THE ICARUS PROJECT: INFLATABLE CONCEPT AEROSHELL FOR THE RECOVERY OF A RE-USABLE LAUNCHER STAGE (A FLIGHT DEMONSTRATION INITIATIVE)

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ABSTRACT

ICARUS is a project funded by the European Union's HORIZON EUROPE program, under the grant agreement #101134997.

The project targets to bring up to TRL-6 the maturation of enabling technologies of the Inflatable Heat Shields (IHS), an innovative re-entry solution for re-usable space transportation systems, deemed applicable for recovery of Launch Vehicles stages.

This paper will present the project overview and set-up, the engineering work executed so far, and the effort planned to be carried out up to completion. A thorough insight will also be included on the system design of the Aerodemonstrator solution with a particular focus on: aeroshape definition and characterization, configuration and layout development, thermal and mechanical design assessment, key sub-system conceptual design and sizing, and system synthesis.

1. INTRODUCTION

ICARUS stands for "**I**nflatable **C**oncept **A**ero-shell for the **R**ecovery of a re-**U**sable launcher **S**tage", and it targets maturing up to TRL-6 the technologies enabling Inflatable Heat Shields for Earth re-entry missions.

In its baseline, an Aerodemonstrator of an IHS will be flight-tested through a sub-orbital flight executed by a sounding rocket launched in ESRANGE and managed by DLR-MORABA.

A concept of the ICARUS re-entry vehicle is given in Figure 1.

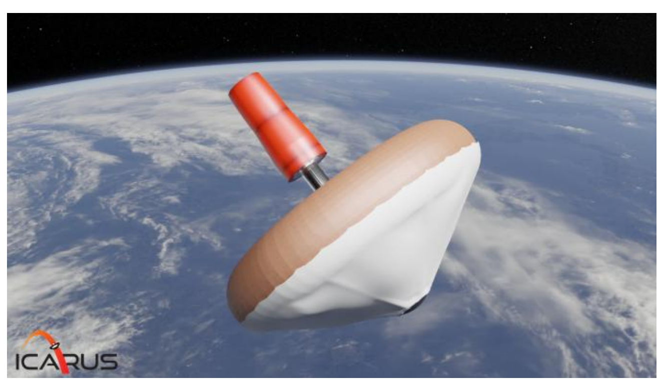


Figure 1 – ICARUS Re-entry concept

In Europe, the two projects EFESTO and EFESTO-2, funded by the European Commission respectively under the programs H2020 (2019-2022) and under Horizon Europe (2022-2024), constitute the solid playground that ICARUS is leaning on, as documented in [1] to [4].

The aforementioned projects can be considered, respectively, the grandfather and the father of ICARUS, because they allowed to bloom and grow-up in the EU the knowledge and capabilities in the field of IHSs.

However, although a significant TRL increase was achieved in the frame of EFESTO and EFESTO-2, both were focused on ground-verification only.

Instead, the ICARUS project is a flight demonstration initiative aiming at bringing together the results obtained so-far, with in addition a significant delta-development together with validation of the technologies and system capabilities in a flight-relevant environment.

From that perspective, the project will pursue the following end goals:

a. complete the maturation on ground of the key technologies, such as Flexible Thermal Protection Systems, Inflatable Structure and Health Monitoring Sensors;
b. carry out a mission/system design loop to realize a meaningful-scale demonstrator of a re-entry vehicle adopting an Inflatable Heat Shield;
c. execute the flight mission and the post-flight analysis for technology performance evaluation, system behaviour identification, and models verification/cross-correlation;

The project organization (**Error! Reference source not found.**) consists of eleven partners under the coordination of Indra-Deimos, for a full EU team, and it brings together key players with a relevant heritage in the field of sounding rockets and flight testing, as well as in engineering and technology development of re-entry systems and Inflatable Heat Shield systems.

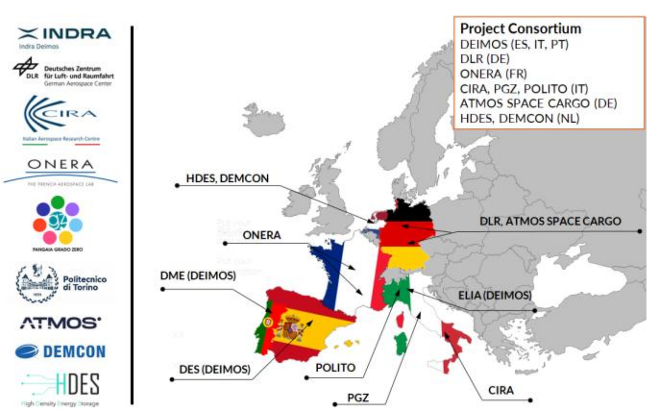


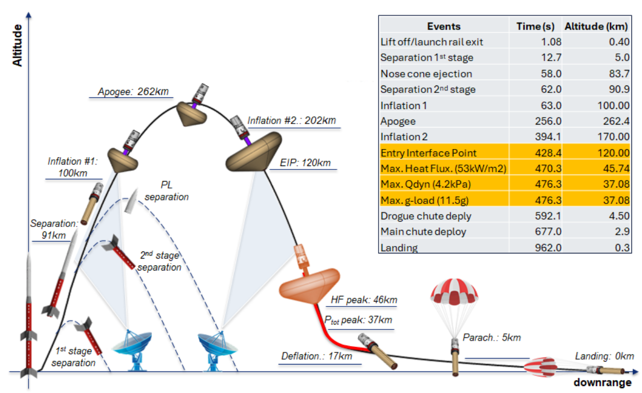
Figure 2 – ICARUS Industrial Team

The industrial team roles are the following:

- Indra-Deimos (ES, IT, PT): programmatic and technical coordination and design authority
- DLR-MORABA (DE): leading the sounding-rocket flight test definition and implementation
- DLR-Cologne (DE): leading the development of a dedicated in-flight measurement system
- ONERA (FR) leading the aeroshape design and investigation
- CIRA (IT) leading the development of the Flexible Thermal Protection System
- ATMOS SPACE CARGO (DE) leading the development of the Inflatable Structure
- HDES (NL) leading the development of the Inflation System
- PANGAIA GRADO ZERO (IT) leading the development of innovative strain-gauge sensors
- DEMCON (NL) leading the development of innovative fiber-based sensors
- POLITO (IT) leading the dissemination, communication and exploitation

2. MISSION DESIGN

As part of the early engineering loop, in tight iteration with aeroshape characterization, launcher configuration customization and trajectory analysis, the mission design yielded to a Concept-of-Operations (ConOps) as depicted in Figure 3.



Events	Time (s)	Altitude (km)
Lift off/launch rail exit	1.08	0.40
Separation 1st stage	12.7	5.0
Nose cone ejection	58.0	83.7
Separation 2nd stage	62.0	90.9
Inflation 1	63.0	100.00
Apogee	256.0	262.4
Inflation 2	394.1	170.00
Entry Interface Point	428.4	120.00
Max. Heat Flux. (53kW/m2)	470.3	45.74
Max. Qdyn (4.2kPa)	476.3	37.08
Max. g-load (11.5g)	476.3	37.08
Drogue chute deply	592.1	4.50
Main chute deploy	677.0	2.9
Landing	962.0	0.3

Figure 3 – ICARUS mission ConOps

The obtained mission is an almost standard "6 min micro-gravity trajectory" pretty close to similar endeavours as DLR's MAPHEUS program, the German national microgravity research program TEXUS, and SSC's Suborbital Express program.

The baseline sounding-rocket configuration is composed of two Red Kite motors and an upper payload segment that is actually a sort of hybrid/synergic combination between the payload segment and the Aerodemonstrator (Figure 4).

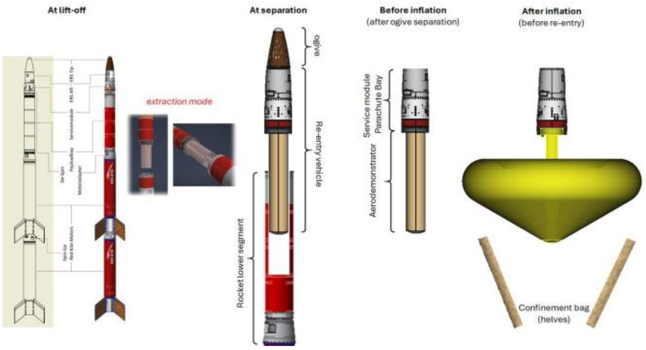


Figure 4 – ICARUS re-entry vehicle & rocket

The trajectory consists of a classical nearly vertical flight-path with launch elevations in the range [85÷89]deg, a maximum ground range of up to 90km, and an apogee in the order of 250km.

During the ascent phase the inflatable aeroshell with the corresponding subsystems is integrated into a cylindrical payload structure (or the rocket upper segment).

After separation (≈90km), the vehicle configuration will change to the re-entry and experimental architecture, featuring an inflated aeroshell attached to a cylindrical body (i.e.: the Aerodemonstrator with the additional payload subsystems).

Opposite to the classical micro-gravity missions, the focus of the ICARUS project is set to the re-entry experiment window opening at 120km on the down-leg until ≈17km altitude. The re-entry experiment vehicle has to be recovered after the flight to allow for post flight inspection, onboard data retrieval and post-processing.

Figure 5 provides the trajectory footprint over the Esrange area obtained by mission analysis.

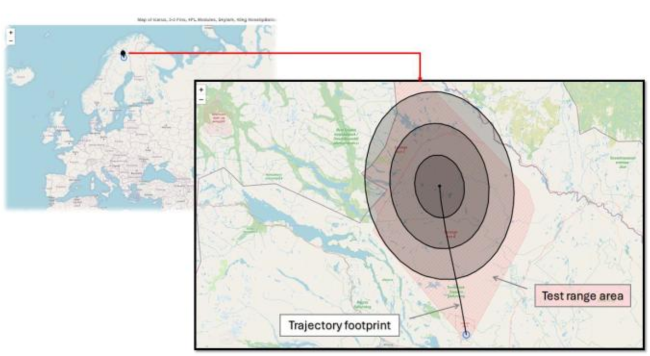


Figure 5 – ICARUS trajectory footprint

The re-entry demonstrator will be launched on board a sounding rocket customized and operated by DLR-MORABA at Esrange in Q1 of 2028.

A detailed description of the flight test design is given in the parallel paper [5].

3. SYSTEM DESIGN

An engineering loop was carried out to feed appropriate trade-off and obtain a design compliant with the system and mission requirements. Different disciplines were involved:

- aeroshape design, with aerothermodynamics and aerodynamics investigations and assessment, including flying quality
- mission and trajectory analysis
- sub-systems engineering: thermal protection, inflatable volume, gas generation, cold structure
- avionics architecture definition and sizing
- definition of measurement system and identification of a related sensors suite

The system engineering yielded a baseline configuration of the re-entry vehicle (RV) as a hybrid combination between the rocket payload segment and the aero-demonstrator of an Inflatable Heat Shield. (Figure 6)

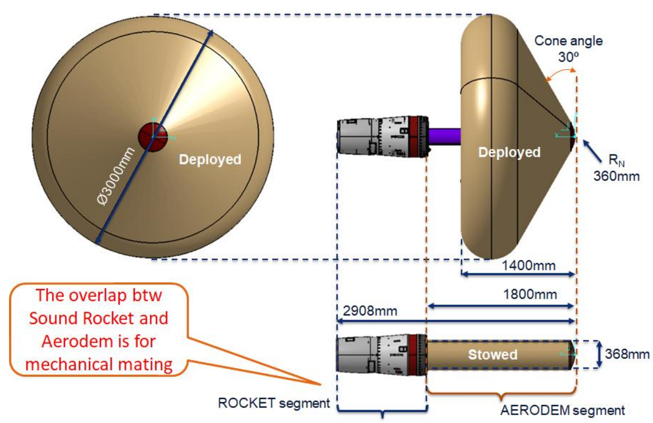


Figure 6 – ICARUS RV configuration

The Rocket P/L segment includes:

- the Service Module
- the parachute bay
- the separation bay

The Aerodemonstrator segment includes:

- the Flexible Thermal Protection System (F-TPS)
- the Inflatable Structure (IS)
- the load-carrying Structure (STR)
- the Avionics system (AVS)
- the Health Monitoring System. (HMS)
- the Cool Gas Generator system (CGG)

The demonstrator will exhibit a sphere-cone aeroshape with a 120 deg cone-angle and 3 m diameter. (Figure 6)

The aeroshape has been obtained with a dedicated engineering effort based on CFD investigation (Figure 7) both for aerodynamic and aerothermodynamic characterization. Details are given in the parallel paper [6].

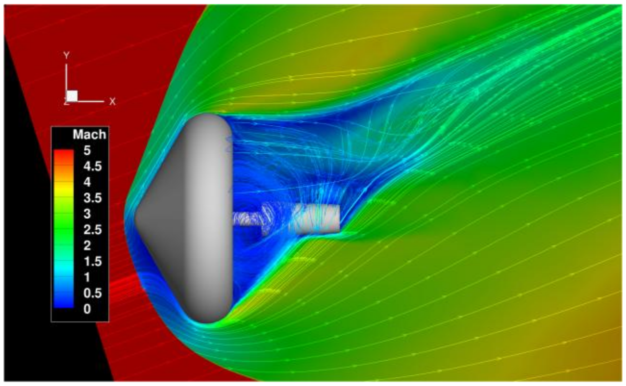


Figure 7 –CFD flow-field (@45 km, Mach 5.1, AoA = 20)

The system architecture and internal layout are the optimized balance among different needs: aeroshape, rocket stay-in volume, functional tree, stability, mechanical and thermal performances, assembly and integration flow. (Figure 8, Figure 9, Figure 10)

Service and sensors harness will go across the full body length to allow interaction among the different equipment.

The RV full-stack estimated mass at launch is ≈340kg, with a mass distribution as resumed in Figure 11.

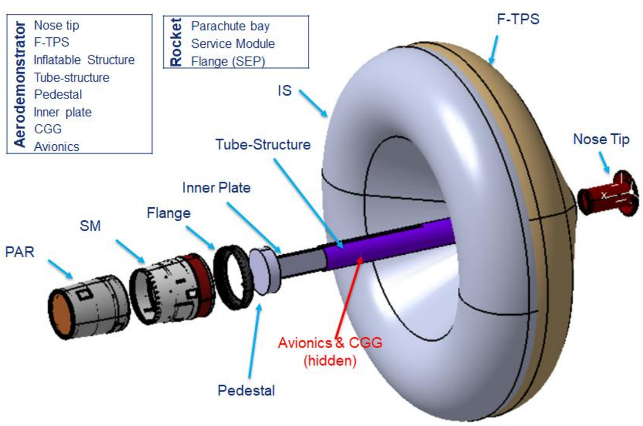


Figure 8 – ICARUS architecture

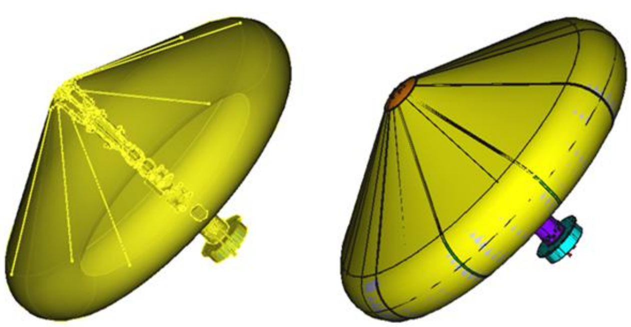


Figure 9 – ICARUS Aerodemonstrator only

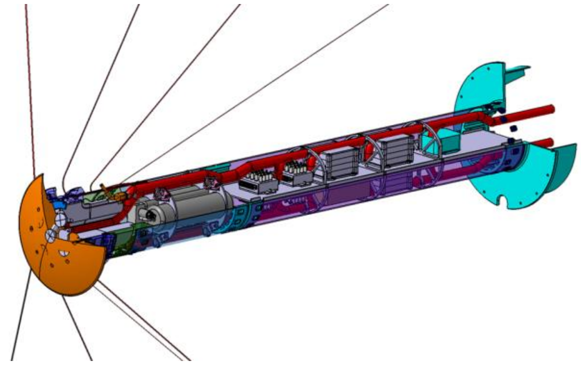


Figure 10 – ICARUS Aerodemonstrator internal layout

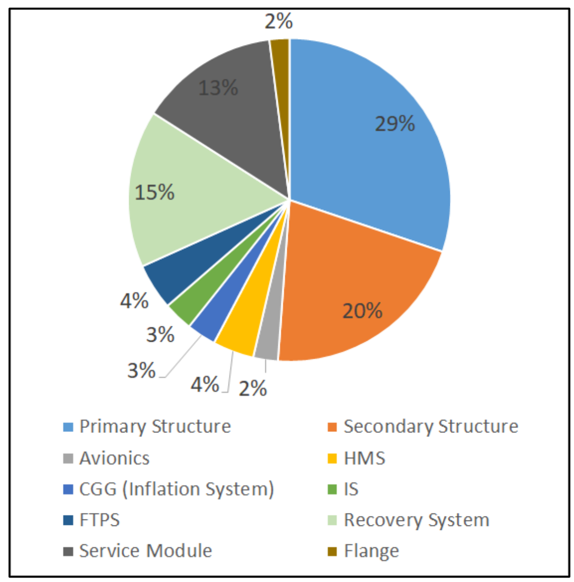


Figure 11 – ICARUS RV mass-budget

4. KEY TECHNOLOGY AND SUB-SYSTEMS

4.1. Flexible Thermal Protection Systems

One of the key elements of an Inflatable Heat Shield is the thermal protection, that in this case shall be also flexible.

For the ICARUS re-entry vehicle, a dedicated effort is being carried out under CIRA lead (IT) to design, develop, test on ground and then in flight a flexible 3D TPS skirt to enable the ICARUS mission to take place.

The activity leans on CIRA and EFESTO legacy heritage, and it is fed by specific system and mission level inputs (e.g.: aerothermal load, shear loads, aeroshape envelope, system configuration and interfaces, etc.).

Figure 12 and Figure 13 show part of the engineering action currently in place for the F-TPS design definition.

Details of the sub-system and the related technology challenges are given in the parallel paper [7].

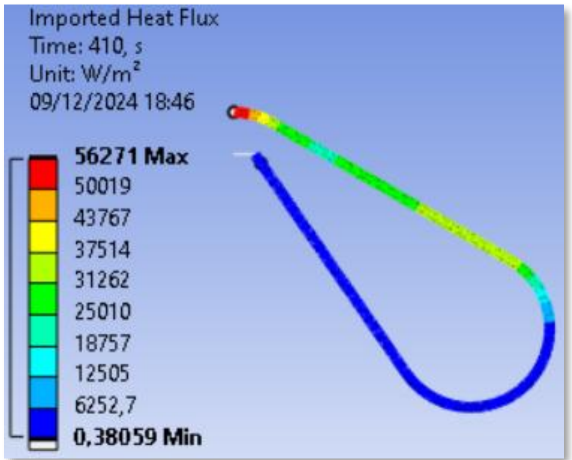


Figure 12 – F-TPS load distribution (heat-flux)

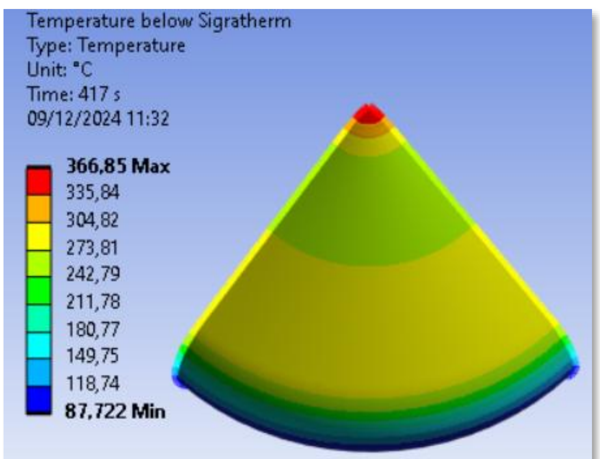


Figure 13 – F-TPS 3D numerical model output

4.2. Inflatable Structure

The second key element of an Inflatable Heat Shield is the inflatable structure. Similarly to the F-TPS, a dedicated effort is being carried out under ATMOS SPACE CARGO lead (DE) to design, develop, test on ground and then in flight a 3D Inflatable Structure.

The activity leans on ATMOS in-house technology and it is fed as well by system and mission level inputs (e.g.: aerodynamic pressure pattern, aeroshape envelope, system configuration and interfaces, etc.).

Extensive modelling, bread-boarding and testing are under way to mature the TRL up to 5 before the flight.

Figure 14 and Figure 15 show part of the engineering action currently in place for the IS design definition.

Details of the sub-system and the related technology challenges are given in the parallel paper [8].

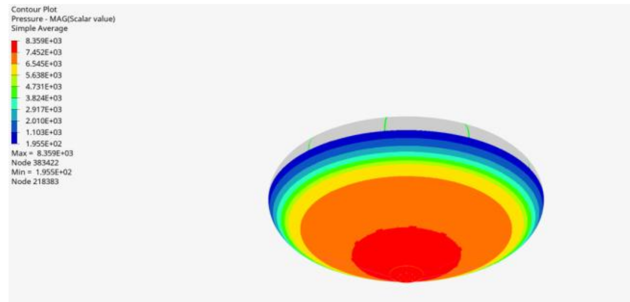


Figure 14 – IS load distribution (external pressure, [Pa])

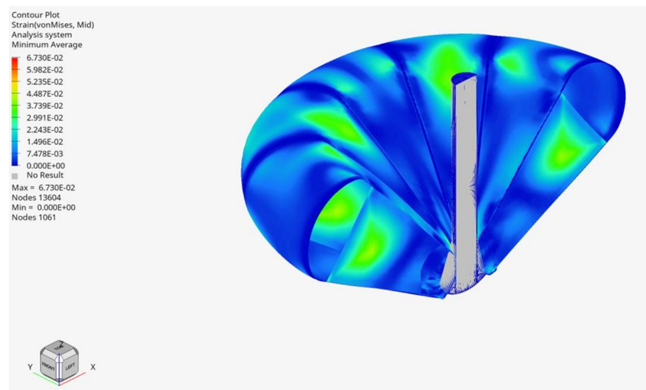


Figure 15 – IS 3D numerical model output (strain)

4.3. Cool Gas Generator

The Cool Gas Generators system is in charge of producing the amount of gas to inflate the aeroshape before atmospheric entry starts (@120km, namely.) The CGG system is being developed by HDES (NL) with an innovative solution based on the adoption of "non-reacted porous grain" collected into a cylindrical cartridge able to produce CO_2 upon firing of a non-explosive igniter (in-house developed).

The current CGG baseline (Figure 16) includes a set of 4 CGG cartridges (two small and two big), integrated into a dedicated segment of the Aerodemonstrator body. The CGG assembly includes also a manifold along with pneumatic lines and interfaces.

Details of the CGG are given in the parallel paper [8].

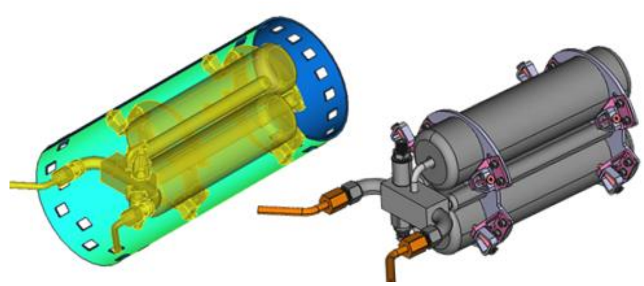


Figure 16 – CGG assembly

4.2. Health Monitoring System

The HMS encompasses the full sensor-suite along with the related avionic components to ensure the conditioning of sensing devices as well as the collection and storage of measurement data.

The HMS will lean on both conventional and innovative sensors: the former includes thermocouples, pressure transducers and heat-flux gauges; the latter include innovative sensors able to cope with flexible matter.

Furthermore, a set of dedicated cameras is also foreseen on board the spacecraft, to perform footage of the flight with a focus on specific aspects within the infrared and visible spectrum.

The HMS design definition is led by DLR-Cologne with the strategic contribution of Demcon (NL) and Pangaia Grado Zero (IT), respectively for the development of fiber-based sensors (strain-gauges, temperature transducers, and accelerometer) and innovative strain sensors.

Figure 17 depicts a partial schematic of the HMS, more details of the HMS are given in the parallel paper [9].

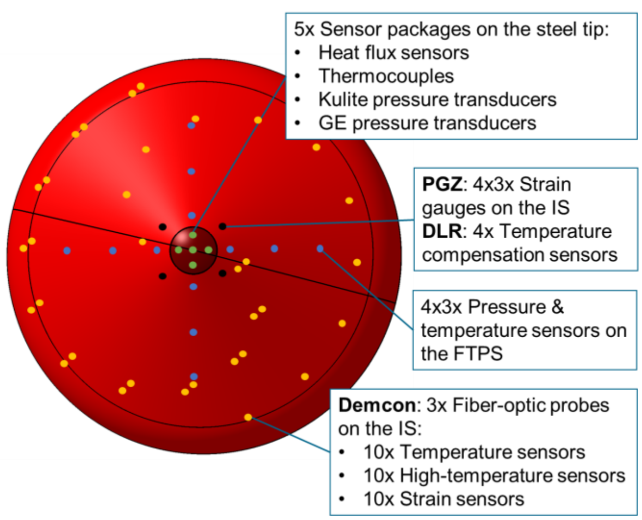


Figure 17 – HMS schematic concept

4.5. Avionic System

As already mentioned, the ICARUS avionic system is based on a synergic combination of the rocket resources (Service Module) and the Aerodemonstrator equipment.

The former is devoted to the management of the mission with respect to rocket motors' ignition, event separations, parachute activation and deployment, power feed, GPS interface and communication to/with ground.

The latter is devoted to management of the inflation, the scientific sensor-suite (HMS) and the GN&C experiment.

The Aerodemonstrator will be electrically mated with the rocket Service Module through the bottom section (pedestal) with a range of interfaces (RS422, GNSS signal, etc.).

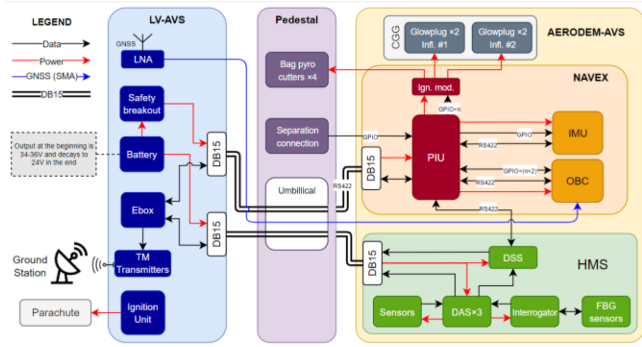


Figure 18 – ICARUS avionic system

Power feeding will be ensured continuously by the rocket Service Model battery pack., while an ad-hoc device (PIU) will handle the activation of a couple of cutters to release a confinement bag and afterwards trigger the inflation by firing the Cool Gas Generators and get an inflated aeroshape before atmospheric entry starts (i.e.: @ 120km).

The HMS is considered part of the avionics system, and it includes a set of data acquisition boards, a set of break-out boxes, a set of cameras, and a dedicated crash-resistant memory device (DSS) to collect the full flight-data set for post-flight analysis.

In addition, part of the flight-data will be transmitted on ground during the mission by the Service Module TT&C.

4.5. Load-carrying Structure

The ICARUS system will be integrated around a central body frame acting as main load-carrying element.

The structural architecture has been designed to combine different needs: mechanical and thermal performance, modularity, flexibility in integration, accommodation of sub-systems, provision of interfaces, material choices, ballast needs, and equipment layout optimization vis-à-vis internal interfaces and mutual interactions of the different elements of the vehicle.

The current baseline builds upon a set of segments that once mechanically mated will concur to both structural and functional continuity from the nose apex to the base.

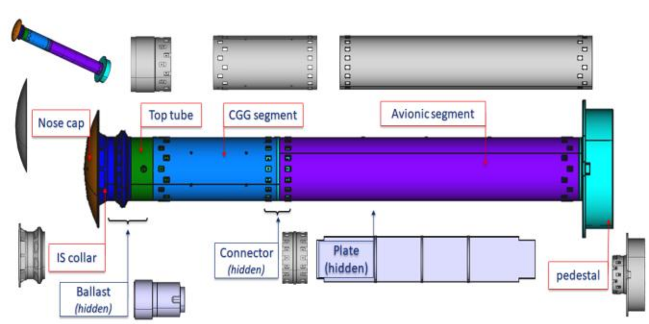


Figure 19 – Load-carrying structure architecture

Both structural and thermal design have been injected into the definition of the main structure. (Figure 20, Figure 21, Figure 22)

The former (led by Indra-Deimos) to verify the capability of the system to withstand the flight environment (e.g.: maximum g-load and vibrations induced by the rocket, maximum g-load during atmospheric deceleration, buckling verification).

The latter (led by Pangaia Grado Zero) to verify the capability of the system to manage and distribute the thermal loads induced either by the atmospheric flight (aerothermal) or by the internal sources (i.e.: power dissipation and CGG heat generation).

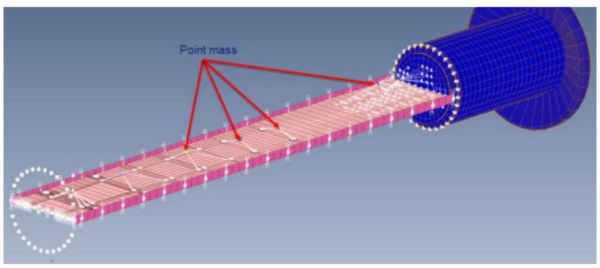


Figure 20 – Structural design and analysis (FEM)

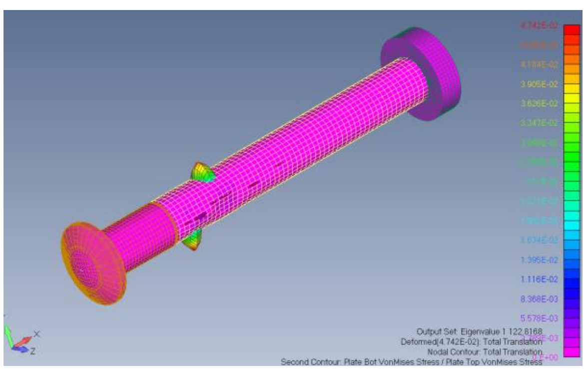


Figure 21 – Structural design and analysis (buckling)

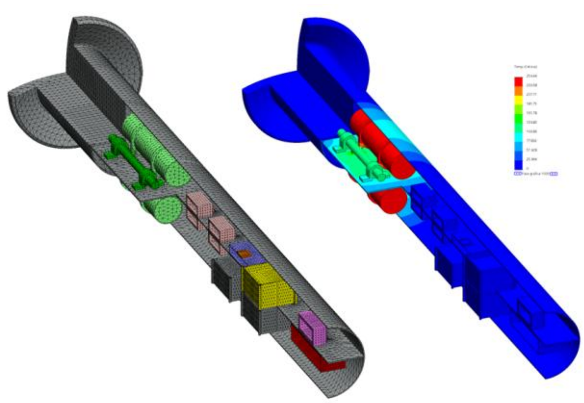


Figure 22 – Thermal design and analysis

The current design definition is very satisfactory from both structural and thermal standpoints because: the structure exhibits always a positive margin-of-safety in quasi-static analysis, no risk of buckling nor lateral bending was identified, and no risk of overpassing material or equipment allowable with respect to maximum temperature reached during the flight was neither collected.

5. PROGRAM ROADMAP AND WAY-FORWARD

The ICARUS project plan spreads over a period of forty-five months (Figure 23). It started in June 2024 with the kick-off and will end beginning of 2028 with the flight execution and post-flight analysis and synthesis.

The work-action implementation is based on a tailored ECSS-standard approach with a set of reviews along the project life-cycle to perform progress checks. The review process involves both the industrial team as well as the Customer (European Commission).

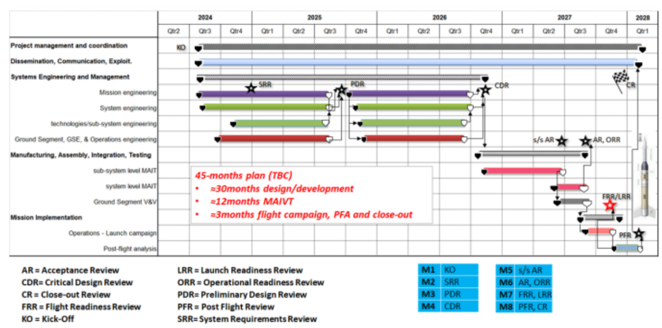


Figure 23 – ICARUS project master-plan

In December 2024 the project passed the System Requirement Review, the current design gives a fair good feasibility figure and a satisfactory outcome with respect to both system and mission aspects.

The project is approaching a Preliminary Design Review before the end of 2025, while 2026 will allow the consolidation of the detailed design to be closed at the CDR.

A significant ground-test effort is planned to take place between Q4-2025 and Q4-2026 to provide qualification maturation as detailed in the parallel papers [7], [8], and [9].

The 2027 will be fully dedicated to manufacturing, assembly, integration and testing (MAIT), at sub-system level first, then at system level. A dedicated GSE will be realised to support this phase (Figure 24, Figure 25).

The flight campaign will start beginning of 2028 with the aim to complete the flight-test and postflight analysis (PFA) by the end of the project foreseen in February/March 2028.

The PFA will be organized in two stages: system assessment and technology assessment. Both will allow for evaluation of the design solution as well as the TRL of the key elements of the project.

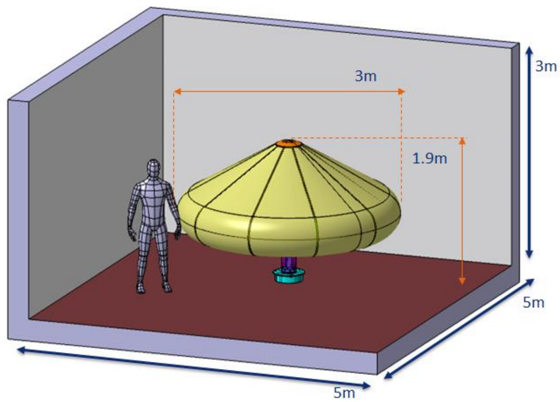


Figure 24 – ICARUS during AIV/AIT

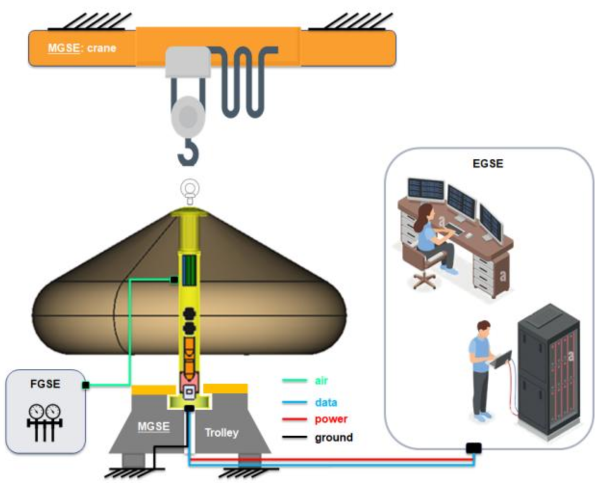


Figure 25 – ICARUS and its GSE

8. ACKNOWLEDGMENTS

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More information at:

- https://www.he-icarus-project.eu/
- https://cordis.europa.eu/project/id/101134997
- https://www.linkedin.com/company/he-icarus/

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