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Focus on Low-Cost Light-Weight Upper Stage within ESA's Future Launchers Preparatory Programme (FLPP)

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Abstract
With a 1:1 impact on payload capacity, improvements on a launcher upper stage result in significant improvements in launcher performance. Starting in 2018 work has been ongoing in FLPP NEO on an optimised upper stage for an evolution of Ariane 6, where configuration studies have shown a payload performance gain of over two tonnes for GTO missions is achievable, whilst also reducing the recurring cost of the stage. The work on the upper stage is integrated in approach, working across the FLPP System/Services – Demonstrators – Technologies domains. This paper presents the current status of the associated projects.

Acronyms/Abbreviations

A(L)M Additive (Layer) Manufacturing
AFP Automatic Fibre Placement
CFRP Carbon Fibre Reinforced Polymer
CNES Centre National d'Etudes Spatiales
COTS Components Off The Shelf
CSG Centre Spatiale Guyanais
DLR Deutsches Zentrum für Luft- und Raumfahrt
EIT Equipped, Integrated Tank
ETF Engine Thrust Frame
ETI External Thermal Insulation
ETID Expander-cycle Technology Integrated Demonstrator
FBG Fiber Bragg Grating
FLINT Fluid system Integrated Thrust frame
FLPP Future Launchers Preparatory Programme
GTO Geostationary Transfer Orbit
H2O2 Hydrogen Peroxide
ISS Inter Stage Structures
LEO Low Earth Orbit
LH2 Liquid Hydrogen
LOX Liquid OXygen
MUSE Multi-functional Upper Stage Express
NDI Non-Destructive Inspection
PDR Preliminary Design Review
PHOEBUS Prototype of a Highly OptimisEd Black Upper Stage
SSO Sun-Synchronous Orbit
T/W Thrust to Weight ratio
TRL Technology Readiness Level

1. Introduction

The ESA Space Transportation Directorate's Future Launchers Preparatory Programme (FLPP) works on new approaches and technologies providing higher performance, larger mission versatility and cost gains to the evolutions of operational launchers as well as supporting new systems, based on the investigation of future space transportation services and advanced/disruptive concepts. FLPP is oriented around a triangle of – System/Services – Technologies – Demonstrators – supporting the maturation of technologies up to their integration into flagship demonstrators, in line with system studies justifying their competitive interest for future service-centric applications, including commercially driven space transportation services. This logic is presented in Figure 1 below.

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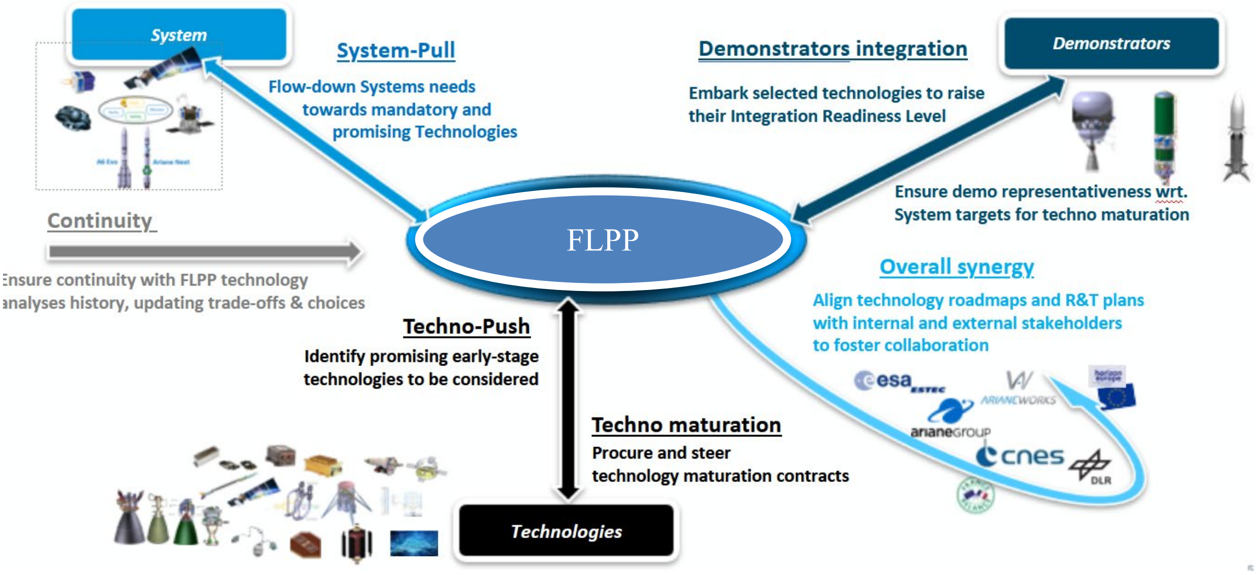

Figure 1: FLPP System/Services – Technologies – Demonstrators Approach

With the 1:1 impact on payload capacity and the identification of promising new technologies applicable to launcher upper stages, FLPP has acted to implement an integrated set of upper stage projects following the System/Services – Technologies – Demonstrators logic:

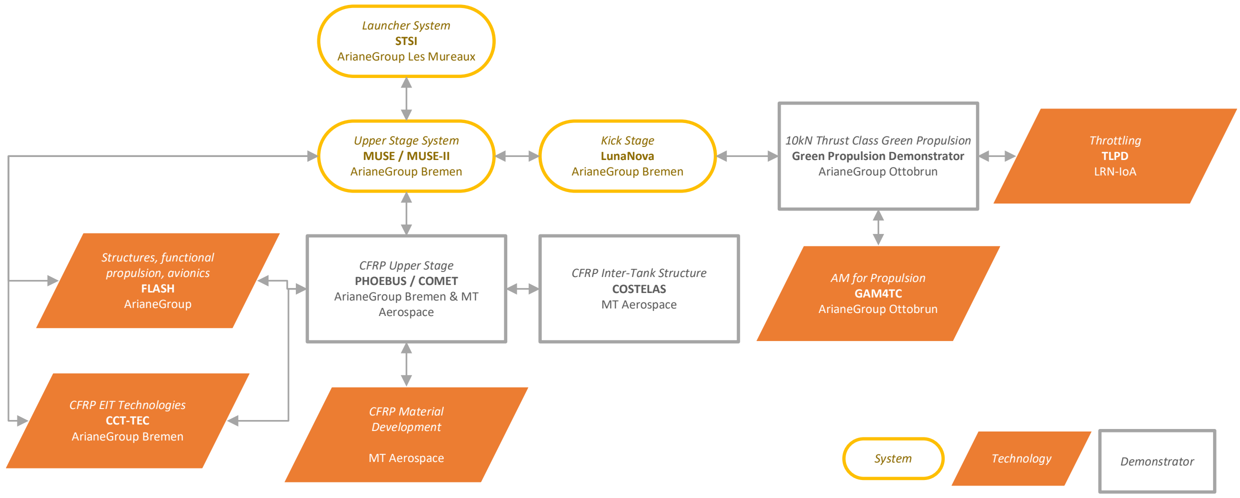

Figure 2: FLPP Upper Stage Project Landscape

Within this project landscape the system level projects identify concepts, architectures and applicable technologies, flowing down applicable requirements to the technology and demonstrator projects. Inversely the technology and demonstrator projects provide updated and confirmed performance data (mass, cost, etc.) for technologies and configurations to refine the system level design. The technology projects mature promising technologies up to a point where they can be integrated onto demonstrators, where they can then be matured in a representative environment up to TRL 6 or even 7. The status of the ongoing projects is outlined in the chapters below.

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1. System

1.1 Launcher System - STSI

Space Transportation phase 0/A corresponds to system activities aiming at investigating future evolutions or evolved Space Transportation concepts, beyond current operational systems. Phase 0/A activities were conducted in three incremental steps, from a large screening (eight macro design loops plus R&T) to two short-listed concepts. Analyses have been conducted against a set of assumptions which were updated at each incremental step and take into account upcoming requirements for institutional missions. The end review of the project took place in Q2 2021 but additional activities were identified and are currently ongoing. The launcher system level analysis provides requirements and relevant environmental conditions (loads) to the upper stage system.

1.2 Upper Stage System – MUSE / MUSE-II

1.2.1 MUSE – Upper Stage Concept

The Multifunctional Upper Stage Express (MUSE) project, kicked-off in 2018, had the initial important task of identifying an upper stage concept, architecture and applicable technologies that would bring significant payload performance gains in future evolutions of Ariane 6. By the end of 2020, an upper stage concept complying to the High-Level Requirements provided by FLPP had been selected, including estimated performance gains and recurring cost reductions and providing outlines of all sub-systems. The selected configuration makes use of the new design possibilities allowed by the application of carbon-fibre reinforced plastic (CFRP) tanks and structures, which are matured in separate FLPP demonstrator and technology projects.

The selected concept has the following principal characteristics:

- Propellant loading 24 tons
- Full composite, separated cryogenic tanks
- LH2 pressurisation: autogenous
- LOX tank pressurisation: Full helium
- Engine Thrust 150kN
- LH2 diameter 5.4m
- LOX diameter 3.6m, suspended
- Integrated Thrust Frame – "FLINT" fluidic and structural component

At the level of a concept review, such an upper stage is compliant with the requirements of performance improvement (> +2 ton to GTO on an Ariane 6) and production cost reduction (-30% estimated). Further information can be found in reference [1].

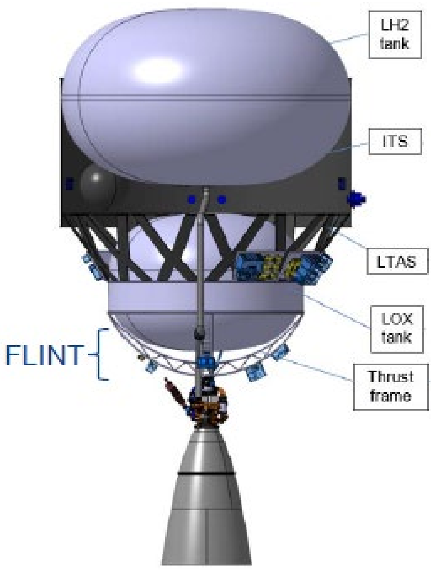

Figure 3: MUSE Upper Stage Concept Design (Credit: ArianeGroup GmbH, Bremen)

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1.2.2 MUSE-II – Versatility

Based on the upper stage concept identified in MUSE, MUSE-II continues the system level work to accompany the ongoing demonstrator and technology projects but also works on the expansion of the upper stage capabilities through mission versatility options i.e. via a kick-stage. but also appropriate end-of-life strategies.

Overall the MUSE/MUSE-II project acts as “Upper Stage System” providing target requirements to PHOEBUS, FLASH etc. but also integrating results from technology and demonstrator projects into refinements of the upper stage model.

1.3 Kick-Stage – LunaNova

This activity is dedicated to the system studies of a versatile green storable kick stage for exploration and heavy payload missions and is coherent with the proof-of-concept missions under study. It aims at finding smart architecture schemes in the upper part of the launcher, and at integrating the latest and emerging innovative technologies like next generation avionics (navigation, communication, telemetry), green storable propulsion or ultra-light structures and tanks. The Architecture Key-Point for this project takes place in summer 2022.

2. Technologies

2.1 CFRP Equipped, Integrated Tank Technologies – CCT-TEC

The objectives of the CCT-TEC project, which ran from July 2018 to June 2021 were the identification and description of potential technologies for a future composite upper stage in cooperation with the project MUSE. The first step was the identification, quantitative ranking and then selection of the most promising technologies for maturation. Following this process, the following technologies were identified and for each technology specific maturation steps were performed, enabling to raise the TRL:

Insulation for CFRP tank: Evacuated sandwich core concept, including thermal and mechanical tests

SMART composite: Fibre Bragg Grating Sensors were selected for maturation and tested at RT, 77K and 4K. Standardized tensile and shear tests were performed. The responses of the FBG were compared with clip-on sensors.

Integrated ETF: A trade-off was performed comparing several concepts, both mass and cost as well as manufacturing aspects, integration aspects etc. were traded. Two concepts were assessed as promising:

- The fluid integrated thrust frame, FLINT, considered as baseline
- Load carrying bulkhead as back-up

Sealed interface: Cryogenic tests of a CFRP cover-plate with metallic pipe interface were performed. Some issues with the sealing occurred under cryogenic conditions. Based on the knowledge gained during these tests the interface design will be improved and retested within the PHOEBUS project.

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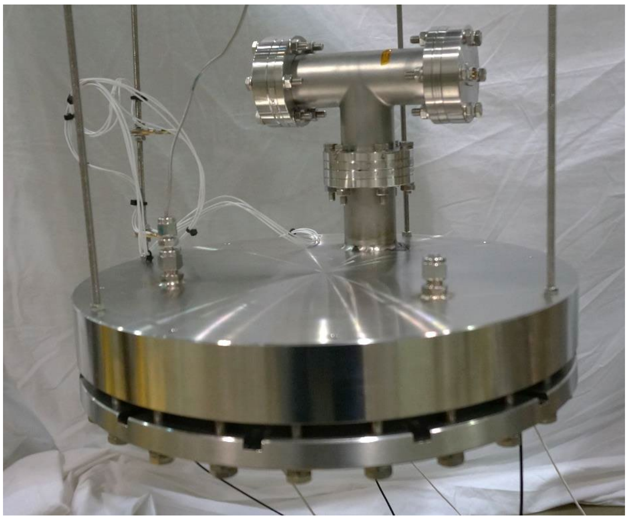

Figure 4: CCT-TEC CFRP Cover – Metallic Line Interface and Fibre-Bragg Grating Test Article (Credit: ArianeGroup GmbH, Bremen and DLR Bremen)

2.2 Structures, Functional Propulsion, Avionics – FLASH

Continuing on from the CCT-TEC project, promising upper stage technologies are matured within the "FLASH" (Future Light-weight Ariane upper Stage tecHnologies) project, kicked off in July 2021.

2.2.1 Structures

Multifunctional sandwich: The technical feasibility of the integration of a radiation shield in the composite cryogenic tank's sandwich structure will be assessed, to ultimately increase the thermal performance, in particular during flight.

Cryogenic bonding: CFRP bonding in cryogenic environments i.e. for the installation of equipment on inter-tanks structures but also within cryogenic tanks is being investigated.

2.2.2 Functional Propulsion

FLINT: The fluid integrated thrust frame (FLINT) is a multi-functional configuration that combines the fluidic routings towards the liquid engine and the thrust carrying structure in one component. The goal is to develop and mature the technology, and then to ultimately test it as a passenger on the PHOEBUS demonstrator. A first demonstrator at ½ Ariane 6 scale of this structure has been built under a German national programme and has now undergone mechanical testing within FLASH up to failure. Detailed analysis is still ongoing but during tests no unexpected ruptures or sudden failures took place and a first look at the results indicates mechanical behaviour similar to predictions.

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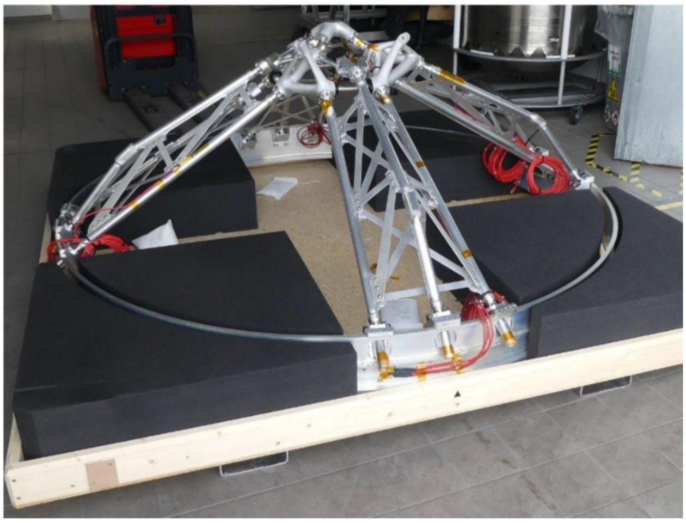

Figure 5: FLASH Project FLINT Thrust Frame Demonstrator (1/2 Ariane 6 scale) for mechanical testing (Credit: ArianeGroup GmbH, Bremen)

Electric Valves Command System: MUSE upper stage system studies have shown the interest of the electrification of the command system – removing the need for pneumatic control. Electrification of valves has the potential to reduce the cost and mass of a future upper stage, as well as providing increased flexibility and functions – for example through valve health monitoring. This electrification at stage level will be investigated and tested at breadboard level, building on electric engine valves designed, built and tested within the ETID project (see Reference [2]).

LH2 Boost Pump: Identified in the MUSE project as a technology with a high potential to allow mass reduction on the upper stage by reducing tank pressure, a first outline of a hydrogen boost pump concept is developed, with the goal to test certain selected technologies.

Evaporation Cooler: To condition the cryogenic propellant, i.e. in the present case liquid hydrogen, during longer duration missions, the evaporation cooler concept is developed and further matured, specifically in terms of manufacturing capabilities.

Helium Strut: Similarly to FLINT, the helium strut approach is a multi-functional configuration that consists of helium pressure tanks, which also serve as tank-connection structure, all combined in one component.

2.2.3 Avionics

Smart On-Board Data Mining: New compression and data pre-processing algorithms would allow for an optimised usage of launcher telemetry during flight. The present activity will identify potential subsets of data that are of interest for a development.

COTS Avionics: New opportunities for commercial of the shelf (COTS) avionics components are identified and characterised with respect to critical requirements.

2.3 CFRP Material Development

One key challenge to a low-cost light-weight upper stage is the CFRP material, which must store the cryogenic propellants under leak-tight conditions, and which must sustain the mechanical loads imposed onto the structure during handling, operations, and flight. As outlined below, the PHOEBUS project successfully conducted testing on sample and small-scale bottle level with a suitable CFRP material and concluded the material choice for the demonstrator programme in late 2021. The material chosen is leak tight under cryogenic conditions with regard to the propellants (liquid hydrogen and liquid oxygen) and withstands chemical reaction with liquid oxygen within the required energy range. However challenges with the selected material remain, such as the source outside of Europe, namely in the United States, the needed know-how for processing the CFRP fibre-tapes, and the large material price costs imposed

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by the supplier. In the long-term, to achieve the price reduction requirements for a future upper stage, and to guarantee Europe's independence, a specific material development project, using the requirements of the PHOEBUS project will be initial in Q3 2022.

2.4 Additive Manufacturing for Propulsion – GAM4TC

2.4.1 10kN Scale (Kick-stage)

Additive manufacturing technologies for the 10 kN thrust range are related to the green-propulsion demonstration activity (outlined below). A Requirements and Concept Key Point has successfully taken place in Q4 2021 for an 10kN scale additively manufactured combustion chamber. During the key point the material choice, specifically compatibility with the propellant combinations and printing heritage of the potential alloys, was identified as a key issue, as a result a material meeting was held in January 2022. The selected baseline material for the 10kN scale and low-cost BERTA AM process is a stainless-steel alloy. As no catalyst is used for pre-decomposition of the hydrogen peroxide, the combustion chamber design is mainly driven by the unknown combustion characteristics of liquid hydrogen peroxide with liquid hydrocarbon fuels. Therefore, several designs are manufactured with different lengths. The AM design is optimised with regard to minimising hydrogen peroxide residuals after testing, as the single elements test campaign (see below)) revealed that, besides system cleanliness, avoidance of decomposition of leftover hydrogen peroxide, is a critical issue.

Tests of the 10 kN demonstrator engine shall be performed with a newly developed low-cost, mobile test bench. Tests are currently planned on a green-field site of AGG in Trauen, Germany with minimum ambient test support. A two-container approach, which can be carried on a lorry is currently favoured, to be operable with the mentioned propellant combination.

2.4.2 100kN Scale (Upper Stage Main Engine)

Activity in the 100 kN thrust class, appropriate for an upper stage main engine, is clustered around the Expander-cycle Technology Integrated Demonstrator (ETID) project (see Reference [2]). Throughout the ETID activity, a great extent of tests has been performed at P3.2 at DLR-Lampoldshausen. More than 270 load points and 2700 s of test-time were accumulated, respectively. During this project, the opportunity for an additively manufactured thrust chamber evolved, and first trials were manufactured and subsequently tested at P8 of DLR-Lampoldshausen. As the initial design of the thrust chamber was based on conventional manufacturing techniques, the need evolved to optimise it to better account for the new additive manufacturing approach.

This new chamber, labelled M4KB, was again tested on P8 in late 2021/early 2022. The objectives were to characterise:
- The thermal performance of the expander based thrust chamber
- The structural temperature distribution in the material
- The hydraulic performance of the cooling channels, and
- To identify certain additional phenomena specifically applicable to an AM-design.

All of the objectives were met, and the test programme was finished in the foreseen time-period. Overall, 6 hot runs were performed, and a total burn time of 211 s was accumulated. As of the time writing, the hot-fired hardware was investigated via NDI. Furthermore, the test data is currently undergoing evaluation, very preliminary results seem to show that the goal of the cooling channel redesign has been reached – with the cooling channel pressure drop vastly reduced compared to the initial printed liner design, whilst maintaining a high heat pick-up. If these results are confirmed, then 3D-printing could be an advantageous process for the manufacturing of expander-cycle combustion chambers. The next step in this project is the preliminary design of a "Generation 2" engine to be tested at the P3.2 test bench in Lampoldshausen, as the original ETID test campaign.

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Figure 6: M4KB ETID “designed for AM” combustion chamber liner hot-fire test at P8 (Credit: ArianeGroup GmbH, Ottobrunn and DLR, Lampoldshausen)

3. Demonstrators

3.1 CFRP Upper Stage – PHOEBUS/COMET

The prototype of a highly optimised black upper stage (PHOEBUS) project has just passed the Preliminary Design Review and will now enter Phase C of the project.

The completed phases A/B of the project have made a major advance in terms of carbon-fibre reinforced plastic (CFRP) proof of concept for leak-tight cryogenic tanks. An extensive material identification and test campaign has taken place, with testing going from small tensile samples/coupons up to sub-scale tanks called “bottles”. A number of bottles have been manufactured with a variety of CFRP material systems (fibre plus resin), including one bottle with a metal foil liner. These bottles have been pressure and leak-tested in nitrogen, hydrogen and oxygen. One specific bottle has been tested in all three fluids, showing leak-tightness at cryogenic temperatures but also compatibility with oxygen. The identification and successful test of such a material is a milestone achievement in Europe. The results of all these activities fed into a Material Selection Key Point in July 2021, which identified the material to be baselined from the PHOEBUS demonstrator.

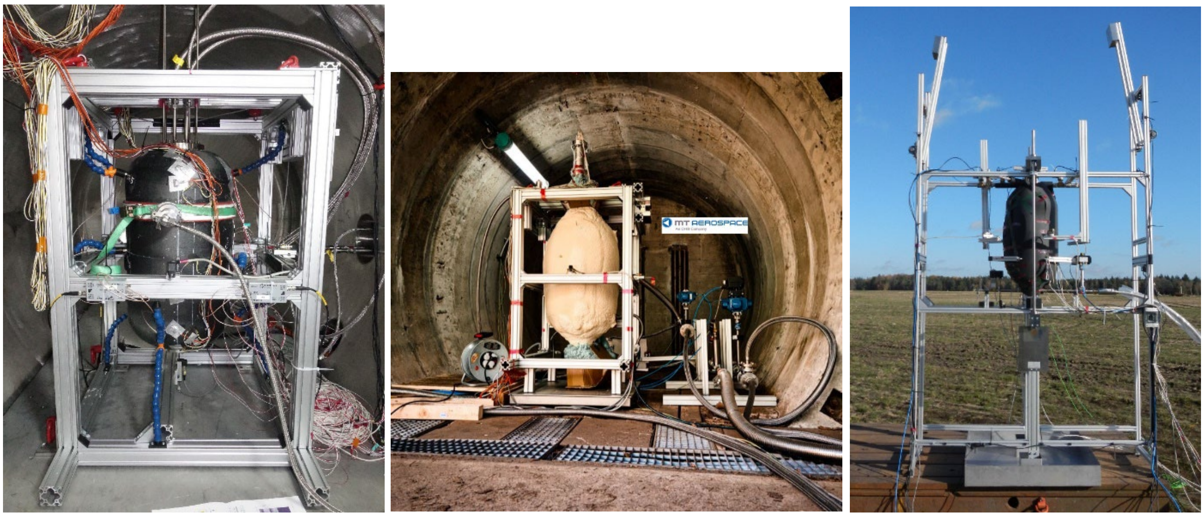

Figure 7: CFRP “Bottle” testing, from left to right (i) in Vacuum chamber at MT Aerospace; (ii) LH2 testing at DLR Trauen; (iii) LOx testing at Rheinmetall (Credit: MT Aerospace)

A Demonstrator Concept Key Point in May 2021 has allowed to confirm the planned demonstrator configuration, derived from the MUSE upper stage concept.

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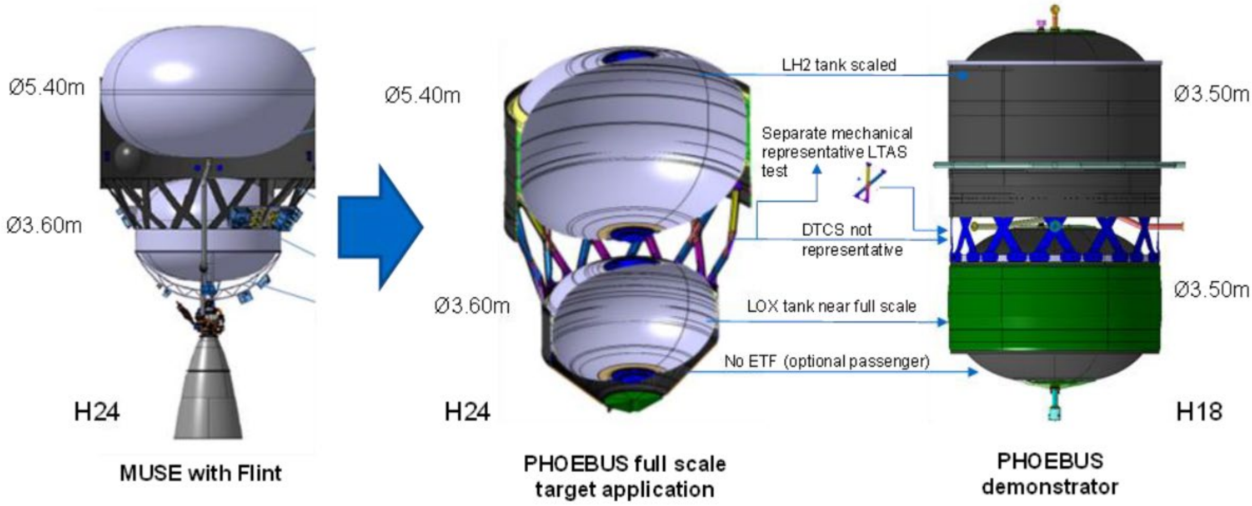

Figure 8: Derivation of PHOEBUS demonstrator from full-scale application

The principal features of the full-scale design that will be matured on the demonstrator are:
- CFRP LOx and LH2 tanks
- CFRP tank covers with metallic feed-throughs
- Evacuated honeycomb core outer tube with structural and thermal functions
- Suspension of tanks in outer tube
- CFRP X-cross inter-tank structure

The PDR has just passed, confirming the demonstrator design, technology maturation logic and test logic. The project will now move forward with the manufacture of the sub-scale "Technology Control Vehicles" to prove the manufacturing processes before the demonstrator MRRs starting in Q2 2023. Cryogenic tests are planned at the P5.2 test bench in Lampoldshausen in 2025. The demonstrator design has a high technology content with respect to CFRP structures, thermal insulation and CFRP-CFRP as well as CFRP-metal interfaces, but will also include a number of passenger technologies, providing an opportunity to test them in representative environments, these include:
- FLINT ETF (TBC)
- FBG strain sensors
- Low-cost supports
- Cryogenic bonding

More information on this project can be found in reference [3].

3.2 CFRP Inter-Tank Structure – COSTELAS

The Cost Optimised Sandwich Technology for Large-Scale Structures (COSTELAS) project was kicked-off in Q4 2021. The pre-runner activity PACE ended in December 2021 with a Preliminary Design Review, during which several experts from ESA, DLR, and industry reviewed the status of the different sandwich technologies and reference architecture design. The focus of the activity is on CFRP sandwich technologies of upper stage intertank-structures. The reference case is an Ariane 6 upper intertank structure (U-ITS) based on the existing aluminium material. Several technology-concepts for cut-outs, high- and low-loaded interfaces, inserts, or non-destructive inspection (NDI) were identified and are matured on sample level. Once the sample development and subsequent testing are successful, results will be incorporated in a large-scale breadboard, i.e. a 5.4 m diameter 1/8 segment of an U-ITS. This breadboard will subsequently be manufactured and tested mechanically. In parallel, a new curing concept is developed, which separates the two functions of a conventional autoclave, namely the pressurisation and the heating. The goal is to have a large-scale pressure chamber that is not fully heated to the curing temperatures, and thus requires less energy. The temperatures needed for curing shall only be imposed to the component locally. The current mass-saving in comparison to the conventional aluminium U-ITS of ~180-200 kg for a CFRP inter-tank structure seems feasible, and no blocking points were identified.

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3.3 Green Propulsion Demonstrator

In the green-propulsion demonstration project, the overall goal is to develop and ground test an engine to demonstrate the reliable, efficient, and repeatable combustion of a storable and green propellant. The target engine shall produce 5kN of thrust at sea level. An initial propellant trade-off identified the following candidates for further development:

- As potential oxidiser fluid, only high-grade hydrogen peroxide was chosen
- Potential fuel candidates are Ethanol, Kerosene, and Isopropanol (IPA)

After the propellant identification, then various injection elements could be designed and manufactured, and their analytical hydraulic performance validated in cold-flow tests. Then single-element hot-fire tests were able to start in autumn 2021, and, after a pause for post-processing and analysis, continue in the spring of 2022. These tests are currently ongoing, performed at the M11 test stand of DLR-Lampoldshausen, Germany. As a first result tests have shown that the H2O2-IPA propellant combination has a lower performance than H2O2-ethanol, therefore H2O2-IPA will currently not be taken further. As of today, it is not planned to use a catalyst for early decomposition of the oxidiser, since liquid/liquid injection is the baseline approach. Figure 9 below shows images of the single element configuration, mounted on top of a generic copper combustion chamber at M11 at DLR Lampoldshausen. The left image indicates incomplete combustion as visible by the white smoke; the right image indicates complete combustion.

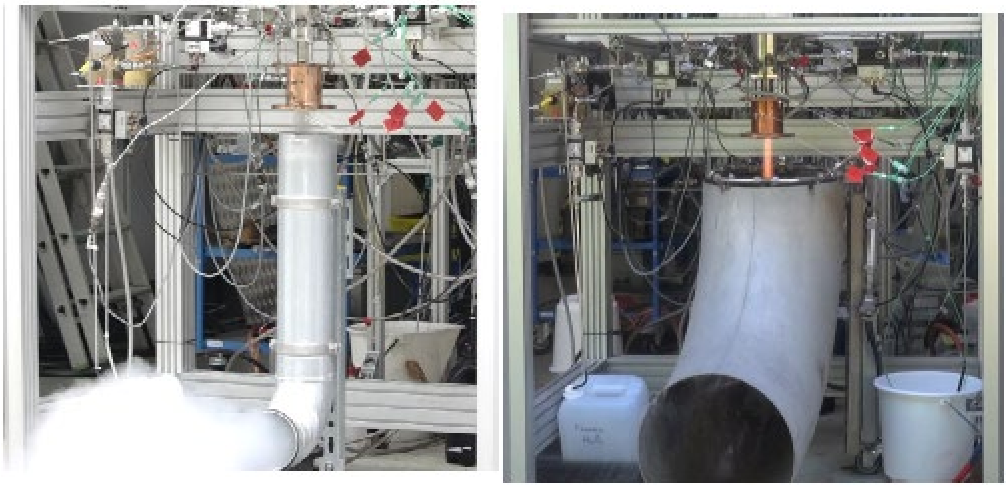

Figure 9: Single element hot firing tests performed at M11; left: incomplete combustion, as visible by white smoke; right: successful combustion test. (Credit: ArianeGroup GmbH, Ottobrunn)

With a suitable single injection element selected in the aftermath of the test campaign, the full-scale demonstrator design will be developed for hot-firing tests with multiple injection elements. More information on this project can be found in reference [4].

3.3 Throttleable Liquid Propulsion Demonstrator

This project, with the Łukasiewicz Research Network – Institute of Aviation in Poland, matures technologies enabling deep throttling of a green liquid propellant engine, using a propellant combination of high-test peroxide (HTP) and ethanol. The throttling is realized by two independently actuated cavitating mass-flow regulatory valves working with an actuated fuel pintle injector. In the project a demonstrator injector system will be built and tested, the demonstrator critical design review is planned for the end of 2022, the concept will build on the knowledge gained during multiple technology tests maturing elements such as:

- AM manifold parts
- Cavitating venturi regulation valves
- Actuator control systems
- Catalyst bed for 98% HTP decomposition
- Pintle injection characteristics

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The technologies that will constitute the demonstrator are considered as future building blocks in green storable propulsion for numerous applications including kick-stages but also for exploration missions. More information on this project can be found in references [4] and [5].

Figure 10:Additively manufactured oxidiser manifold. (Credit: Łukasiewicz Research Network - Institute of Aviation)

4. Conclusion

All technology areas of a launcher upper stage are matured across various projects within FLPP, all linked to a system-level analysis, providing the functional requirements for the sub-systems and technologies and permanently evaluating the system-level impact including mass and recurring cost and therefore the interest of the application of the technologies. The ongoing project landscape shows the potential of a large performance improvement (> +2 ton to GTO on an Ariane 6) and production cost reduction (-30% estimated) for a future upper stage.

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