THE EFESTO PROJECT: DESIGN, DEVELOPMENT AND TESTING OF THE INFLATABLE STRUCTURE AND ITS GROUND DEMONSTRATOR

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ABSTRACT

The European Union H2020 EFESTO project has as end goal the advancement of the European Technology Readiness Level (TRL) of Inflatable Heat Shields for atmospheric entry vehicles from 3 to 4/5, thereby paving the way towards flight (TRL 6 with a future In-Orbit Demonstration).
Two different applications have been identified and studied within the scope of the project. The first application considers a 2.5-ton Mars payload destined for a Mars Orbiter Laser Altimeter (MOLA) target altitude of +3 km. The Mars application combines a 9-meter diameter Hypersonic Inflatable Aerodynamic Decelerator (HIAD) with a Supersonic Retro-Propulsion system. The second application addresses re-entry and recovery of the first stage of an orbital launcher, using the AVUM upper stage of the Arianespace VEGA vehicle as baseline study case.
For both applications, the EFESTO project devoted a significant effort to maturating the two key technologies that constitute the core of Inflatable Heat Shields, i.e., the Flexible TPS and the Inflatable Structure.
This paper provides insight into the design of the EFESTO Inflatable Structure for both Mars and Earth applications, as well as into the development and testing of a Ground Test Unit (GTU). Particular attention is given to discussion of the design, fabrication, integration, and test of the 1:2-scale Inflatable Structure GTU, and how the experimental results have been used to improve the numerical prediction capabilities. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821801.

Keywords: Launcher Reusability, Mars Exploration, EDL, Flexible TPS, Inflatable Structure, Aerodynamic Decelerators, HIAD, IAD.

1. INTRODUCTION

The EFESTO project [1] seeks to advance the Technology Readiness Level of Hypersonic Inflatable Aerodynamic Decelerators (HIAD) for atmospheric entry vehicles. With the continuous increase in space flight activity there has been a commensurate desire to advance technologies that increase the landed mass of payloads without increasing the cost and burden associated with launch vehicle payload constraints.

Primary drivers for advancement of inflatable atmospheric entry technologies are associated with commercial space operations, primarily for Earth atmosphere (for example launch vehicle booster recovery); return of science related payloads (sample return); and robotic and manned planetary missions, most notably those challenged by the thin, low-density Mars atmosphere.

Larger payloads, such as those contemplated by the manned Mars missions, require atmospheric entry decelerator technology presenting drag surface areas far in excess of the dimensions afforded by any launch vehicle payload fairing. As such, and further to the ubiquitous constraints that launch vehicles impose on payload mass and volume, the immediate technology need is for robust, lightweight atmospheric entry decelerators that present the greatest possible distension ratio in their transition from tightly packaged to operationally deployed.

2. STATE OF THE ART

On the European front, the last mission to fly an inflatable heatshield technology demonstrator was the Inflatable Reentry and Descent Technology (IRDT), an ESA/Russia mission that performed three test flights since 2000, unfortunately ultimately resulting in only one partially successful recovery of telemetry

[3]. Since 2005, European studies of the likes of STEP2 (2014), IRENA (2015), HYPMOCES (2016) and IAD/DAD (2017) focused on lower TRLs, restricting activities to design and test of inflatable components and flexible TPSs without advancement to a scaled system test or demonstration flight.

In the global context, over the last two decades, NASA has steadily increased the TRL of Inflatable Aerodynamic Decelerator (IAD) and F-TPS technology through their IRVE [4] and HIAD [2] programs. In 2012 IRVE-3 performed a successful demonstration mission after flying a suborbital arc, re-entering at a velocity of Mach 10 and the inflated heatshield reaching 1000ºC. NASA is currently building on the experience gained on their stacked toroid configuration and flexible TPS materials, pushing the technology forward with programs such as LOFTID [2] and SMART [5]. The first is currently developing a 6-meter diameter class demonstrator designed to re-enter from orbital velocities, both for Earth and Mars applications, while the latter is a NASA and ULA joint effort to adapt the technology for launch vehicle booster stage recovery. China is also developing inflatable decelerators with a Flexible Inflatable Cargo Re-entry Vehicle. Tested in 2020, the vehicle with a deployed HIAD of 3-meter diameter, suffered a destructive anomaly during entry.

On the European front the TRL remains lower. Only preliminary studies have been performed since the partial failures of the IRDT program. The EFESTO project intends to advance the European TRL for IAD and F-TPS technologies from 3, to 4 or 5, by performing ground tests of material assemblies and full-scale IAD architectures in preparation for a European in-orbit demonstration (IOD) to further support increasing the TRL to 6. In preparation for the latter, the EFESTO team is defining an IOD mission with results being expected by the end of the current EFESTO project stage.

3. IAD INFLATABLE STRUCTURE DESIGN

During the Preliminary Design phase, a trade was performed between the NASA approach of multi-toroidal or "stacked-torus" architecture, and the innovative "Dual Body" (DB) IAD design developed by Thin Red Line Aerospace, an EFESTO team member. The primary objectives of the DB technology are to increase overall simplicity of the inflatable IAD structure while simultaneously demonstrating its structural scalability to the large drag profile diameters required, for example, for launch vehicle booster recovery and manned Mars missions. Since structural determinacy and predictable scalability have long been Achilles' heels for inflatable architectures—particularly for HIAD, the DB design was selected due to intrinsic advantages of higher specific strength (strength-to-mass ratio) combined with its structural determinacy that opens the door to performance predictability and scalability.

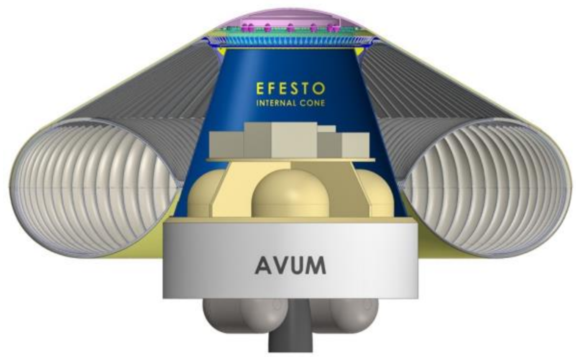

Figure 1: The "Dual Body" IAD architecture pictured in the EFESTO configuration for the AVUM stage of the VEGA launch vehicle.

Conspicuous in Figure 1, the Dual Body IAD architecture comprises two inflatable volumes: (1) An Annular Volume (AV, or "Annulus") that defines the IAD's cross-sectional drag "footprint" while simultaneously providing the structure to support accurate distention of (2) a Conic Volume (CV) that maintains the IAD's desired conic frontal drag surface geometry. Effective interaction of these two inflatable sub-structures depends largely on their relative inflation pressures: The CV need only be marginally higher than the dynamic ambient to maintain a desirable drag profile, while higher pressure in the AV will be required primarily to maintain dimensional stability of the drag area while counteracting the radially compressive forces imparted by aero loading.

As provider of the structural "backbone" for the IAD, the Annulus is a standalone inflatable pressure vessel derived and benefitting from most exceptional attributes of Thin Red Line's Ultra High Performance Vessel (UHPV). UHPV's structural determinacy, scalability, and exceptional specific strength have been widely validated in recent years, opening the door to expanded mission capabilities for space habitation, airlocks, propellant tanks, and the like.

The Annulus architecture is based on the integration methodology of the three primary UHPV components to facilitate maximum design flexibility by allowing each component to be individually optimized for a specific functionality. The following three components are readily associated with Figure 1 and Figure 4 schematics:

1. Pressure Restraint Tendons – An exterior meridional array of structurally uncoupled cordage tendons bears the inflatable structure's entire global inflation pressure load.

2. Inflation Gas Bladder – The internal bladder is optimized for impermeability performance to best retain the IAD's inflation gas.
3. Carrier Fabric Shell – A gossamer yet structural woven carrier that envelopes the bladder, and that is just strong enough to carry the small local bladder loads where it bulges outwards between pressure restraint tendons.

An exceptional attribute of these UHPV-based inflatable structures is their structural determinacy that is a consequence of (a) the absence of global hoop stress (global pressure loads are borne exclusively in the meridional sense); (b) determinate global geometry (due to the absence of global hoop stress); and (c) circumferential spacing of meridional tendons (thereby eliminating coupled loads). While the hoop structure of an axisymmetric inflatable determines its profile of revolution, and hence also the inflatable vessel's shape, the hoop structure inevitably interacts with the vessel's meridional structure to also impart structural indeterminacy associated stressed pressure shells. Conversely, the geometrically and structurally determinate UHPV-based architectures are obtained by removing all shape constraining circumferential (hoop) structure, causing the global pressure load to be borne exclusively in the meridional sense (typically by a tendon array). Such determinacy of load paths and global stress distribution are virtually unprecedented in any pressure vessel architecture. Geometric definition and structural performance are therefore characterized by straight-forward analytical methods.

The scalability of the Annulus design is derived from the fact that (a) pressure restraint tendon strength and count is tailored to any Annulus size and pressure requirement, and (b) tendon count is strategically balanced with carrier strength to achieve absolute lowest mass.

Two primary Dual Body configurations have been developed to accommodate different mission requirements:

1. **Dual Body 1** (DB-1, Figure 2 left)

DB-1 incorporates an Annulus with a sufficiently low Aspect Ratio (AR) to ensure that its inner circumference generally conforms to the outer mold line (OML) of the vehicle payload.

<u>Advantages</u>:

- Payload coupling enhances deployed IAD predictability and minimizes body flex
- Design simplicity
- Exceptional off-axis stability
- Best suited to smaller cone angles

<u>Disadvantages</u>:

- Payload contact considerations
- Larger volume and mass than Dual Body 2

2. **Dual Body 2** (DB-2, Figure 2 right)

Contrary to the DB-1 Annulus, the inner circumference of the DB-2 Annulus does not conform to the OML of the vehicle payload.

<u>Advantages</u>:

- Does not interfere with payload
- Lower volume and mass
- Annulus AR and volume can be modified to optimize mass, stiffness, and drag effect
- Accommodates larger cone angles

<u>Disadvantages</u>:

- More complex integration with payload

4. INFLATABLE STRUCTURE MODELLING

Several Inflatable System (IS) design cycles were performed for both Earth and Mars study cases. A suitable Dual Body configurational adaptation was sought that would showcase the applicability of this technology for these two distinct applications. Numerical simulations of the folding and unfolding sequence have been performed using Altair Radioss software. Additionally, both study cases support derivation of requirements for IAD system design and integration. The general design process and results are presented below, highlighting key observations and requirements as identified during the design cycles.

Mars Application

The Mars application baselines a 9-meter diameter HIAD with a supersonic retro-propulsion system to support landing a 2.5-ton payload destined for a Mars Orbiter Laser Altimeter (MOLA) target altitude of +3 km. at Oudemans Crater. The thin Martian atmosphere and the high site elevation clearly require a large decelerator, notionally with frontal surface with a 70-degree half-cone angle in order to present a drag coefficient as large as possible without jeopardizing aerodynamic stability.

Application of the Dual Body 1 (DB-1) configuration to a 70-degree cone geometry would require the DB-1 Annulus to assume a very large volume in order for its Inner Diameter (ID) to conform to the payload's Outer Diameter (OD) while simultaneously presenting the requisite OD needed for the large IAD drag footprint. Furthermore, larger cone angles ("blunter" cones), such as needed for Mars, become progressively more challenging to implement due to the increasing difficulty of restraining aftward axial displacement of the deployed IAD in the dynamic flow environment. Increased Inflatable Structure (IS) stiffness is the primary remedy to control conic displacement, with stiffness corresponding with higher inflation pressures and therefore also structural mass.

As such, the Dual Body 2 (DB-2) configuration becomes the preferred architecture because Annulus

AR and volume can be manipulated as needed for balanced optimization of mass and stiffness. While clearly attractive in its design simplicity, application of the DB-1 configuration would be less mass efficient with its large volume Annulus needed to facilitate the requisite 70-degree geometry, and high inflation pressure to provide the requisite stiffness. While numerous other configurational extrapolations were considered, Figure 2 compares baselined DB-1 and DB-2 configurations. DB-2 Version 1 (v1) presents a larger Conic Volume (CV) than DB-2 v2. DB-2 v2 eliminates much of v1's stiffness enhancing CV mass by incorporating an array of radial tendons.

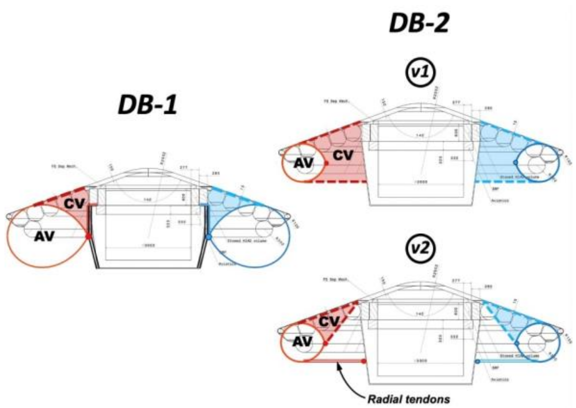

Figure 2: Dual Body 1 and Dual Body 2 comparisons for the Mars application.

Table 1 shows the comparative masses of the DB-1 and DB-2 Mars configurations. Masses include the IS components (bladder, carrier, and tendons) as well as the inflation gas.

IS CONFIGURATION	IS MASS [KG]
DB-1	215
DB-2 V1	160
DB-2 V2	118

Table 1: Inflatable Structure mass estimations.

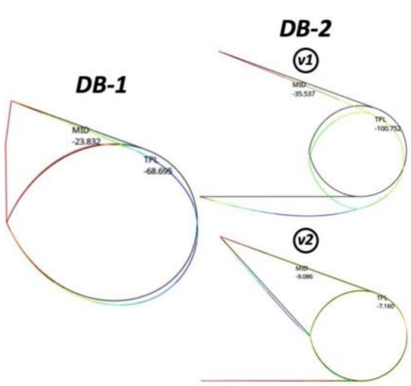

Figure 3: MARS configs deflection analyses.

Deflection analyses were compared for two design conditions: (1) at time of IAD initial inflation in a vacuum (i.e., prior to experiencing effects of the dynamic flow environment), and (2) when subjected to peak aerodynamic loads. Figure 3 compares deflection of the DB-1 and DB-2 Mars configurations under peak entry load.

In conclusion, DB-2 v2 is the preliminary Mars configuration that minimizes mass and deflection. Figure 4 schematically shows a section of the DB-2 v2 IAD integrated with its payload.

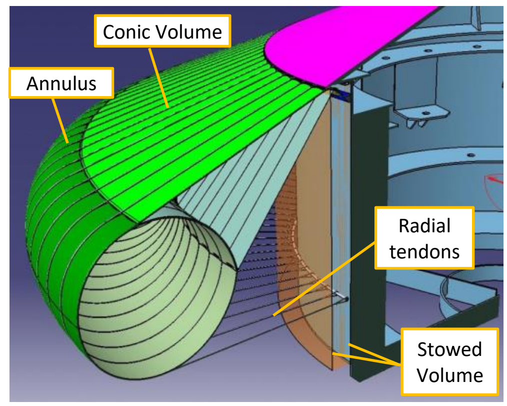

Figure 4: 3D model of the integrated Mars DB-2 v2 showing internal structure and volume needed for stowage.

Earth Application

The Earth application addresses re-entry and recovery of the first stage of an orbital launcher, using the AVUM upper stage of the Arianespace VEGA vehicle as baseline study case.

The same approach to Dual Body IAD version down-select was applied to the Earth application IAD as it was for Mars. As with Mars, the primary contenders remain the DB-1 and DB-2 v2. However, the key difference between Earth and Mars applications is that atmospheric entry for an Earth-bound IAD favors a less blunt conic frontal surface with 60-degree half cone angle. Further to the earlier Mars application comparison of DB-1 and -2 configurations, the Earth application's smaller cone angle opens the door to the benefits of DB-1, i.e., design simplicity and enhanced stiffness through form-fitting physical interfacing with the AVUM payload. Besides the requisite structural connection of the IAD at the AVUM apex, no other direct mechanical connection between the two is implemented.

Figure 5 compares the peak entry load deflections of the Earth application DB-1 with DB-2 v2, demonstrating that the differences are quasi negligible. Figure 6 shows a section of the Earth application DB-1 IAD integrated with its AVUM payload. Figure 7 provides a preliminary mass distribution for the EFESTO reentry configuration of the AVUM study case. A more thorough mass optimization study of the DB-2 v2 variant is identified as future task.

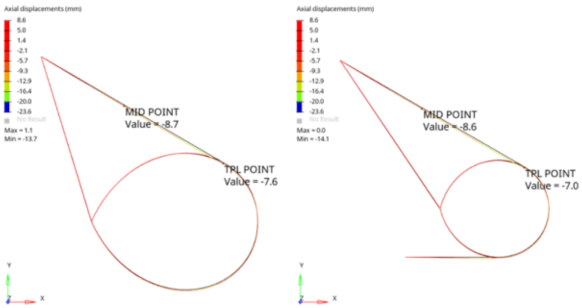

Figure 5: Comparison of DB-1 (left) and DB-2 v2 (right) deflections at peak entry load.

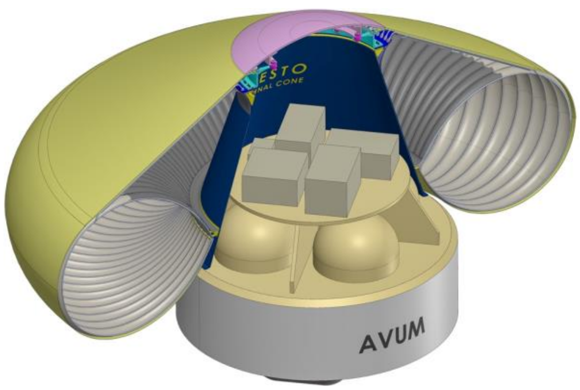

Figure 6: 3D model of the Earth application DB-1 IAD integrated with AVUM payload.

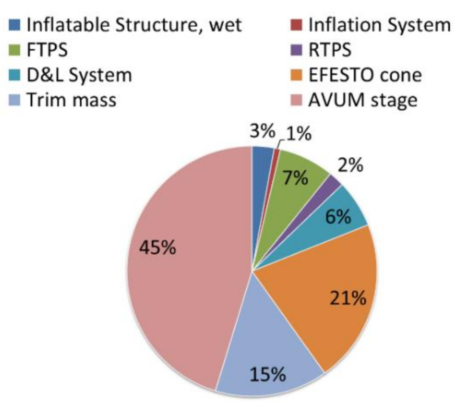

Figure 7: Mass distribution for the reentry configuration of the AVUM study case.

5. DEMONSTRATOR MANUFACTURE

A 2.4-meter diameter (one-half scale) Earth application DB-1 HIAD Demonstrator was fabricated that simultaneously served as Engineering Development Unit (EDU). The HIAD's Inflatable Structure (IS) was fabricated in accordance with the Dual Body design described in Section 3 that incorporates two discrete inflatable volumes. Flight fidelity Zylon® fiber tendons were incorporated to restrain the HIAD's global pressure load. The Zylon® fiber weave of the carrier structure was replaced with Kevlar® as cost saving measure.

The IS structure was integrated with an AVUM representative nose cone and apex bulkhead assembly. A commensurately scaled conical mock-up of the AVUM payload was fabricated for interfacing and support for static deflection testing of the IS. After final assembly and integration, the Demonstrator was suspended for proof pressurization, pressure decay tests, and for general review and inspection. Nominal Annulus pressure is 27 kPa and 5 kPa for the Conic volume.

Figure 8: Aft view of the deployed DB-1 HIAD Demonstrator.

6. DEMONSTRATOR TESTING

Numerous ground tests were performed on the HIAD EDU, primarily to demonstrate its structural integrity under loading the conditions anticipated during re-entry phase and to provide key data to anchor numerical model correlation. The test campaign comprised:

1. Packaging, compression, stowage, and deployment testing
2. Integration of the IS with the exterior F-TPS assembly
3. Investigation of IS geometry in static deflection testing that mimics the effect of the full range of flight-like dynamic pressures
4. Pressure restraint tendon load measurements throughout operational loading conditions

After IS integration with the simulated AVUM payload, IS packaging, compression, stowage, and deployment phases were investigated. The perimeter of the IS was folded upward to reduce its axial length to match the height of the payload. To facilitate dimensional reduction in the circumferential sense, the excess IS material was absorbed in six flange folds (Figure 9 left) that were subsequently pleated flat (Figure 9 right). A plexiglass "bell" had been fabricated to simulate the geometry of the payload fairing. To assume the correct fit within the dimensional constraint of the fairing, the folded IS was circumferentially “reduced” through progressive tensioning of compression straps. The test assembly was configured to release the straps upon removal of the fairing bell to permit IS inflation. Multiple trials comprising folding, compression, stowage, and ultimate release of the IS were performed according to the test plan, leading to successful final deployment of the IS (Figure 10).

Figure 9: IS folding and stowing phase

Figure 10: IS static inflation phase (prior to deflection).

In the second test phase, the Flexible TPS system was fitted to the IS. Inflation of the integrated assembly was successful, demonstrating the desired F-TPS geometry and deployed tautness.

The HIAD, complete with its F-TPS, was subsequently subjected to static load testing. Atmospheric entry conditions corresponding with maximum dynamic pressure were replicated in the test by applying uniform loading to the frontal surface of the HIAD. To replicate these loads, the HIAD was positioned in a vacuum pool (Figure 11). The vacuum pool test simulates application of frontal dynamic pressures associated with atmospheric entry by allowing a vacuum to be drawn on the aft surface of the HIAD. The support application of a vacuum, the frontal surface of the HIAD was covered with a non-porous membrane that was hermetically sealed to the rim of the vacuum pool. Upon application of vacuum-induced deflection loads, the frontal surface of the HIAD assumed the desired conic profiles, and no leakage of inflation gas was discerned.

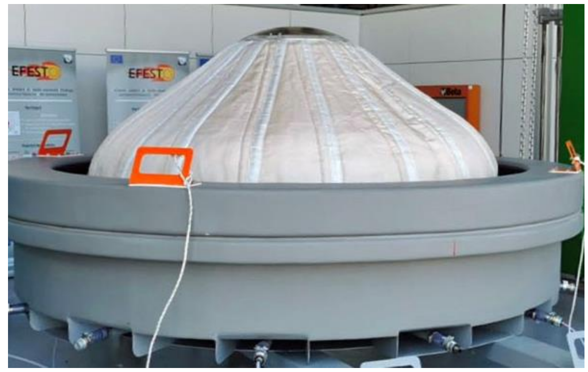

Figure 11 : IAD with integrated F-TPS positioned in static deflection test pool.

For the fourth and final phase of testing, load cells were installed to measure the tensile forces assumed by eight different meridional tendons under a variety of HIAD load conditions. This test phase supported further characterization of the HIAD structural performance, and provided key data to help validate the computational model. A favorable, predominantly linear, correlation of tendon force with HIAD load was observed (Figure 12).

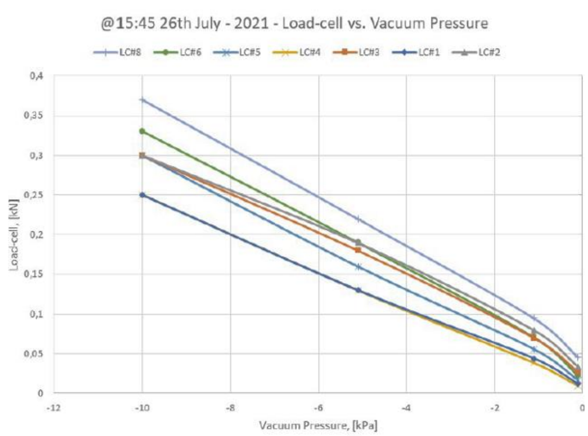

Figure 12: Tendon force correlation with simulated dynamic pressure.

To further correlate observed HIAD deflection with analytical models, a rudimentary measurement system was implemented in conjunction with photogrammetric analysis.

7. PHOTOGRAMMETRY

To gain a clearer perception and a quantitative evaluation of the behavior of the inflatable system under flight-like pressure loads, the test conditions were numerically reconstructed and modelled using 3D photogrammetry. The process consists of acquiring imagery of the HIAD under test conditions to recreate a 3D model of its observed shape. The 3D reconstructed models are then interpolated with smooth surfaces that are then usable for quantitative evaluations.

Figure 13 shows the 3D reconstructed model of the test article for one particular test case. The model also includes realistic colorization as well as camera location for each picture acquired.

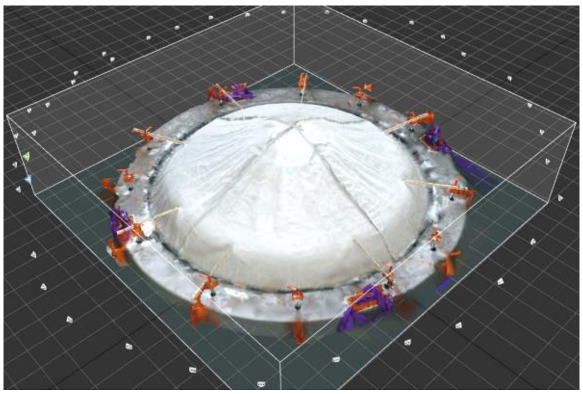

Figure 13: 3D reconstructed model of the test rig and test article at epoch 1 of the TC 4.

Figure 14 shows the comparison between the section of the theoretical model (continuous black lines) and the reconstructed model at initial application of the load, and at the end of the loading phase, when the frontal HIAD surface assumes its full load.

8. NUMERICAL/EXPERIMENTAL CORRELATION

It was observed during the static deflection tests that the inflated HIAD sustained a greater deflection than was analytically predicted by the models. This discrepancy was found to be the result of the added vacuum load to the unsupported perimeter regions of the non-porous membrane. As discerned in Figure 14, the non-porous membrane no longer enjoys the support of the HIAD once it extends outwards past the outer diameter of the HIAD and towards the edge of the vacuum pool where the perimeter of the membrane is clamped. Not only does this rather large unsupported surface area add to the deflective loads on the HIAD, a notable portion of the non-porous membrane load also pushes the outer edge of the HIAD radially inward. It was concluded that the noteworthy discrepancy between experimental and numerical data was induced by the additional loads caused by the test setup, i.e., forces not present in flight conditions, and therefore not modelled in the design phase.

Moreover, calculations demonstrated that the cumulative non-supported surface area of the non-porous membrane is actually greater than the area supported by conical part of the HIAD. The final of evaluation of loads indicated that, during the tests, the global frontal load applied to the HIAD was almost two times greater than the design load. Experimental results were used to update the numerical model developed for the structural predictions. Figure 14 compares the HIAD's axial profile of the analytical model with both the measured deformation and the updated numerical results, showing good correlation between the updated model and the measured deformation.

In retrospect, this "unwanted" overload proves the extreme resilience of this HIAD Dual Body architecture.

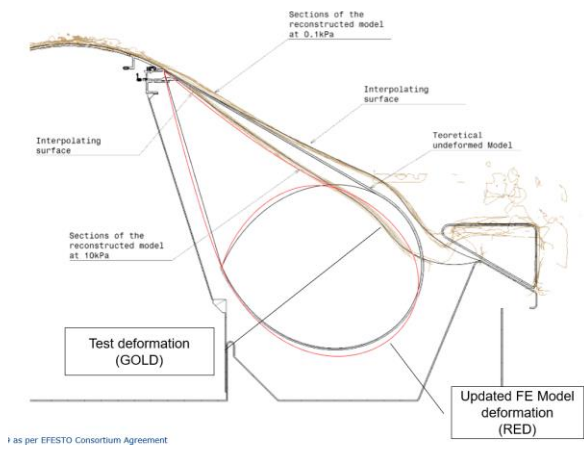

Figure 14: Comparison axial profiles of the analytical model with both the measured deformation and updated numerical results.

9. CONCLUSIONS AND PATH FORWARD

Activities Completed

The following activities have been completed in fulfillment of the intended scope of the EFESTO project:

- The novel Dual Body IAD design has been adapted to the proposed Earth and Mars mission scenarios.
- IAD design has been executed by means of simplified and thereafter highly detailed CAD models.
- Progressively iterated, axially symmetric FEM models were generated to support structural verification of the Dual Body design in flight conditions, as well as definition of the optimum pressures for the two inflatable volumes.
- A high fidelity, half-scale HIAD Inflatable Structure Engineering Development Unit was

manufactured and ground tested with a focus on flight-like static deflection.

- The comparison of the design displacements with the measured displacements showed discrepancies. However, after review, the test conditions revealed commensurate discrepancies in load conditions.
- Post-test numerical FEM models were improved, implementing a more sophisticated material modeling, as well as implementing modified pressure lever for the conical volume to provide a very small IAD deformation under flight loads.
- Experimental activities have also been beneficial in updating the numerical modeling of the folding and deployment phases that are fundamental for estimating the stowed volume that must be allocated, and for predicting the inflation dynamics.

Figure 15: Dual Body EDU incorporating permanent conic profile architecture.

The Dual Body architecture as reflected by the current Demonstrator was configured in such a way that its geometry assumes the desired conic frontal profile under influence of the dynamic load environment.

As such, in case of an initial deployment in a vacuum—and prior to encountering dynamic flow—the IS initially assumes the slightly "circularized" axial profile as seen in Figure 10. While this design approach embraces the absolute simplest Dual Body configuration, there may arise mission constraints wherein a defined conic geometry is desired—even in a vacuum. While more complex to facilitate, a high fidelity, 2.5-meter class "permanent geometry" version of the versatile Dual Body architecture was fabricated and is pictured in Figure 15.

The activities carried out have increased the TRL to 4 "Component and/or breadboard functional verification in laboratory environment".

Future Activities

The primary focus of future activities will be to move the herein investigated novel IAD architecture towards flight—both at sub-scale, and ultimately at full scale. As such, immediate follow-on activities would encompass more advanced deflection testing of flight-like hardware; implementation and assessment of flight-like interfaces and materials; and development of advanced 3D FEM modeling simultaneously suitable for modal investigations.

10. ACKNOWLEDGMENTS

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12. ACRONYMS

IS	Inflatable Structure
AV	Annulus Volume
CV	Conic Volume
D&L	Descent and Landing
DB-1	Dual Body type "1"
DB-2	Dual Body type "2"
TPS	Thermal protection System
F-TPS	Flexible Thermal Protection System
R-TPS	Rigid Thermal Protection System
TRL	Technology Readiness Level