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Pushing the limits of re-entry technology: an overview of the Efesto-2 project and the advancements in inflatable heat shields

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Abstract. As space exploration technology advances, the need for reliable re-entry systems becomes increasingly critical. The European Flexible Heat Shields: Advanced TPS Design and Tests for Future In-Orbit Demonstration – 2 (EFESTO-2) project is a Horizon Europe-funded initiative aimed at improving the Technology Readiness Level of Inflatable Heat Shields (IHS), an innovative thermal protection system that can be deployed during re-entry. The project seeks to further advance the work achieved in the EFESTO project, with a focus on expanding investigations into critical aspects of IHS and increasing the confidence level and robustness of the tools and models used in the field. The EFESTO-2 project is built on four pillars, including consolidating the use-case applicability through a business case analysis for a meaningful space application, extending the investigation spectrum of the father project EFESTO to other critical aspects of the IHS field, increasing the confidence level and robustness of tools/models, and consolidating the roadmap to guarantee continuity in presiding the IHS field in Europe among the scientific and industrial community. This paper provides an overview of the EFESTO-2 project's objectives, achievements, ongoing activities, and planned activities up to completion. The project's advancements in the fields of thermal protection systems, inflatable heat shields, and technology readiness level are described in detail, highlighting the project's contributions to the European re-entry technology roadmap. Through this project, the European Space Program aims to push the limits of re-entry technology and reinforce its position as a leader in innovative technology for space exploration. This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 1010811041.

Introduction

The EFESTO-2 project builds upon the success of the previous H2020 EFESTO project and aims to advance European expertise in the field of Inflatable Heat Shields (IHS). With the increasing demand for reusable space transportation systems, the development of innovative thermal protection solutions is crucial for safe and cost-effective space missions. Inflatable Heat Shields have shown great potential in enabling controlled re-entry and recovery of spacecraft, making them a promising technology also for future space exploration missions.

Project Objectives

The EFESTO-2 project, funded by the European Union's Horizon Europe program, aims to achieve the following objectives. Firstly, it seeks to consolidate the use-case applicability of Inflatable Heat Shields (IHSs) through a comprehensive business case analysis for a meaningful space application. Secondly, it aims to expand the investigation spectrum by conducting extensive tests focused on aerodynamics and mechanical aspects, complementing the previous EFESTO project. Thirdly, the project aims to enhance the confidence level and robustness of the tools and models developed in EFESTO by incorporating test data. Lastly, it aims to consolidate the definition of a roadmap towards the near-future development of IHS technology up to Technology Readiness Level 7 (TRL7). The study-logic applicable within the EFESTO-2 initiative for implementing the planned effort is represented in Figure 1.

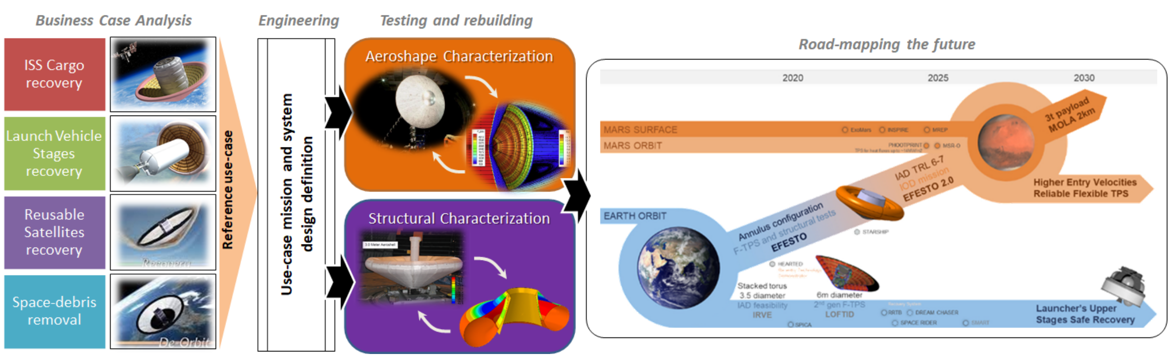

Figure 1 EFESTO-2 project study-logic

Business Case Analysis

The Business Case Analysis (BCA) was conducted as the initial task in the EFESTO-2 project to identify the most promising use-case application for inflatable heat shields (IHSs) and guide the subsequent design study for a reference mission/system. The BCA focused on exploring potential applications of IHSs in the re-entry and recovery of space systems meant for reuse. Examples of potential applications included the recovery of launch system stages, ISS cargo systems, and de-orbiting and recovery of reusable satellites.

The BCA workflow involved several stages. An overview of target markets for IHS technology was conducted, followed by the identification of the most promising commercial applications using a trade-off analysis. Qualitative evaluations were performed using frameworks such as SWOT and PESTEL, considering market trends, substitutes, competitors, and potential customers. Additionally, a cost-oriented assessment of a reference use-case for re-entry and recovery was carried out.

The evaluation of IHSs application scenarios considered different planetary re-entry scenarios, including Earth, Mars, and others. The trade-off criteria included market size, market timeline, complexity, and technological score. The outcomes indicated that stage reusability, small payload recovery, and space mining cargo recovery were promising applications for IHS adoption.

In the Earth re-entry scenario, LV stage recovery, small payload recovery, and space mining cargo recovery were identified as the most commercially interesting cases. These use-cases were further assessed using SWOT and PESTEL frameworks, considering factors such as political, economic, social, technological, environmental, and legal aspects. Based on the SWOT/PESTEL assessment, the best candidate use-case for Earth re-entry was identified as "LV stage recovery," which demonstrated relevant characteristics for both micro and macro IHSs, achievable marketability in a short time, and good profitability opportunities.

Therefore, the recovery of an LV stage will serve as the reference use-case for the subsequent work presented in the conference paper.

Reference Mission

A review of over 70 launch systems worldwide resulted in the identification of 20 potential candidates. Key parameters and indicators were considered to classify the launch systems into four clusters. Cluster II was selected as the most promising due to its compatibility with the IHS technology development and a significant technology development step already taken during the EFESTO project. The concept of operations (ConOps) for the Inflatable Heat Shield exploitation is based on the recovery of a launch vehicle upper stage. The ConOps includes two main phases: LEOP/ORBITAL and RECOVERY. The baseline strategy for the EFESTO-2 project is to execute the recovery via mid-air retrieval by helicopter. The engineering effort focused on the re-entry part of the recovery, and the descent and mid-air retrieval phases are out-of-scope.

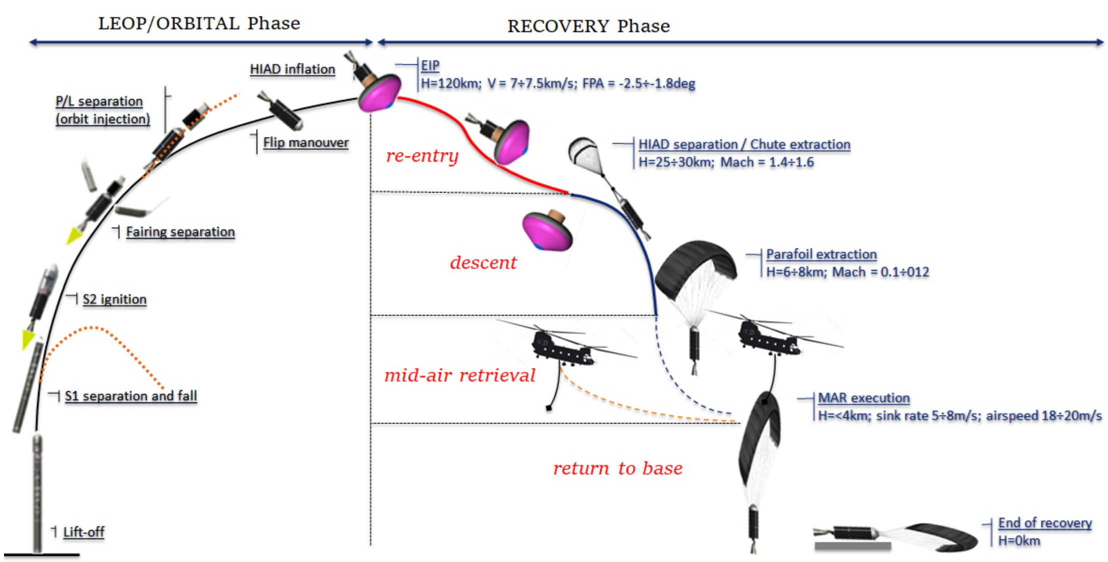

Figure 2 EFESTO-2 baseline ConOps

Mission Analysis / Aerodynamics and Aerothermodynamics

A parametric analysis was conducted to determine the combination of boundary conditions that offer a good initial flight path angle range and compliance with system constraints. Reference and sizing trajectories were calculated, and a Monte Carlo analysis confirmed compliance with all constraints.

Aero-shapes with varying parameters were investigated, and an aerodynamic database was developed for the selected flight points. CFD simulations were conducted to evaluate aerodynamic and aerothermodynamic behavior and obtain load distributions along the body.

System Design

A system design loop was performed to obtain a coherent layout for the IHS and its subsystems integrated with the Firefly Alpha upper stage. An option with a diameter of 5.32 m and a half cone angle of 60°, was selected based on qualitative assessment, aerodynamic performance, and mass estimation. Further efforts were made to reduce system mass, resulting in a minor reduction in the diameter of the inflated IHS.

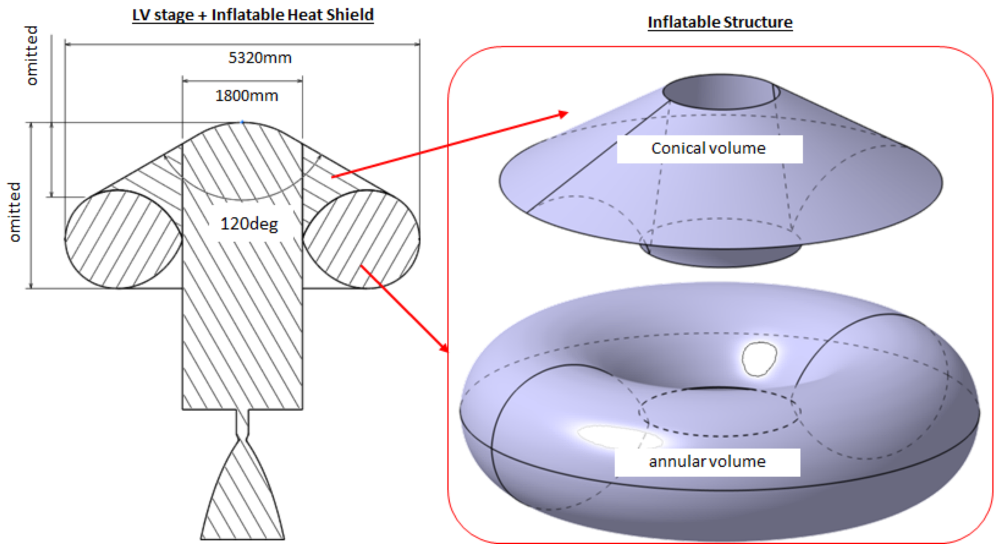

Figure 3 LV-stage and Inflatable Heat Shield integration (left), Inflatable Structure model (right)

Future Work

In the future, the project will focus on conducting ground tests for aerodynamics and flying qualities, as well as mechanical characterization of the Inflatable Structure. The aerodynamics testing will involve wind tunnel experiments with subscale models to study stability, while the mechanical characterization will use a ground demonstrator to evaluate structural behavior. The collected data will be used to improve numerical models and enhance the understanding of inflatable heat shield technology. The project aims to consolidate the technology up to TRL7 and has made progress in the initial stages, including a Business Case Analysis and reference system design. The project will conclude with test campaigns and the dissemination of findings through additional papers.

Acknowledgement

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