Advanced European Re-Entry System Based on Inflatable Heat Shields: EFESTO-2 project overview

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Abstract

EFESTO-2, or "European Flexible Heat Shields: Advanced TPS Design and Tests for Future In-Orbit Demonstration-2", is a project funded by the EU program Horizon Europe. It aims to further increase the European know-how in the field of Inflatable Heat Shields (IHS), an innovative technology used for thermal protection during re-entry. The project builds upon the great achievements of the father project EFESTO (H2020 funds No 821801) and seeks to improve further the Technology Readiness Level (TRL) of IHS.

The EFESTO-2 project has four main pillars: (1) to consolidate the use-case applicability through a business case analysis for a meaningful space application; (2) to extend the investigation spectrum of the father project EFESTO to other critical aspects of the IHS field; (3) to increase the confidence-level and robustness of tools/models; (4) to consolidate the roadmap and guarantee continuity in presiding the IHS field in Europe among the scientific and industrial community.

This paper presents the project's objectives, achievements, ongoing activities, and planned activities up to completion. The aim is to provide a comprehensive overview of the project's contributions to the European re-entry technology roadmap.

This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 1010811041.

Keywords: Inflatable Heat Shields, Re-entry, Reusability, Reusable launchers.

Acronyms/Abbreviations

Business Case Analysis (BCA)
Computational Fluid Dynamic (CFD)
Center of Gravity (CoG)
Finite Element Analysis (FEA)
Finite Element Model (FEM)
Fluid Structure Interaction (FSI)
Inflatable Heat Shields (IHS)
Flexible TPS (F-TPS)
Inflatable Structure (IS)
Launch Vehicles (LVs)
Rigid TPS (R-TPS)
Thermal Protection System (TPS)
Technology Readiness Level (TRL)
Wind Tunnel Test (WTT)

1. Introduction (DEIMOS)

Innovative heat shields based on inflatable systems have received great attention for a decade because of their capability of featuring reduced mass/volume impact on a launch vehicle, then opening possible applications for planetary re-entry and recovery of reusable LVs items. The recent success of NASA LOFTID mission has widely given a concrete proof of that potential [1].

In Europe, the EFESTO project, funded by European Union's Horizon 2020 program (from 2019 to 2022), contributed to increase the TRL from 3 to 4/5 ([2] to [7]), with a broad scope of activities inherent the two key technologies of an Inflatable Heat Shield system (i.e. Flexible TPS and Inflatable Structure).

In November 2022, the EFESTO-2 project [8] received funds from the European Union's Horizon Europe program under grant agreement No.1010811041 to put in-place a follow-up of EFESTO-1 with four main macro-tasks (Fig.2)):

- consolidate the use-case applicability through a business case analysis;
- extend the investigation spectrum in complementary way to what was done in the frame of EFESTO father project;
- increase the confidence-level and robustness of tools/models developed so-far, by implementation of an extensive testing effort;
- consolidate the definition of the roadmap toward a near-future development up to TRL7.

The EFESTO-2 project is managed by a European consortium (see Fig.1) coordinated by Deimos Space (ES), that includes ONERA (FR), DLR (DE), CIRA (IT), POLITO (IT), DEIMOS ENGHENARIA (PT), and PANGAIA-GRADO-ZERO (IT).

Fig. 1: EFESTO-2 project consortium.

The EFESTO-2 project is currently being run according to the study-logic below (see Fig.2).

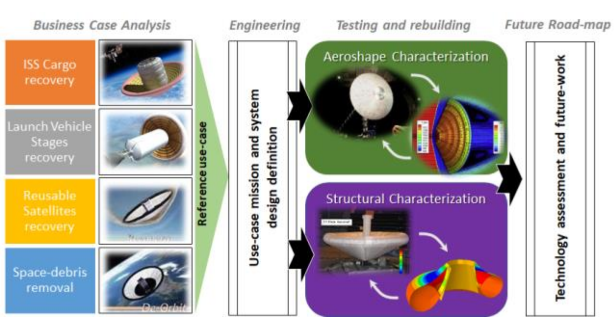


Fig. 2: EFESTO-2 study-logic

2. Business Case Analysis

1.1 BCA approach and implementation

The very first macro task was the execution of a BCA to support selection of a reference study-case for a baseline application and then feed properly the engineering tasks afterwards.

A literature review allowed to screen different applications potentially using IHSs for recovery and re-use purposes as: LV stages, of ISS cargo systems, reusable satellites ([9] to [11]).

Then a BCA was executed across an articulated workflow (see Fig.3) by the following steps:

- overview of reference target markets;
- definition of application scenarios;
- identification of most promising applications;
- trade-off based on key performance indicators (interest, timeline, complexity, and technological fit);
- evaluation of marketable applications using SWOT and PESTEL frameworks;
- cost-oriented assessment of the reference use-case.

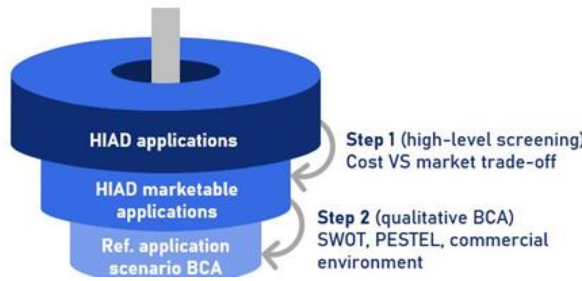


Fig. 3: BCA workflow.

1.2 BCA outcomes

The first outcome of the BCA has been the identification of potential reasonable applications and their cross-comparison in terms of system scale and commercialization time-line (see Fig.4).

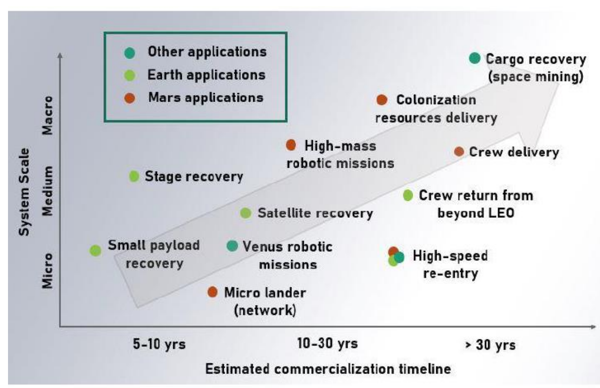


Fig. 4: Application range for the BCA.

Afterwards, a trade-off was carried out to down select the most interesting applications from a commercial point of view based on a total of 4 evaluation criteria:

Market Size; Market Timeline (MT); Complexity (IC); Technological Score (TS).

Tables 1 and 2 show the trade-off results for Earth and Mars applications, respectively. Table 3 reports instead the final ranking.

As far Earth cases, stage reusability (A1) and small payload recovery (A3) seem to be the promising applications to commercially justify adoption of IHSs.

As far Mars cases, micro-lander (A7) and large cargo delivery (A10) appear to be the most commercially interesting cases.

Table 1. LEO applications appraisal

	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]

Table 2. Mars applications appraisal

	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]

The Table 3 reports the final ranking results. 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.

Table 3. BCA final ranking

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

Afterwards, pros and cons of the Earth scenario winners were further assessed within the frameworks of SWOT and PESTEL to down-select one unique reference use-case for the final step of the BCA.

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'.

Hence, a final step was set to determe the most promising 'class size' of LVs for exploitation of the IHS technology with the different classes given in Table 4.

Table 4. Clusters' classification for the LVs application

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

The analysis of potential candidates turned into the chart of Fig.5, based on which the '*Cluster II class-size*' was selected as the most promising because:

- it exhibits the greater number of potential LV systems to which the IHS may be applied;
- and, it includes cases relatively close to those for which a significant technology development step was already undertaken during in EFESTO.

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.

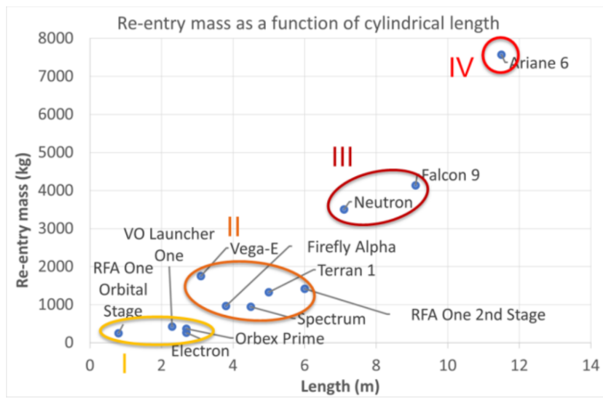


Fig. 5: Re-entry mass of LVs stages

3. Reference Study Case design loop

3.1 Mission definition

A reference study case was selected within Cluster II (Fig. 5) for the design effort. The choice fell on the Firefly Alpha launch system as being an interesting application for this technology with respect to its good performance, its operational status and its geometry, which seemed well suited to the integration of an EFESTO-2 Inflatable Heat Shield (IHS).

These launchers generally aim at low Earth application which would be the natural field of application for a reusable upper stage and aligns well with EFESTO-2 needs. Hence, only low Earth missions were considered within the presented activity.

For the selected study case, the concept of operations had to be defined with a specific focus on the on-orbit operations and events as this will set the basis for key functional requirements of the system and its integration to the launcher.

Fig.6 presents an overview of the end-to-end mission for the study case from launch to recovery.

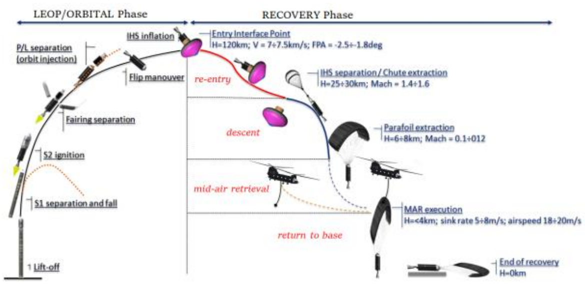


Fig. 6: End-to-end mission for the Firefly Alpha study case.

Fig.7 presents further details on the concept of operations (ConOps) from IHS cover separation to IHS inflation. The ascent until fairing separation is conventional as is the ascent until payload separation with the exception that, shortly before fairing separation, the IHS cover must be separated but not before the suitable heat flux threshold is passed. This IHS cover protects the IHS wrapped around the cylindrical from aerothermal loads during ascent and maintains a smooth outer surface of the launcher.

After separating the payload in the proper orbit, the upper stage has to perform the de-orbiting manoeuvre, which most conventionally would consist of a de-orbiting burn providing the necessary deceleration. This deceleration has to be such that appropriate re-entry conditions are achieved when hitting the atmosphere. The upper stage is now on a descending path where it shall shed the payload adapter that will enter the atmosphere passively where the adopted design shall ensure that it fully burns during atmospheric re-entry. After that, the upper stage has to orient itself such that the front parts face in the appropriate direction, i.e. forward. When this is achieved, the IHS itself is inflated before it enters the atmosphere.

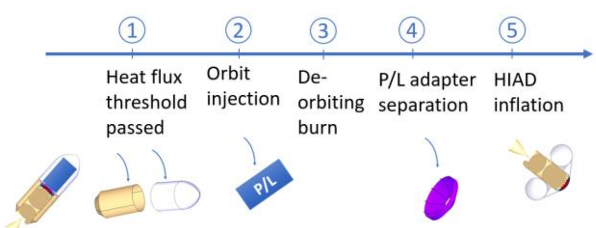


Fig. 7: Details on the ConOps for the Firefly Alpha study case.

3.2 System engineering

Based on the design effort performed in the EFESTO project preceding EFESTO-2, the design process was initiated by preliminarily determining key figures of the external shape such as the outer diameter of the inflated heat shield and the cone angle. To this end, four variants (Fig. 10) were defined and traded against each other, with the purpose to identify a suitable starting point for further detailing of the design. This preliminary design step was supported by AEDB calculation, F-TPS and inflatable structure design as much as by mission analysis and flying quality assessment. A first trade-off eliminated two of the four candidates as they either too heavy or did not meet essential requirements. The remaining two variants (diameter 5.79 m and 6.4 m, both half-cone angle of 60°) were further detailed in a system design loop and again subjected to a trade-off. The smaller candidate proved to be clearly superior with respect to system mass which led to its selection as the preferred shape design. This design was then in a third loop further optimized to reduce its system mass and hence reduce the payload penalty induced by the additional hardware necessary for recovery. Fig.8 shows the final retained system design with key geometric figures. It shall be highlighted that the shape of the toroidal cross section as depicted is simplified to a circular cross section while in reality it is more tear-shaped.

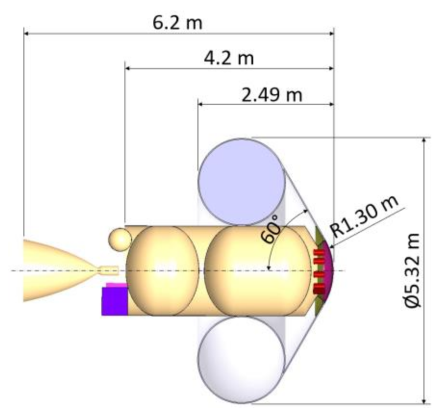


Fig. 8: Cross-section of the selected study case with inflated heat shield.

Fig.9 presents the mass distribution for the system re-entry mass at the end of the design process within the presented activity. As can be seen, the additional systems for recovery make up about 31% which however includes the de-orbit fuel. The inflatable system (inflatable structure, inflation system, F-TPS, parental structure and R-TPS) make up for 20% of the re-entry mass of the system.

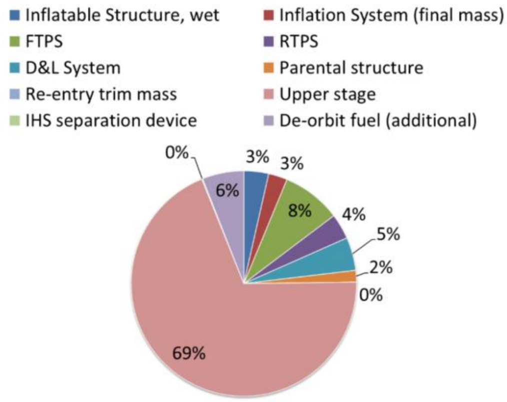


Fig. 9: Re-entry mass distribution.

3.3 Aeroshape investigation

Various aero-shapes have been investigated (Fig.10) varying key parameters as cone-angle and diameter. For each aero-shape, 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 the ONERA engineering tool ARES; 2) the investigation of aerodynamics and aerothermodynamics physical phenomena for selected flight point of the trajectory using the ONERA CFD code CEDRE.

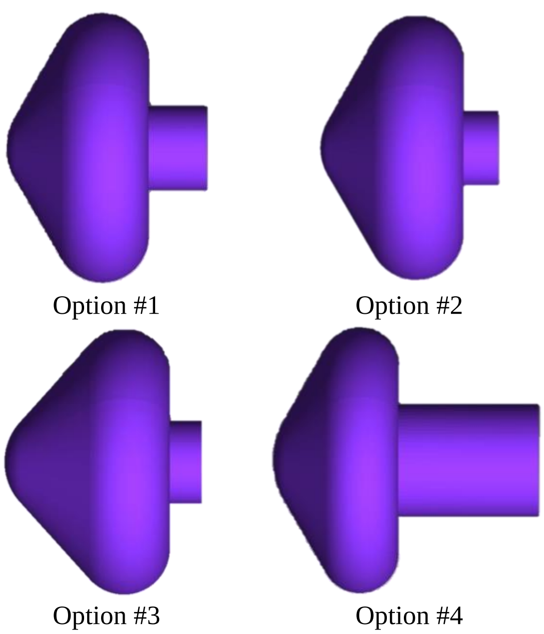


Fig. 10: Aero-shapes investigated in the preliminary phase.

Based on the project objectives, the flight domain investigated is limited to hypersonic and supersonic flows in continuum regime; the parachute being deployed around Mach 1.5. 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. The aerodynamic database being built with engineering tool, uncertainties are associated to the force and moment coefficients. These uncertainties take into account discrepancy between engineering and CFD simulations as well as ground-to-flight extrapolation.

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 multi-disciplinary investigations allowed us to converge towards the most suitable aero-shape (option #1.1, visible in Fig.11, which is a variant of option #1): a diameter of 5.32 m, an half cone angle of 60°, and a nose radius of 1.3 m.

Extended CFD simulations have been conducted, focusing on the critical flight points as maximum heat flux and maximum pressure flight points but not only (Fig. 12). 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. 13.

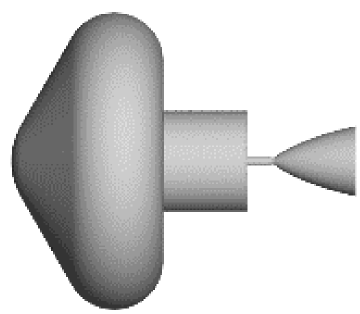


Fig. 11: Visualisation of the chosen aero-shape - option #1.1.

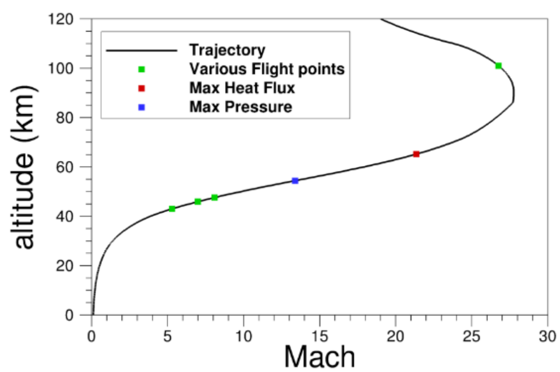


Fig. 12: Flight point under investigation for the CFD simulations for the reference shape (option #1.1).

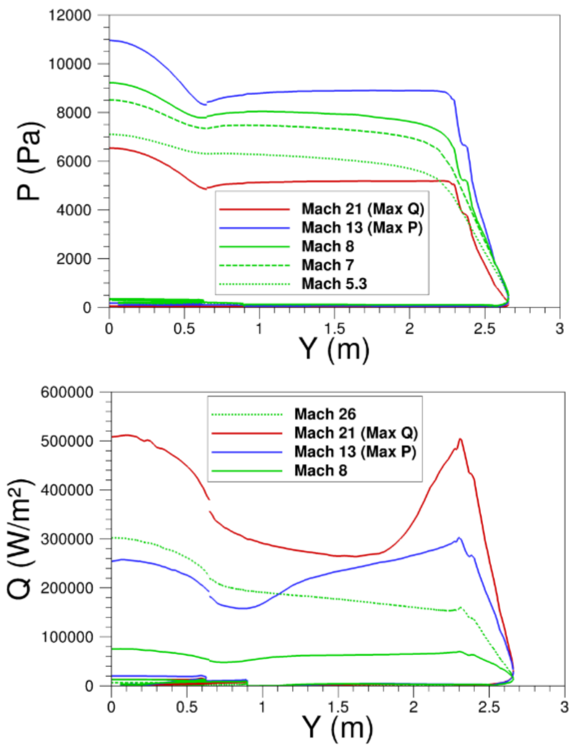


Fig. 13: Pressure and heat flux distribution along the wall of the option #1.1 obtained by CFD simulations.

3.4 *Trajectory analysis and flying quality*

Within the design loop, a specific engineering effort was put in place to analyse the re-entry part of the mission for the refence selected scenario.

Exploiting DEIMOS proprietary tools, an extensive trajectory analysis was first appointed to verify the mission feasibility in terms of entry corridor existence and compliance of constraints.

Different trajectories were propagated from the Entry Interface Point (i.e.: 120 km above ground) down to ground, considering a ballistic entry.

The analysis was fed by fundamental data as aero-shape aerodynamics, system mass, as well es external factors (wind, atmosphere, etc.). Monte Carlo runs were also executed to ensure feasibility of the re-entry mission also when uncertainties are injected.

The mission analysis allowed to retrieve a set of outputs for the pursuit of the system design, namely mechanical and aerothermal loads. Results are given in Fig.14 and Fig.15.

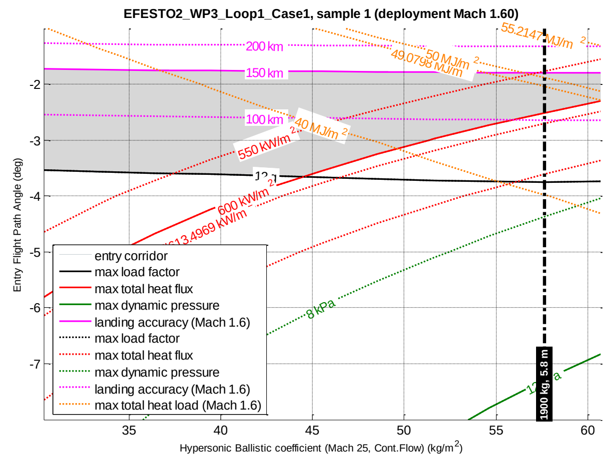


Fig. 14: Re-entry corridor spectrum.

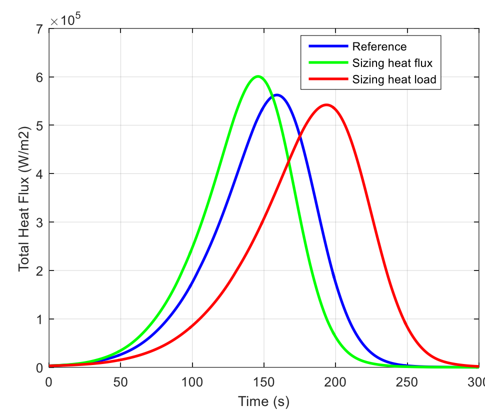


Fig. 15: Re-entry loads – heat flux.

Afterwards, a specific activity was also carried out to assess the flying quality performance of the aero-shape with the aim to verify the vehicle static stability along the Mach envelope of the re-entry trajectory and to provide the suitable CoG positions and the Lift-over-Drag performance (see Fig.16).

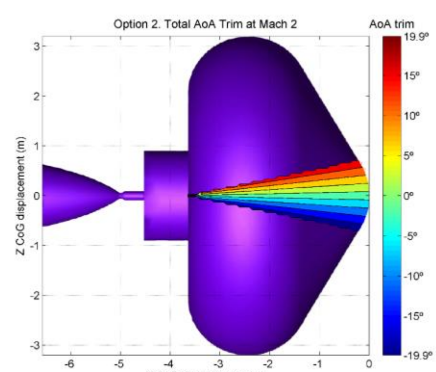


Fig. 16: Vehicle flying quality – trim angle of attack.

3.5 Flexible TPS and Inflatable Structure

The Flexible TPS and Inflatable Structure sub-systems being the most critical items of the re-entry spacecraft, they underwent a dedicated design action through modelling and analysis efforts based on approaches, models and material data inherited from the previous project EFESTO.

As far as the F-TPS, different solutions of material stack-up were investigated and verified against the aerothermal loads. Then a final optimized architecture was identified as a baseline with a fixed stack-up of material layers and thickness. (Fig.17)

As far as the IS, again the EFESTO engineering know-how was widely applied to define the geometry and size of the inflatable volumes as well as the material to be adopted. From a structural standpoint the IS was verified against the main mechanical load that is the external flow-field pressure pattern. (Fig.18)

For both the F-TPS and the IS, consequently, mass and volume budgets were obtained to feed the system synthesis.

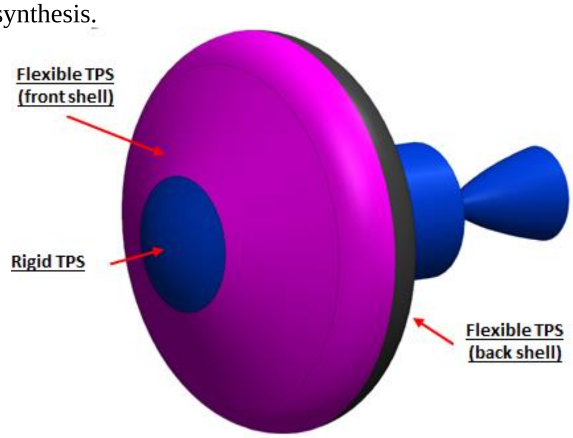


Fig. 17: TPS layout.

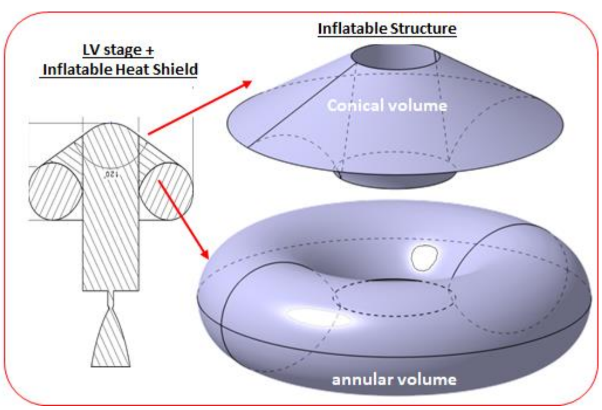


Fig. 18: Inflatable Structure layout.

4. Fluid Structure Interaction loop

As part of the extended spectrum with respect to the father project EFESTO, in EFESTO-2 a Fluid Structure Interaction investigation was executed through the following steps:

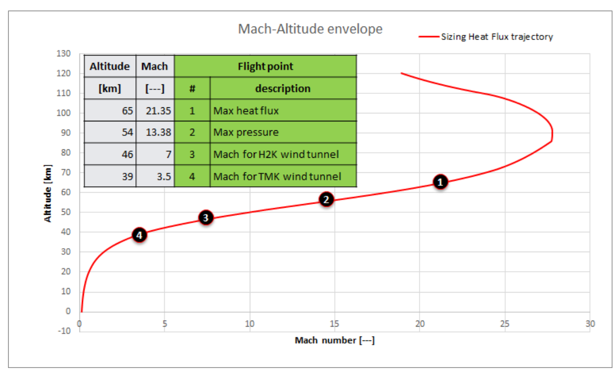
1. Review of literature [11];
2. Settlement of an ad-hoc strategy with definition of a convergence criterion;
3. Identification of trajectory meaningful points;
4. Execution of CFD↔FEA iterations;
5. Evaluation of results;
6. Elaboration of synthesis and remarks on the FSI outcomes for the future-work.

Because of the quasi-static nature of the aeroelastic problem, a weak/loose coupling methodology was adopted, relying on serial-staggered interaction between CFD and FEA. The CFD being managed thanks to ONERA proprietary tool "CEDRE", whilst the FEA exploited COTS tool for FEM simulations (i.e.: ABAQUS).

The selected critical monitoring parameters were the wall pressure distribution along the body as well as the drag coefficient (as CFD output), and the deformed shape displacement (as FEM output).

A convergence criterion was also established to stop iterations based on a reasonable threshold of the rate-of change of the key parameter values.

The FSI loop focused on 4 meaningful flight conditions as reported in Fig.19.



Altitude	Mach	Flight point	
[km]	[---]	#	description
65	21.35	1	Max heat flux
54	13.38	2	Max pressure
46	7	3	Mach for H2K wind tunnel
39	3.5	4	Mach for TMK wind tunnel

Fig. 19. Trajectory points for the FSI execution.

Fig.20 shows an intermediate step of the loop with Mach field distribution and shape profile in a deformed status.

The FSI loop ended up successfully with the following main outcomes:

A. quantification of impacts on aerodynamics and aerothermodynamics of the aeroshell due to deformation;
B. identification of the reference deformed shape to be replicated for WTT runs;

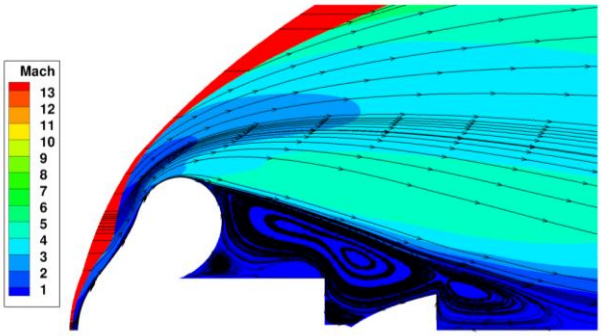


Fig. 20. Mach on a deformed shape (intermediate run).

4.1 GN&C investigation

With respect to the father project, an important novelty of the EFESTO-2 is injection into the objectives of the GN&C development with a particular focus on implementing a guided re-entry in order to reduce dispersion due to uncertainties and re-entry boost accuracy, and then allow for the Mid-Air Retrieval operation to be executed with reasonable resources and fair-good operational feasibility.

The GN&C aims to manage the re-entry leg of the trajectory by implementing active control/planning of down-range and cross-range through a combination of lift generation, lift-over-drag modulation, and bank manoeuvring.

Currently being at its early stage, the GN&C work-package will be run from literature review and requirements definition, to detailed design development and verification including effort of model-in-the-loop, software-in-the-loop and finally process-in-the-loop.

5. Ground Development Effort

By the time this paper is presented, the EFESTO-2 project has entered the second important stage of its life-cycle and where two ground test actions are being conducted in parallel, as describe here below.

5.1 Wind-tunnel test effort

The first testing effort focuses on the aerodynamic characterization of the Inflatable Heat Shields. This will be implemented by testing sub-scaled models in wind tunnels at meaningful flow conditions.

Based on the work performed at the Stage I of EFESTO-2, as descripted in Section 3 in this paper, a promising strategy is: 1) to perform static stability test with a deformed shape of the vehicle heatshield in hypersonic regime in the DLR H2K wind tunnel, at Mach number 5.3 and 7.0; 2) and, in addition, to perform dynamic and static stability test with a non-deformed shape of the vehicle heatshield in supersonic regime in the DLR TMK wind tunnel in the Mach number range of 1.4 to 4.

The H2K facility is operated as a blow-down wind tunnel. Fig.21 provides a schematic diagram of the wind tunnel setup. The heated compressed air flows through a contoured axisymmetric nozzle, which has a diameter of 600 mm, into a test section and exhausts to a vacuum sphere. By exchanging the wind tunnel nozzle, various Mach numbers such as 4.8, 5.3, 6.0, 7.0, 8.7, and 11.2 can be achieved.

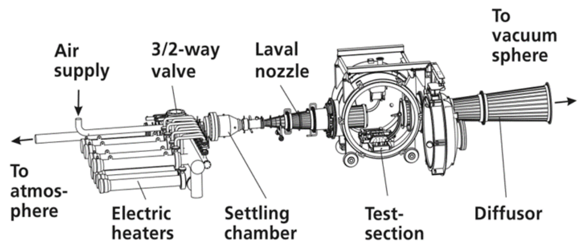


Fig. 21. Schematic drawing of H2K.

Three test conditions are defined for each Mach number for H2K. At one condition, the Reynolds number of the trajectory is replicated (Fig.22) and at the second condition, the dynamic pressure is replicated (Fig.23). A third condition gives the possibility to study a potential Reynolds number effect.

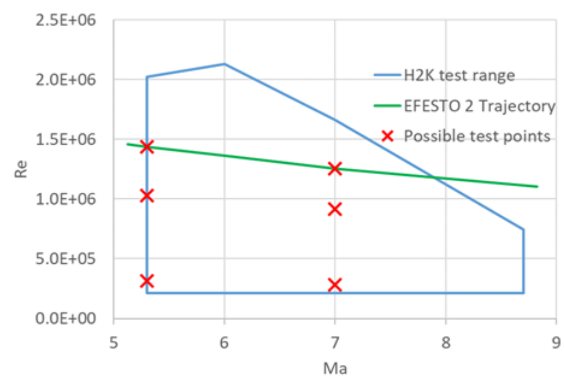


Fig. 22. Flight and H2K test conditions: Re/Ma.

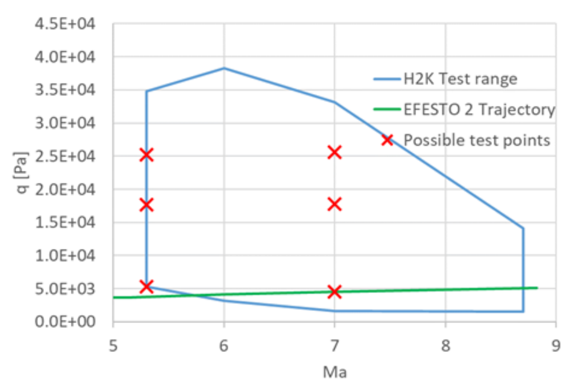


Fig. 23. Flight and H2K test conditions: Dynamic pressure/Ma.

The facility TMK is a tri-sonic blow down wind tunnel with a rectangular test section of 0.6m x 0.6m. As sketched in Fig.24, the compressed air passes through a storage heater and a settling chamber is then accelerated in an adaptable Laval nozzle. The flow is decelerated downstream in the diffuser system. Depending on Mach and Reynolds conditions, a maximum testing time of up to 60 seconds is achieved.

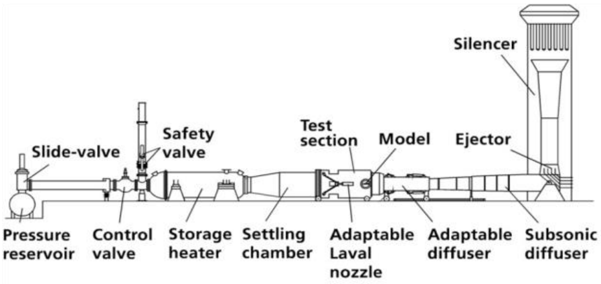


Fig. 24. Schematic drawing of TMK.

The test conditions for TMK are illustrated in Fig.25. The flight conditions are well replicated in the wind tunnel test. Because the flight dynamic pressure is below 5kPa in the low Mach number range, the caused shape deformation is quite small at such pressure rate and the non-deformed shape is used for the test.

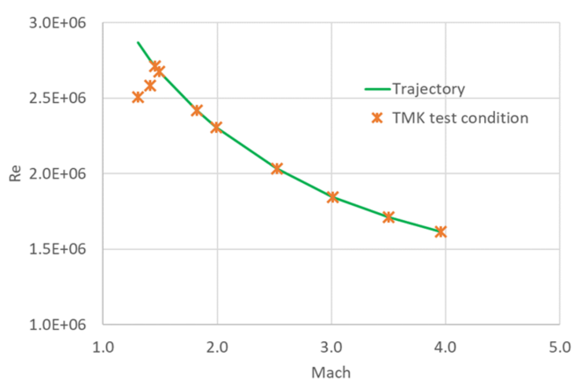


Fig. 25. Flight and TMK test conditions: Re/Ma.

The dynamic stability tests in TMK are performed using the free oscillation measurement technique. The key element of the whole device is an elastic cross-flexure. It is designed to provide the necessary motion around the CoG. The test conditions for the dynamic tests are identical to that of the static test campaign.

The hypersonic and supersonic stability tests performed in H2K and TMK respectively will be subject to numerical rebuilding; the main objectives being to evaluate the uncertainties associated to numerical simulations and evaluate the aerodynamic deviation between deformed and non-deformed heatshield. These uncertainties will allow to consolidate the aerodynamic database and thus the mission and system design.

5.2 *Structural test effort*

The second testing 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.

A ground demonstrator with a diameter of 2.4m will be utilized, along with a dedicated test rig developed in the previous EFESTO project (Fig.26).

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 localized periodical solicitation at controlled frequency).

The demonstrator will be instrumented with accelerometers (monoaxial and triaxial) to identify the modal behaviour, and photogrammetric reconstruction will be employed to analyze the deformed shape under load and calculate the applied axial force.

Fig. 26. IS ground demonstrator in its test-rig.

6. Future Initiatives and roadmap

EFESTO-1 and EFESTO-2 are on pace with a technology and development roadmap as illustrated in Fig.27.

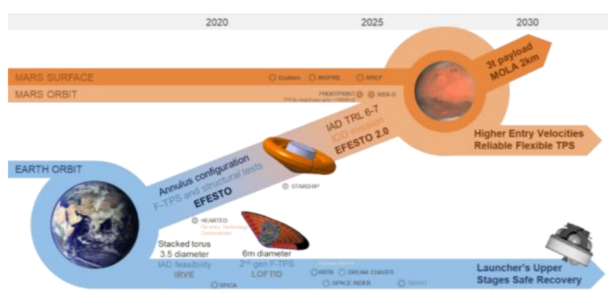


Fig. 27. EFESTO legacy technology roadmap.

EFESTO-2 sets out to achieve several pivotal milestones that will significantly elevate the Technology Readiness Level (TRL) of inflatable heat shield technology.

Notably, following the impressive success of the previous Horizon 2020 EFESTO project, which elevated the TRL from 3 to an impressive 4/5, EFESTO-2 aims to advance this technology to TRL 5/6. Among its activities, essential milestones include rigorous aero-shape and mechanical characterization, which will be carried out through wind tunnel testing and comprehensive testing on a substantial 2.4-meter ground demonstrator.

These critical tests will serve as a litmus test for the technology's readiness and effectiveness, particularly for the Earth re-entry scenario.

Once the feasibility and robustness of the Earth re-entry use case are convincingly demonstrated at TRL 5/6, this technology could serve as both an enabler and an enhancer for numerous future space exploration missions. Of paramount importance is its capability to facilitate atmospheric deceleration for large payloads, effectively reshaping the possibilities for space missions of varying scales and objectives.

Furthermore, it's imperative to underscore the broader significance of inflatable heat shield technology for the sustainability of space activities. This technology carries the promise of space hardware recovery and reusability, presenting an effective strategy for mitigating space debris generation - a growing concern in orbit.

By enabling the safe return and reuse of space hardware, inflatable heat shields contribute significantly to the endeavour for more sustainable and environmentally responsible space exploration. This dual role, as an enabler for advanced missions and a key player in space sustainability, underscores the pivotal role EFESTO-2 plays in advancing the future of space technology and exploration.

The next logical step in the roadmap (Fig.26) involves planning a follow-up project that envisions the development and deployment of an in-orbit demonstrator (IOD). This ambitious endeavour is expected to be a transformative milestone, targeting a TRL of 6/7, thanks to an extensive flight campaign. The IOD will play a central role in highlighting the real applicability and robustness of inflatable heat shield systems, paving the way for their integration into future space missions and further solidifying Europe's leadership in this cutting-edge technology.

7. Conclusions

The EFESTO-2 project is currently being run by a European consortium as follow-on of the father project "EFESTO".

As of today, the project team has already succeed into executing a Business Case Analysis with particular focus on IHS applicability to recover Launch Systems segments meant to be reusable; and into completing a design loop at mission and system levels to get the feasibility of a specific mission/system scenario.

The project passed the milestones foreseen so far, and it will now enter a second yet important stage of action with preparation and implementation of two parallel test efforts to cover structural and aerodynamic aspects. Inherent results and considerations will come next year.

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