MULTI-SCALE DEVELOPMENT OF CFRP PRESSURE VESSELS FOR LIQUID HYDROGEN APPLICATION

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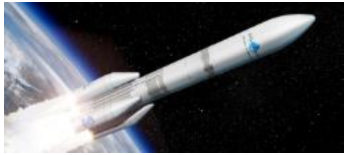
MT AEROSPACE – WHO WE ARE

MT AEROSPACE
An OHB Company

OHB

OHB Systems



Aerospace & Industrial Products

MT AEROSPACE
An OHB Company

- **OHB SE** one of the largest European space companies
  - Revenue 1 BN€
  - ~ 3000 employees
- **MT Aerospace AG** is the launcher division of OHB
  - Established in 1969
  - ~ 500 employees
  - Revenue 122 M€ (2021)

Space

- Launcher
- Spacecraft
- Satellite Components
- Structures & Tanks
- Development & Manufacturing

Aeronautics & Defence

- Water Tanks & Structures
- Development & Manufacturing

Infrastructure & Ground Services

- Ground Infrastructure
- Launch Site Operations

MT AEROSPACE – WHAT WE DO

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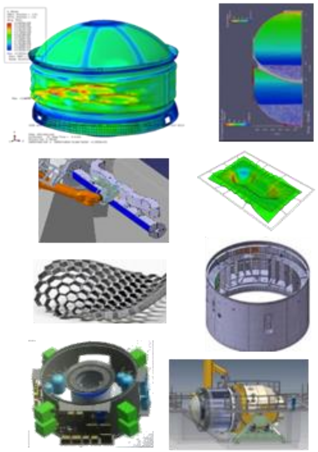
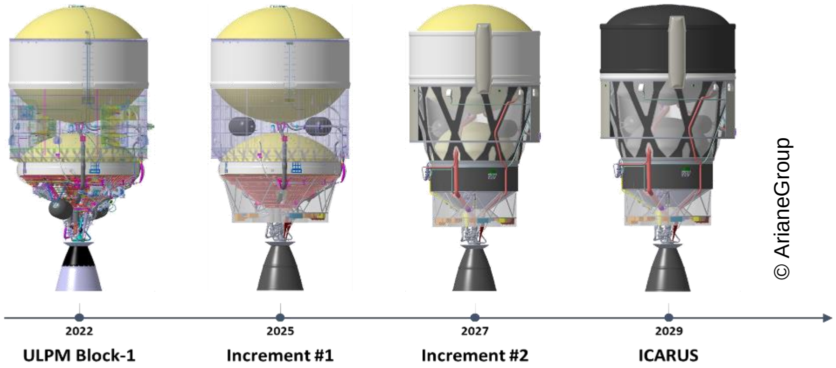
Matured over decades to a Tier 1 Aerospace Supplier



Large Machining
Advanced Forming
Welding (FSW / EB / TIG)
Assembly
Additive Manufacturing
Automated Fiber Placement
Winding
Sandwich
Light-RTM
Hybrid
Out of Autoclave
Advanced NDI
Testing
System Engineering
Aynalysis & Simulation
Design

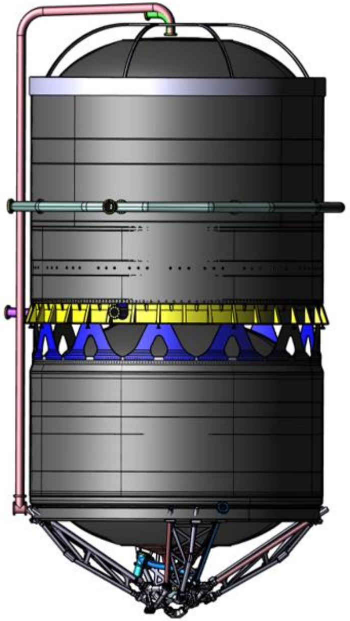
- Upper Stage Evolutions
  - Ariane 6 upper stage ULPM (**U**pper **L**iquid **P**ropulsion **M**odule) is currently mainly composed of aluminium primary structures
  - Only exceptions are the **U**pper **P**art (UP) and the **I**nter**f**ace **S**tructure (IFS) between ULPM and main stage (LLPM), which are made out of carbon fibre composite material
  - The upper stage dry mass is one important parameter for the payload performance
  - To reduce the upper stage dry mass a step wise approach is used:
    - Increment #1: a mass reduction of 250 kg
    - Increment #2: a mass reduction of 550 kg
    - ICARUS: full composite upper stage with a mass reduction of 1500 kg



Foreseen evolutions of the ULPM

PROJECT PHOEBUS

- **P**rototype of a **H**ighly **O**ptimiz**E**d **B**lack **U**pper **S**tage
- ESA **F**uture **L**aunchers **P**reparatory **P**rogramme (FLPP)
- Demonstration of mechanical, thermal, functional and economic superiority of a CFRP (**C**arbon **F**iber **R**einforced **P**lastic) upper stage on a scaled ground test demonstrator (d ≈ 3.5m)
- Phase C: performed under prime contract ArianeGroup Bremen and MT Aerospace as design definition authority for bare tanks and structures
- Work share (mechanics aspects: MT Aerospace – functional and thermal aspects: ArianeGroup):
  - Main components of the demonstrator like both bare tanks and the inter-tank structure are manufactured at MT Aerospace in Augsburg
  - ArianeGroup manufactures the Fluidic Integrated Thrust frame (FLINT) below the LOx tank
  - Integration and assembly is performed at the A6 ULPM Final Assembly Line (FAL) at ArianeGroup in Bremen
  - Functional testing under the lead of ArianeGroup at the DLR facilities in Lampoldshausen



PHOEBUS demonstrator - CAD view

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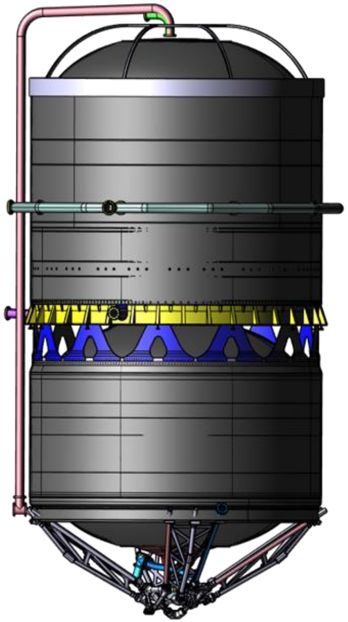
PHOEBUS UPPER STAGE DEMONSTRATOR

- Main objectives are
  - To maturate technology, manufacturing and industrial readiness level (TRL, MRL and IRL) to 6
  - To reduce the stage mass at a considerable scale
  - To demonstrate the expected mechanical and functional characteristics and the operability of a CFRP cryogenic upper stage
  - To project the real field data from the demonstrator on a future upper stage serial production

- After a technology screening the most challenging topics identified are
  - LH2 leak tightness
  - LOx compatibility
  - CFRP manhole flange/cover connection
  - Core suspension: CFRP suitable design feature for bifurcation area between tank dome, tank cylinder and skirt
  - Evacuated core insulation: outer sandwich cylinder of the LH2 tank is evacuated, eliminating the need for an additional external thermal insulation
  - LOx Tank Attachment Structure (LTAS)

  ➔ Based on this screening, technology topics (TTs) and technology control vehicles (TCVs ≙ scaled bread boards) are defined and tested



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PHOEBUS demonstrator

DEVELOPMENT WORK LOGIC

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Reference A6 Upper Stage

Comparison of payload and cost performance to Ariane 6 upper stage for tanks and intertank structures

Target Application

Target Application configuration trade off depending on configuration and loading

Demonstrator Cryogenic Ground Stage Test

Verification of mechanical, thermal, functional and economic performance up to TRL 6

Technology maturation and risk reduction on TCVs and TTs

Aim: Reduction of technological risks before implementing technologies into the demonstrator

- New technologies are investigated in detail in **T**echnology **T**opics (TTs) (TRL 3)
- **T**echnology **C**ontrol **V**ehicles (TCVs ≙ subscale breadboards) are developed, manufactured and tested (TRL 4)

SELECTED REFERENCE CONFIGURATION

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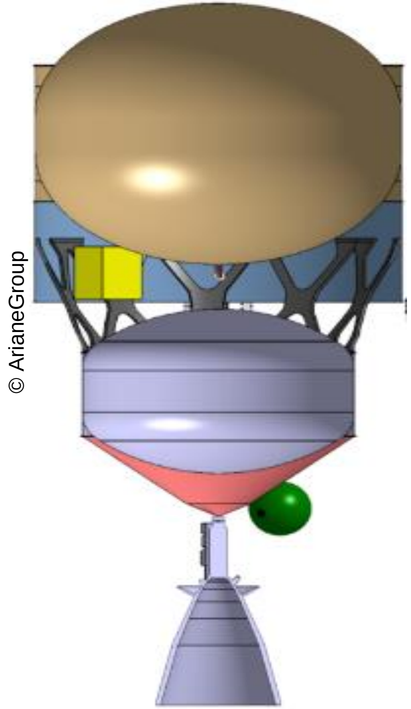

Chosen target application configuration for PHOEBUS

LOX Tank Suspension-Configuration

- LH2 tank Ø ≈ 5.4 m
- LOX tank Ø ≈ 3.6 m
- LOX tank suspension via X-bracket LTAS

Reference from ESA-FLPP MUSE upper stage system trade-off (ArianeGroup)

Most balanced between mass, cost, industrial performance and technological risk.

OVERVIEW

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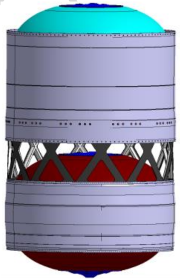
- Major functional challenges of a CFRP upper stage tanks (liner-free Type V)
  - LH2 leak-tightness
  - LOx compatibility
- LH2 leak-tightness requirement given by ArianeGroup
  - Requirements given for different temperatures, pressures and durations for domes and cylindrical regions
- Objective: off-the-shelf CFRP material
- Step-by-step development and verification approach

LH2 LEAK-TIGHTNESS AND LOX COMPATIBILITY
DEVELOPMENT AND VERIFICATION APPROACH

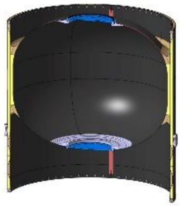
PHOEBUS ground demonstrator – 2025:
- Verification of key technologies at near full scale level
- Tested under representative loading – cryogenic test (1g environment)
- Verification of mechanical, thermal, functional and economical performance



Ø ≈ 3.5 m

Ground Demonstrator with LH2 and LOX (led by ArianeGroup)

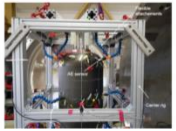
TCV – End 2023
Tested under representative loading
➔ Prove of LH2 leak-tightness / LOX compatibility
➔ Mechanical justification
➔ Verification of manufacturing quality
➔ Improve of numerical methods



Ø ≈ 2 m

Sub-scale Breadboard (TCV) with LH2 and LOX

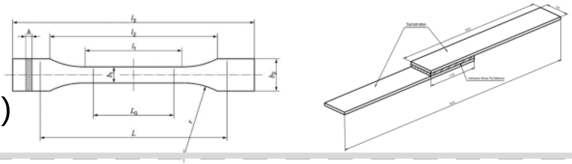
Understanding of leak-tightness under multiaxial loading



Test Elements at RT and 77K

Characterization of used materials
- Degradation due to temperature

Understanding of Diffusion (w/o loading)



Coupon Samples at RT and 77K

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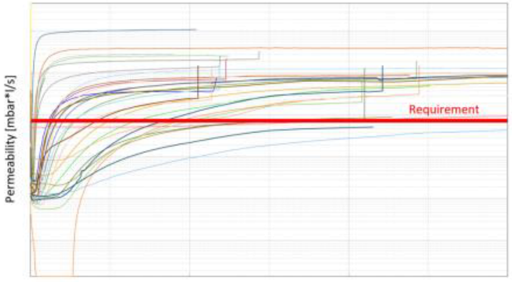
- Permeation at RT on flat samples with He (without loading)
  - Depending on CFRP material leakage occurs short term (< 1h) or long term (> 24h)

  ➔ Leak-tightness requirement must be a function of time

Permeation *of CRFP materials at RT*

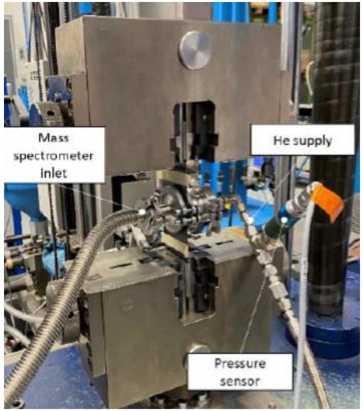


- Permeation at 77K on flat samples with He (without loading)
  - Leakage is not an issue long-term ➔ He molecules have lower kinematic energy at cryogenic temperatures

  ➔ Leak-tightness requirement must be a function of temperature
    - Acceptance requirement: at RT, but only during acceptance test (minutes ≙ short term)
    - Operations requirement: at cryogenic temperatures, but for hours (≙ long term)

- Unidirectional tensile tests at RT and 77K to understand mechanical degradation (ULL = Unidirectional load leak test)
  - Depending on CFRP material matrix performance decreases drastically
  - Materials with highly toughened matrix systems show very promising results

  ➔ Leak-tightness requirement must be a function of loading



ULL test set-up

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- Multidirectional strain state with respect to leakage at RT and cryogenic
  - Depending on the position in the tank different strain states are present (e. g. dome vs cylinder)
  - To cover these strain states bulge and MLL (multidirectional load leak) tests were investigated
  - → Both tests have limitations in test conduction and evaluation
  - → Replaced with bottle tests (multiaxial loading)

- LOx compatibility tests
  - → A holistic LOX compatibility logic with respect to critical energy was agreed between MT Aerospace and Ariane Group Bremen
  - → Pressure surge test showed that all materials are GOX compatible

LH2 LEAK-TIGHTNESS AND LOX COMPATIBILITY
TEST RESULTS: TEST ELEMENTS

- Multidirectional tensile tests at RT and 77K of flat samples verified that materials with highly toughened matrix systems are promising candidates

- 80-litre pressurized bottles designed and manufactured by MT Aerospace
  - Under the applied thermo-mechanical loading a similar stress-strain state is present in the bottle laminate as for the target application
  - Test sequence:
    1. Initial leak test at RT for low, artificial delta pressure (≙ requirement for metallic tanks)
    2. He leakage at representative pressure and ≈120 K
    3. H_2 leakage at representative pressure and 20K
    4. Recheck of global leak tightness with 1) and 2)
    5. LOx compatibility campaign at representative pressure and 90K including impact event
    6. Recheck of global leak tightness with 1) and 2)
    7. Cryogenic temperature cycling at 77K and representative pressure
    8. Recheck of global leak tightness with 1) and 2)

LH2 bottle test @ DLR Trauen

LOx bottle test @ Rheinmetall

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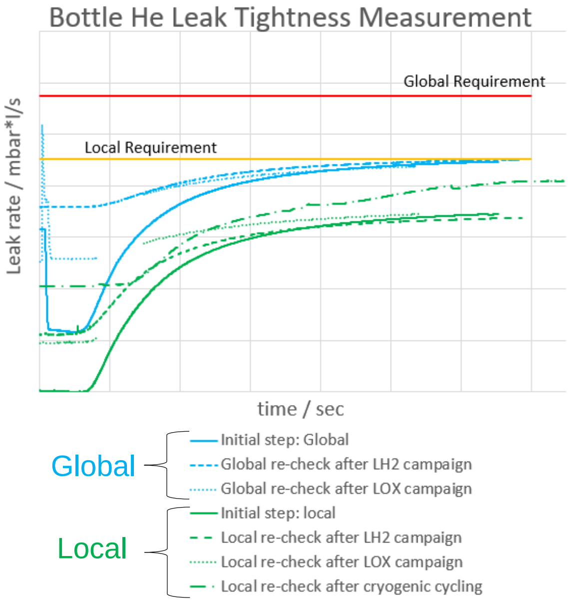
One material was successful in LH2 and LOX test campaign

- Both requirements of LH2 leak tightness and LOx compatibility were fulfilled
- Local and global leak rate do not change between the initial leak tightness check and the re-checks after LH2 and LOx test campaigns
- After additional six cryogenic cycles the global leak rate exceeded the requirement because the material degraded locally at several positions
- Local measurement shows still leak rates below the requirement
- Based on these results and micrographs a material law was defined to predict leak tightness for future applications



LH2 AND LOX STRUCTURAL TANKS
TT: CORE SUSPENSION AND EVACUATED SANDWICH

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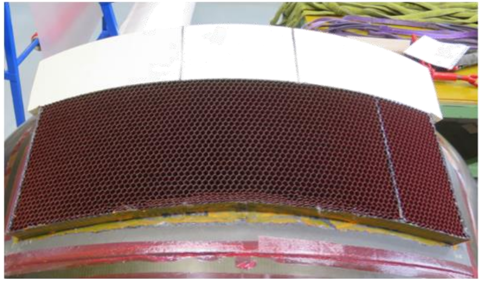
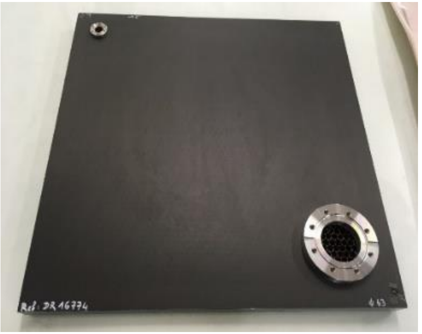
- **Core Suspension**
  - Connection of the pressure vessel with the unpressurised outer sandwich cylinder
  - Combines two functions in one element:
    - Structural connection: it decouples the different strains from tank and skirt, but is capable to transmit inertia loads between tank and the outer sandwich tube
    - Thermal insulation: the sandwich design contributes to the thermal insulation of the tank

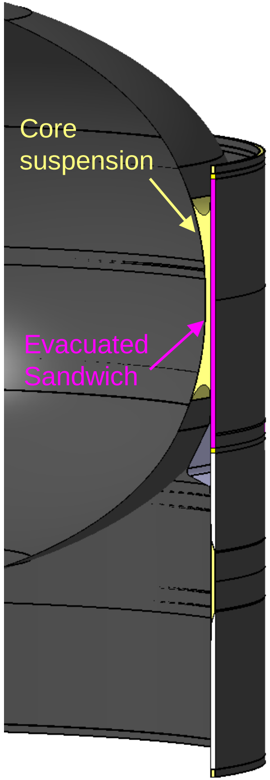
TT: Core suspension samples



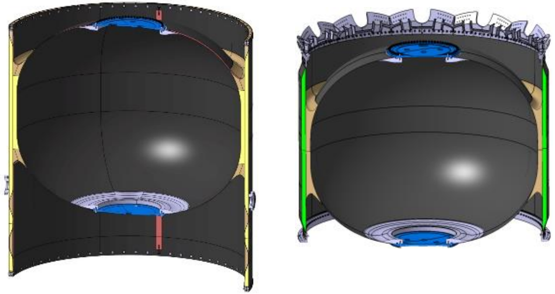
- **Evacuated Sandwich of outer tube**
  - Combines two functions in one element:
    - Transfer of the general loads
    - Thermal insulation of the LH2 tank
  - The "functional integration" is a significant contributor to reduce the structural mass and the propellant boil-off of the composite upper stage

TT: Evacuated sandwich





- LH2-TCV1 and LOx-TCV6 are structural tanks with d ≈ 1.9 m and l ≈ 2.0 m (LH2-TCV1 incl. ELS) and l ≈ 1.5 m (LOx-TCV6)
  - Main focus of the TCVs is the LH2 leak tightness and LOx compatibility of the pressure vessel
  - Secondary objectives
    - Verification of core suspension (Y-joint) performance between vessel and tube
    - Verification of insulation performance of outer tube evacuated sandwich
  - Following test campaigns are defined for the TCVs:
    1. RT tests with He up to artificial delta pressure:
       To demonstrate the leak tightness at RT
    2. LN2 tests (acceptance test):
       To measure strains and deformations under cryogenic temperature and internal pressure and ensure structural safety for LH2/LOx tests (acceptance test)
    3. LH2/LOx tests:
       To simulate fill, pressurization and drain cycles. Measurement of mechanical strains, deformations, temperature fields and leakage under cryogenic conditions and inner pressure
    4. LN2 tests with external mechanical loads:
       To evaluate the structural response of the core suspension and outer sandwich tube under cryogenic temperatures, inner pressure and flux load



LH2-TCV1 (left), LOx-TCV6 (right)

LH2 AND LOX STRUCTURAL TANKS
LH2-TCV1 AND LOX-TCV6

- Both TCVs are designed and manufactured at MT Aerospace in Augsburg
  - Strength and LH2 leak tightness justification
    - Based on a nonlinear analysis using ABAQUS
    - To implement non-symmetrical effects a 360° global model is used combined with detailed models
  - Digital process simulation was part of the design loop
  - Digital interfaces between manufacturing and CAD/FE software guarantee that the design definition is always ensured

  - LOx-TCV6 is manufactured ➔ test in autumn 2023
  - The pressure vessel of LH2-TCV1 is already manufactured ➔ currently manufacturing of outer tube

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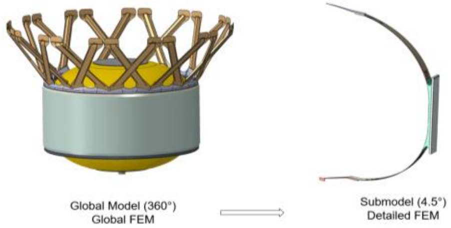
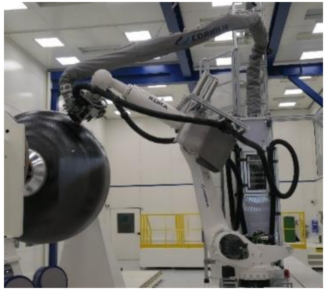
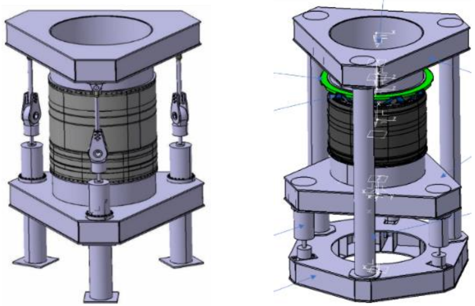


FE-model of LOx-TCV6





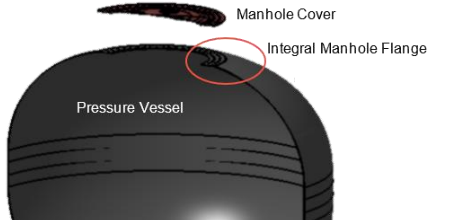
Manufacturing (top) and Test Rigs (bottom) of Tank-TCVs: LH2-TCV1 (left), LOx-TCV6 (right)

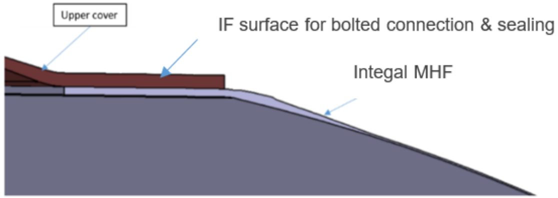
CFRP MANHOLE FLANGE AND COVER

- Manhole flanges (MHF) and covers are part of the pressure vessel
  - High wall thicknesses necessary due to interfaces

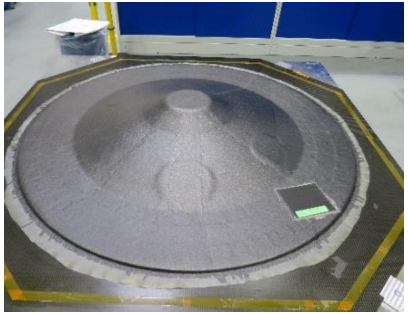
    ➔ high impact on pressure vessel mass

    ➔ aim in PHOEBUS to not only have CFRP tank shells, but also CFRP manhole flanges and covers
  - Bolted connected must be reusable to have access into the tanks at every phase of the stage assembly
  - Upper and lower cover do not look similar due to different interfaces
  - Integral manhole flange chosen (no separate flange): tank shell is locally thickened at the pole region, where the bolted connection and sealing will be present





Manhole flange and cover



MBB of lower cover

TCV20: CFRP MANHOLE FLANGE AND COVER

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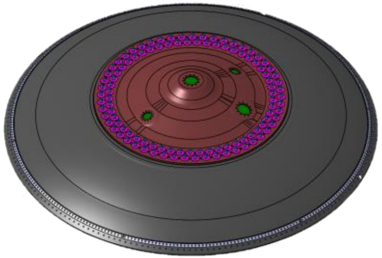
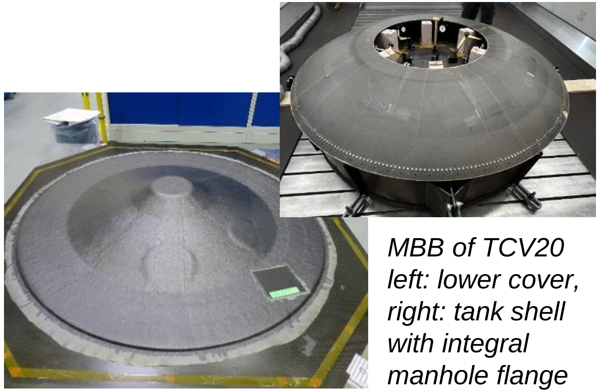
- TCV20 is a half CFRP tank including tank shell, manhole flange and cover (d ≈ 2.5 m, l ≈ 0.3 m)
  - The diameter of the flange and cover is the same as for the target application
  - LH2 leak tightness checked with helium at 77 K in combination with inner pressure
  - Different leak paths possible, e.g. main sealing or through the wall thickness of the parts
  - TCV20 is designed and manufactured at MT Aerospace in Augsburg
    - Complex lay-up strategy close to the pole: a transition zone of polar placed plies coming from the tank shell and Cartesian placed plies is necessary

      ➔ Create degree of exchange between strength/LH2 leak tightness justification and process simulation necessary
    - TCV20 test in December 2023



TCV20: CFRP manhole flange and cover



MBB of TCV20 left: lower cover, right: tank shell with integral manhole flange

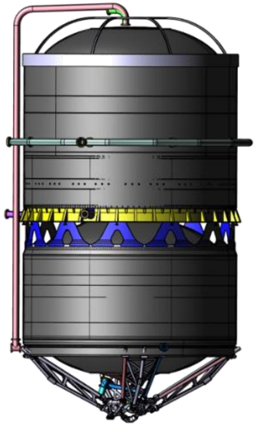
CONCLUSION AND OUTLOOK

- The requirements for the TCVs and the PHOEBUS demonstrator H/W were derived from the system requirements of the target application ICARUS by ArianeGroup in Bremen
- TCVs are currently manufactured according to the design and justification by MT Aerospace

  ➔ TRL level will be 5 after successfully testing of the TCVs in 2023
- The manufacturing of the PHOEBUS demonstrator H/W will start in autumn 2023
- The functional testing is scheduled for 2025 using the DLR facilities in Lampoldshausen

  ➔ A successful functional test would demonstrate a TRL close to 6
- A final design loop for the target application is planned to implement the technical expertise into the target application design definition

PHOEBUS demonstrator - CAD view



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A6 with CFRP Upper Stage ICARUS

ACKNOWLEDGMENTS

- MT Aerospace and ArianeGroup would like to thank our customers. The development of a ground demonstrator for maturing technologies, which are key for a future Ariane 6 CFRP upper stage, is only possible thanks to the German funding of the DLR Agency via ESA’s Future Launchers Preparatory Programme (FLPP).
- Furthermore, we thank all our partners, especially Rheinmetall Waffe Munition as well as the DLR institutes in Bremen, Trauen, and Lampoldshausen for the good collaboration.

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