch system; minimises the delta-TRL needed for its eventual exploitation vis-à-vis a prompt marketability; exhibits great growth potential and capability to trigger new solutions and services in the space transportation realm; minimises cost penalties.

The SWOT framework embedded the following assessment factors:

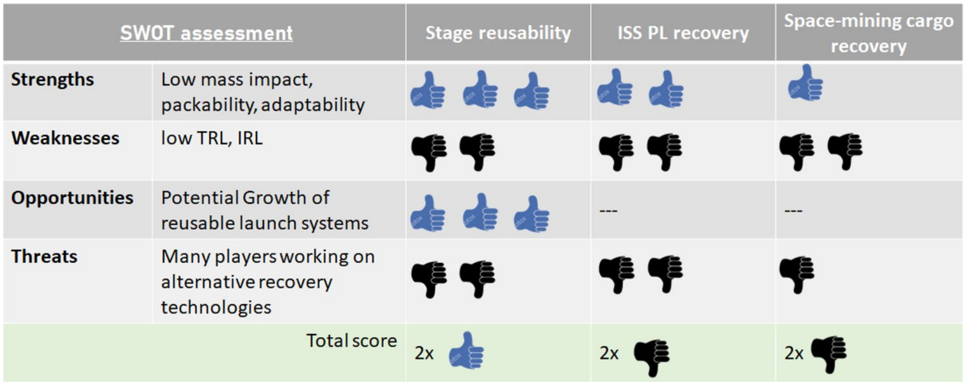
- Political and economic factors as EU and ESA favour with respect to reusability of launch systems and the positive impact of re-sue for launch cost reduction
- Public interest for innovative technology and perception of EU autonomy needs in the field of innovative technologies as the ones relate d to space applications
- Contribution to scientific community know-how
- Compatibility with the green deal philosophy
- Compatibility with future legal aspects regarding LV stage disposal, re-entry and reuse

Results of PESTEL and SWOT evaluation, summarised in Tables 5, 6, respectively, show that the best candidate use case in the frame of Earth re-entry is the ‘*LV stage recovery*’, and it will be the reference use case for the work presented in the following section.

2.6 Engineering-Based Selection of the Best Alternative Within the LV-Stage Recovery use Case

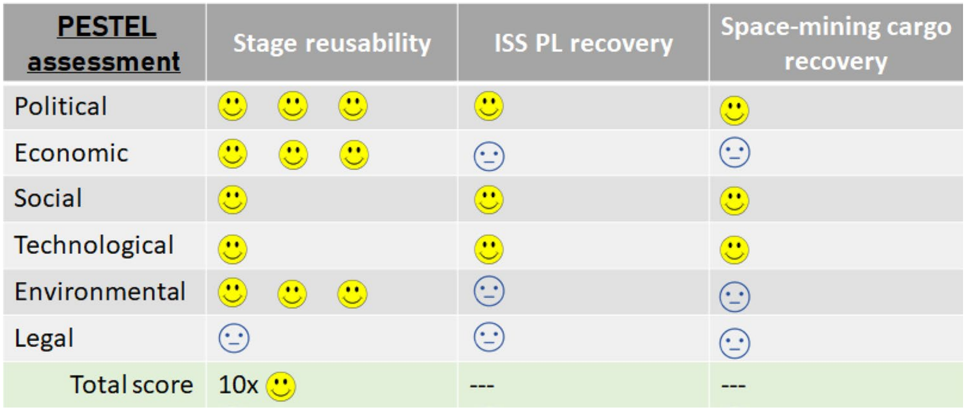
Once the recovery of a ‘reusable LV stage’ has been identified as the most promising commercially profitable scenario for an Inflatable Heat Shield, the aim is to identify a range of launch vehicle to determine the most promising class size for applying the IHS technology. In this regard, a review of potential candidates was performed in order to clarify the bandwidth of size and mass of the application.

Table 5 SWOT assessment outcome



SWOT assessment		Stage reusability	ISS PL recovery	Space-mining cargo recovery
Strengths	Low mass impact, packability, adaptability	👍 👍 👍	👍 👍	👍
Weaknesses	low TRL, IRL	👎 👎	👎 👎	👎 👎
Opportunities	Potential Growth of reusable launch systems	👍 👍 👍	---	---
Threats	Many players working on alternative recovery technologies	👎 👎	👎 👎	👎
	Total score	2x 👍	2x 👎	2x 👎

Table 6 PESTEL assessment outcome



PESTEL assessment	Stage reusability	ISS PL recovery	Space-mining cargo recovery
Political	🙂 🙂 🙂	🙂	🙂
Economic	🙂 🙂 🙂	😐	😐
Social	🙂	🙂	🙂
Technological	🙂	🙂	🙂
Environmental	🙂 🙂 🙂	😐	😐
Legal	😐	😐	😐
Total score	10x 🙂	---	---

Launch systems for which a minimum level of information is available, either by literature research or by in-house crosscheck analysis, were considered 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 a potential future application of the IHS technology. Furthermore, the selected launch systems are to be understood only as a study case and 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 organise the different cases within 'classes' in order to ease the further down-selection. By analysing the KPIs, it is possible to appreciate that the launch systems can roughly be classified in four clusters as summarised in Table 7.

Again, it shall be highlighted that this categorization is only based on candidates for which sufficient data were available to perform this analysis.

As a result, for the application of EFESTO technology, the Cluster II was selected as the most promising one, because of two reasons: on the one hand, it exhibits the greater number of potential LV systems to which the IHS may be applied; on the other hand, in terms of size and mass, it includes cases comparatively close to that for which a significant technology development step was already taken into account 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 within the range [500–2000] kg.

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 Concept of Operations (ConOps) for the Inflatable Heat Shield exploitation relies on the recovery of a launch vehicle upper stage as for Figs. 7, 8.

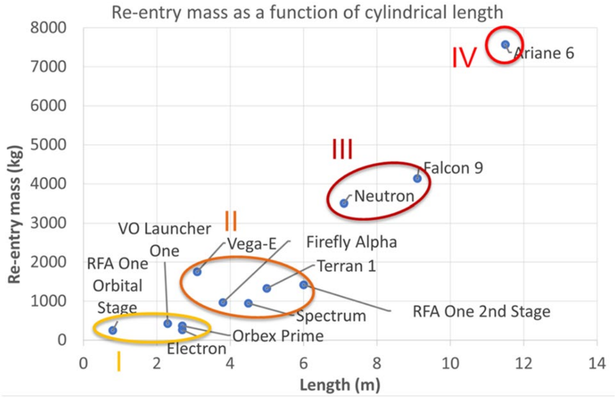


Fig. 7 Re-entry mass of LVs stages as a function of stage length

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 120 km), 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 RECOVERY 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 to decelerate passively the

Table 7 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 500 kg and below or equal to 5000 kg
IV	Very large stage	Above 5000 kg

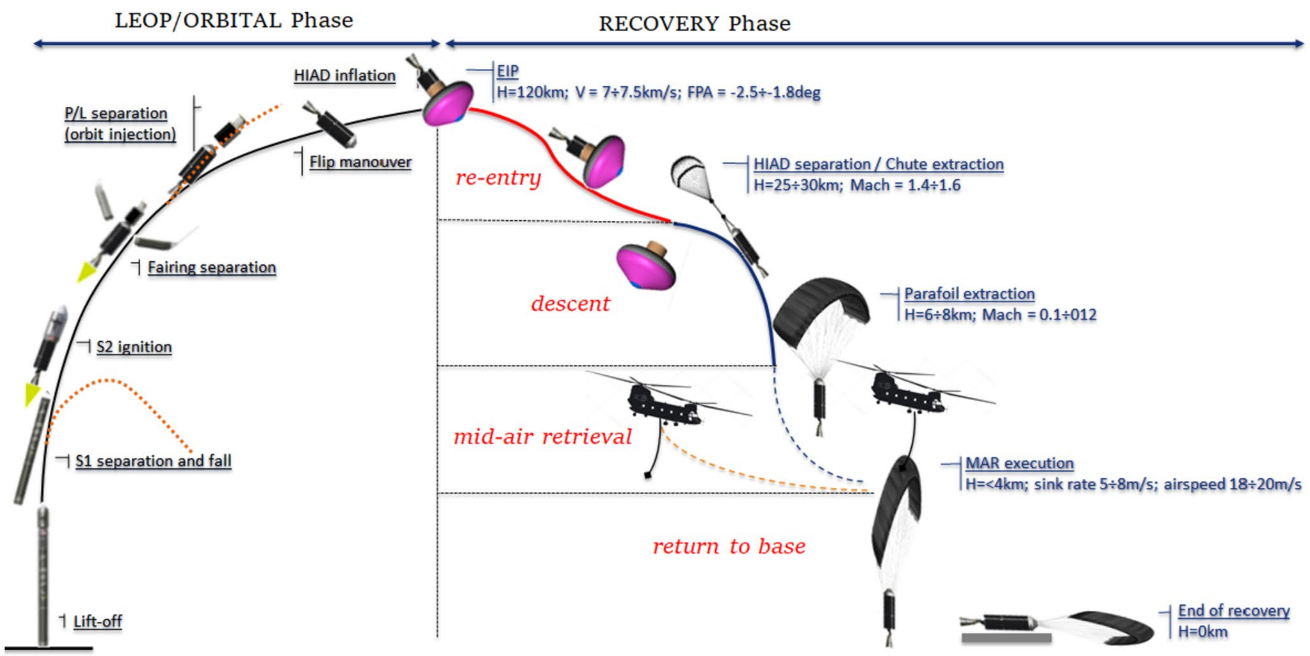


Fig. 8 EFESTO-2 baseline ConOps

system trajectory. Prior to triggering 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 a parafoil to be extracted and then to obtain the controlled flight towards 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 focussed exclusively on the re-entry part of the recovery 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. It is all about the missions' sections of descent, and MAR is out of the scope of the EFESTO-2 project objectives.

3.2 Mission Analysis

Based on ConOps, a mission design loop was executed through a parametric analysis conducted to determine which combination of ballistic coefficient (BC) and flight Path Angle (FPA) range could allow a re-entry trajectory in compliance with system constraints listed in Table 8, namely aerothermal and mechanical loads limits.

The 2-D local entry corridor (LEC) analyses were conducted by simulating multiple trajectories with variations in the entry co-rotating flight path angle and the ballistic coefficient. The variation in the ballistic coefficient was utilised also in tight relation with aeroshape design to assess different vehicle sizes and shapes.

The Local Entry Corridor (LEC) analyses were performed with a predetermined landing site located on Kourou (French Guyana) and an inertial re-entry velocity of approximately 7.5 km/s.

Table 8 LEC constraints

Constraint	D10 Req. on F-TPS region	Value on stagnation area
Heat flux (kW/m^2)	450	600
Heat losd (MJ/m^2)	45	60
Axial load factor (earth g's)	12	12
Entry dynamic pressure (kPa)	12	12
Max. land. accuracy (km)	150	150

Reference and sizing trajectories were also calculated for an entry flight path angle range between -2.56° and -1.70° and ballistic coefficient of 57 kg/m^2. Those are in fact the extreme FPA values for which two limits design conditions are reached, respectively (max q dot and max landing accuracy) as it can be noticed in Fig. 9.

Sizing trajectories correspond to shallow case limiting the LEC superiorly (by landing accuracy constraint), and to step case limiting inferiorly (by heat flux constraint). The reference trajectory is the balanced one corresponding the maximum margin in terms of FPA.

Furthermore, 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.

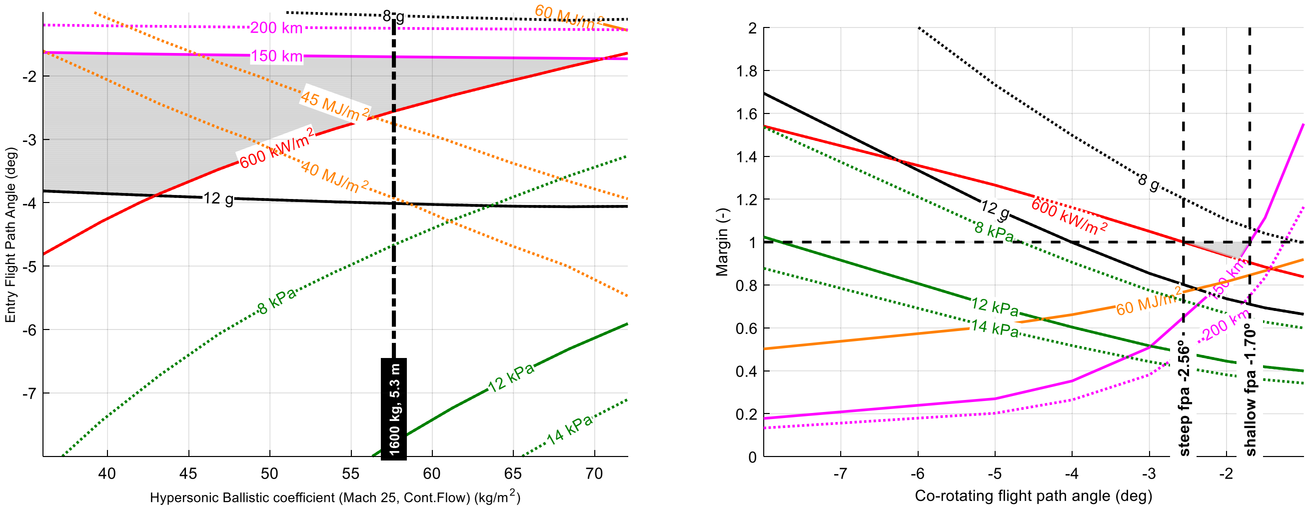


Fig. 9 EFESTO-2 Local Entry Corridor (left) and flight path angle margin (right)

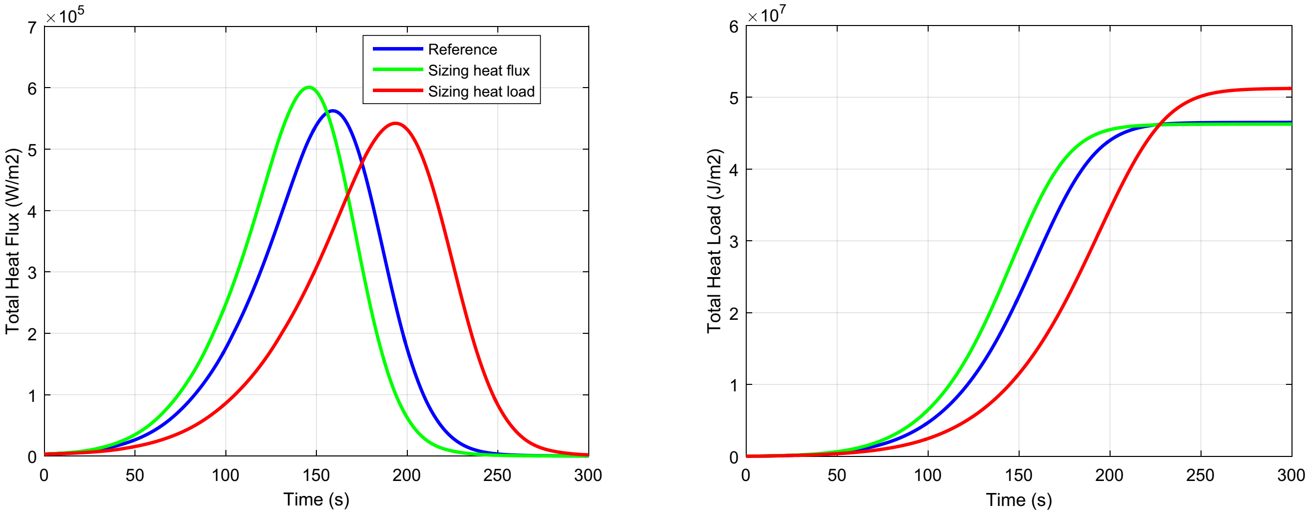


Fig. 10 EFESTO-2 reference trajectories time history: heat flux (left), heat load (right)

Results of Figs. 9, 10, 11 refer to the most promising combination of shape size and entry conditions that allow us to obtain an existing flight corridor for a feasible shape. Key parameters represented are the flight corridor map; the time history of different loads (heat flux, heat load, dynamic pressure and g-load).

3.3 Aerodynamics and Aerothermodynamics

Based on EFESTO heritage, different variants of a reference aero-shape have been investigated by varying key parameters as cone angle and diameter (Fig. 12). For each of aero-shape under investigation, the aerodynamics and aerothermodynamics studies have been 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 maximisation 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, focussing on the critical flight points as maximum heat flux and maximum pressure flight points (Fig. 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 Fig. 14.

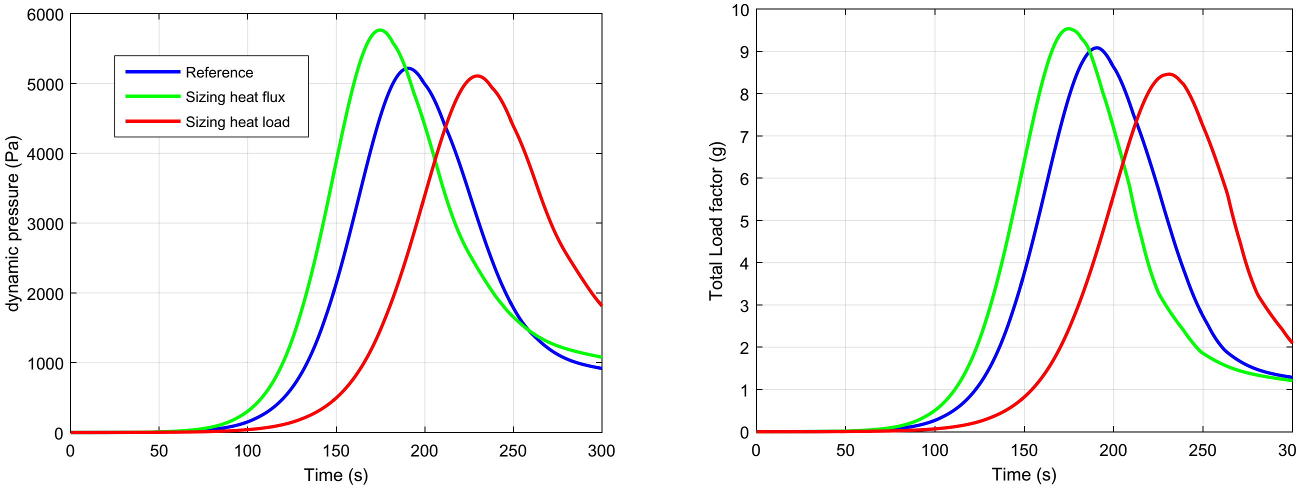
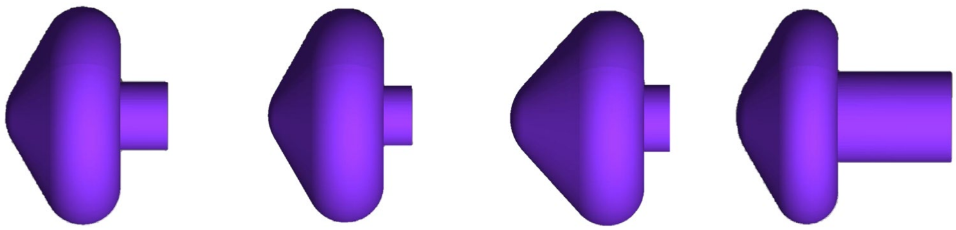


Fig. 11 EFESTO-2 reference trajectories time history: dynamic pressure (left), g-load (right)

Fig. 12 Various aero-shapes investigated during the preliminary phase of EFESTO 2 project



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

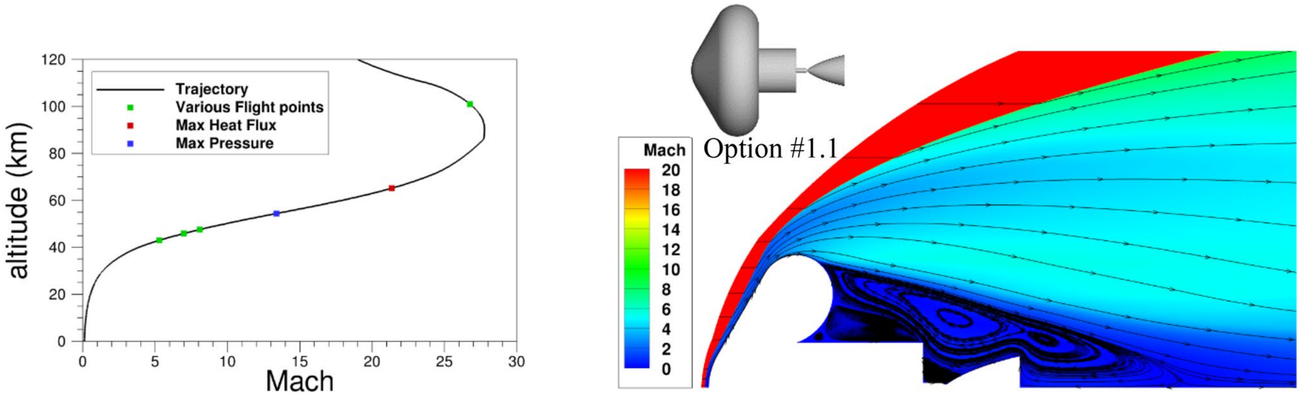


Fig. 13 Flight point under investigation for the CFD simulations for the reference shape (option #1.1) (left), flow topology for the Mach 21 flight point (right)

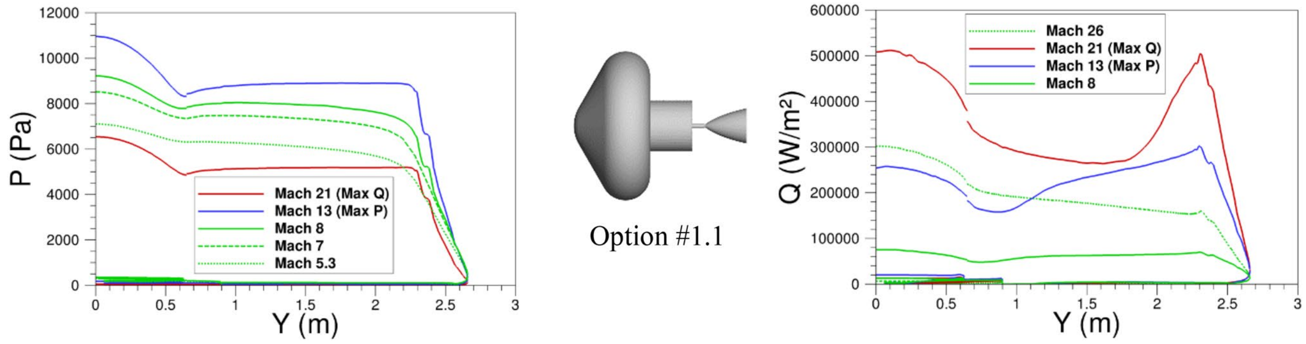


Fig. 14 CFD results for the reference shape (option #1.1): pressure distribution (left), heat flux distribution (right)

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 Sect. 3.3) led to a down-selection of Options 1 and 2 and finally to retain Option 1, due the estimation with a more favourable mass. This geometry was then elaborated to higher detail, involving aerothermodynamics simulations (Sect. 3.3) and mission analysis (Sect. 3.2). These results were used for F-TPS sizing (Sect. 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 annulus volume is simplified to a circular cross section, whilst it is actually tear-shaped.

The mass distribution for the re-entry configuration can be consulted in Fig. 16. As it can be seen, the additions to the system in re-entry configuration sum up to no more

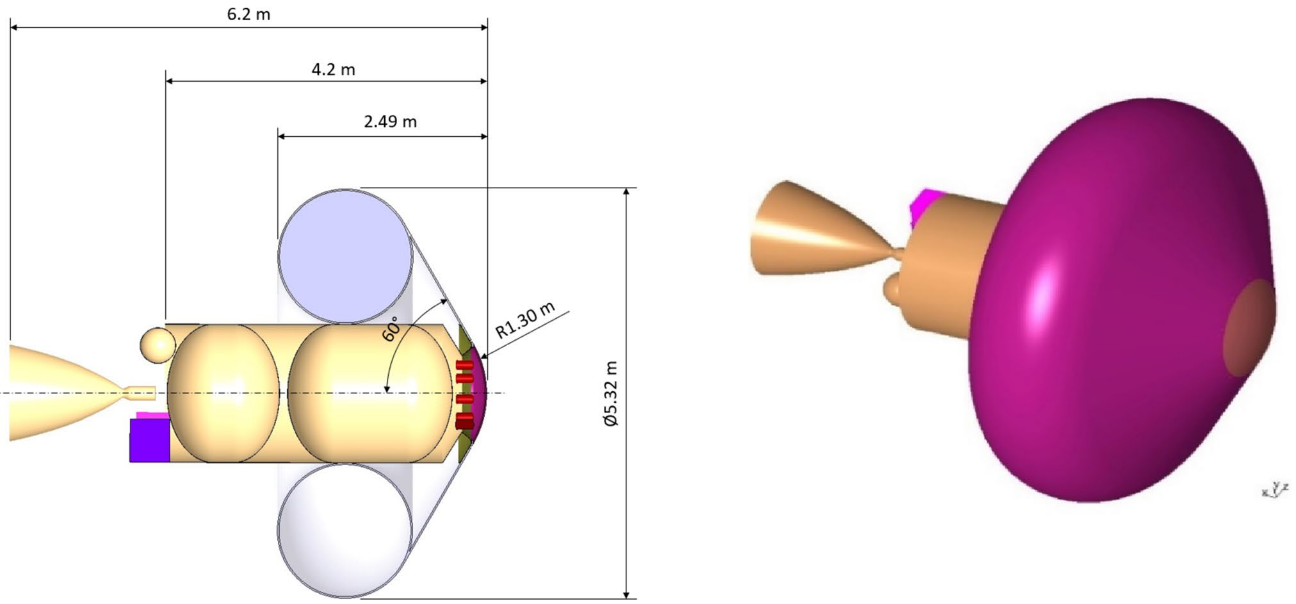


Fig. 15 Key dimensions (left) and exterior view (right) of the retained configuration during re-entry

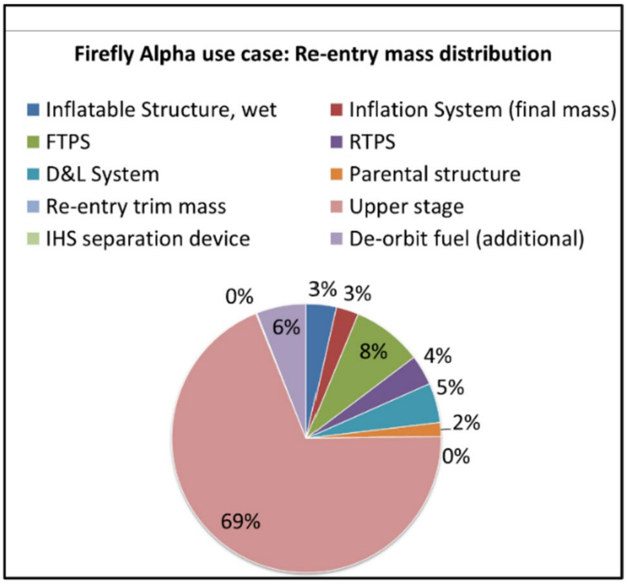


Fig. 16 Mass distribution of the reference configuration during re-entry

than 31% of the total re-entry mass. It shall be highlighted however that all masses, including the one 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.

3.5 Flexible TPS and Inflatable Structure Design

The system design loop mainly involved the two key subsystems of the Inflatable Heat Shield (i.e.: Flexible TPS and Inflatable Structure) that underwent modelling and analysis through a dedicated effort, covering thermal and structural investigation by adopting design approaches, models and material databases inherited from the previous project, EFESTO.

The numerical investigation allowed the evaluation of different architectural solutions, also ensuring the identification of the optimal ones as well as to obtain system budgets in terms of mass and volumes.

Figure 17 and Fig. 18 depict the design outcomes for the two subsystems along with key elements.

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, involving the investigation of aerodynamics and flying qualities, will be conducted through cold-flow wind tunnel testing of subscale models at DLR-Cologne facilities (H2K, TMK). For that purpose, it will study the dynamic and static stability of capsule-like bodies, particularly focussing on deformed shapes at relevant flow regimes.
- The second effort, focussing on the mechanical characterisation of the Inflatable Structure, will aim at further exploring 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 (Fig. 19).

Two wind tunnel test (WTT) campaigns have been planned: the first one, at the H2K facility, to cover static stability tests in the Mach number range of 5.3 to 7, and the other one, at the TMK facility, to cover both static and

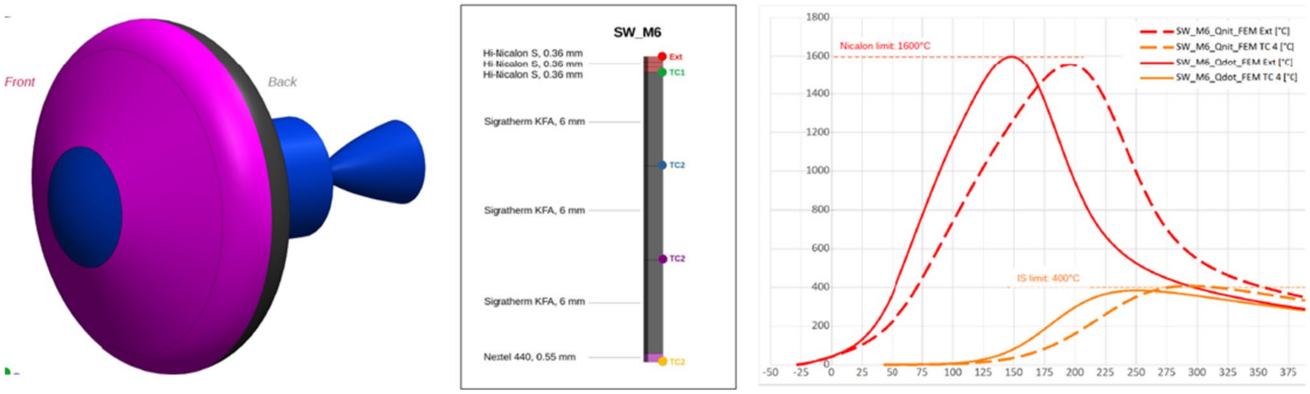


Fig. 17 LV stage and Inflatable Heat Shield integration (left), F-TPS layers and temperatures (centre/right)

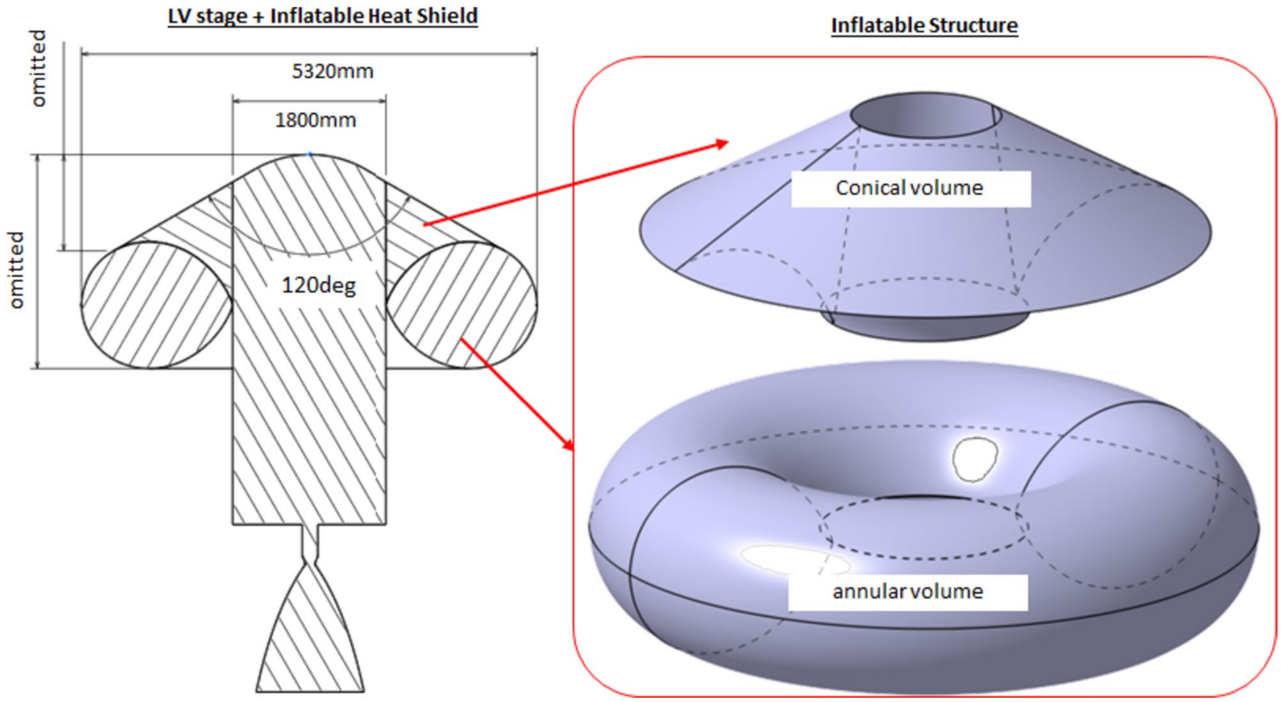


Fig. 18 LV stage and Inflatable Heat Shield integration (left), Inflatable Structure model (right)

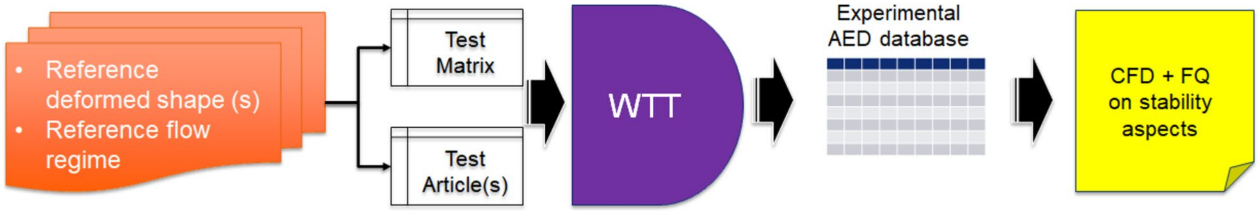


Fig. 19 Reference flow of wind tunnel testing for the EFESTO-2 tasks

dynamic stability tests in the Mach number range of 1.4 to 4, with variations in terms of Reynolds number. The WTT tasks will include the characterisation of surface properties, calibration, integration of strain gauge balances for static tests and free oscillation devices for dynamic stability tests. Then, 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.

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

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.

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

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 provides an overview of the project's objectives, scope and ongoing activities, as well as a glimpse of the planned work for the next 2 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 steps will deal with the organisation and the conduction of 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 results.

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Data availability The request of the dataset generated and analyzed during the study will be evaluated on a case-by-case basis and it will be subjected to the consortium decision.

Declarations

Conflict of interest No conflict of interest/competing interests to declare.

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