MT AEROSPACE
An OHB Company

COUPLED THERMAL AND STRUCTURAL OPTIMIZATION OF A METAL- OR CFRP-BASED CRYOGENIC PROPULSION STAGE

SFB TRR40, 16.-17.11.2020

TABLE OF CONTENTS

MT Overview: Portfolio

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SPACE

Launcher
Spacecrafts
Satellites

- Structures
- Tanks
- Booster
- Satellite Panels
- Pressure Vessels
- Bulkheads
- Tank Components

AERONAUTICS & DEFENCE

Commercial & Military
Product Applications

- Watertanks
- Structures
- Missile Component
- Tanks Systems
- Shafts
- Struts

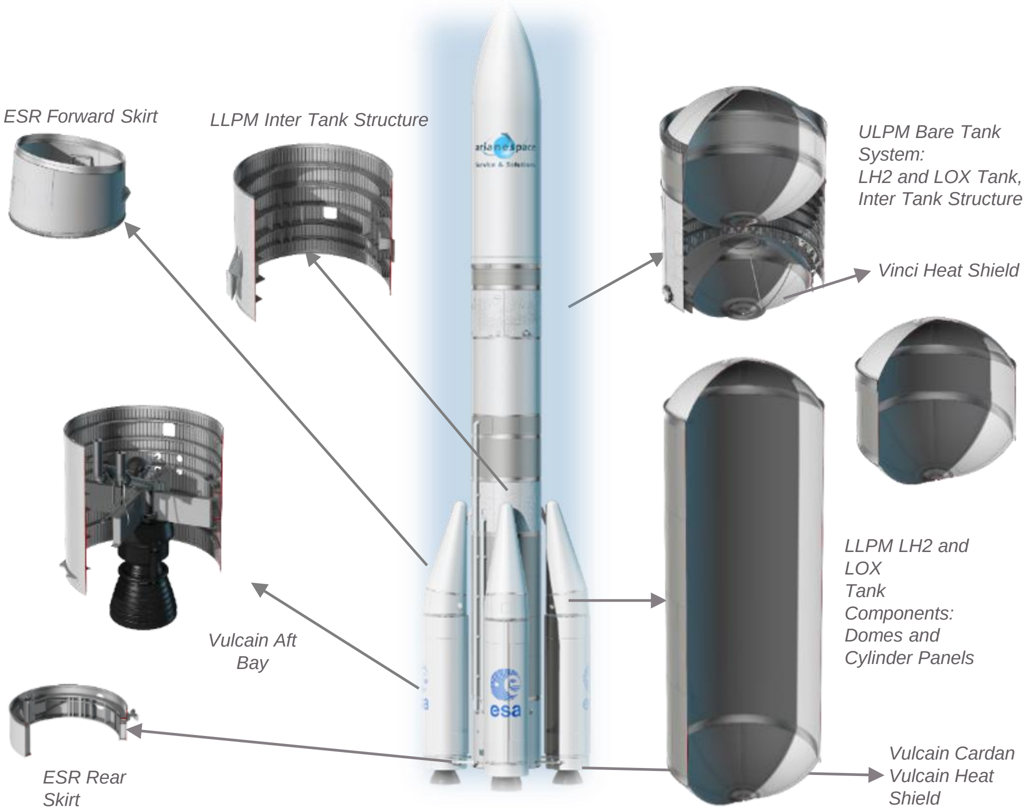
SERVICES

Comprehensive Ground Services – remote, field and stationary – for Integration & Launch Facilities and Astronomical Observatories

- European Space Center (Kourou, French Guiana)
- ARIANE 5 Launch Facilities
- ALMA/ Paranal Observatories

Ariane 6 – Workshare mt Aerospace

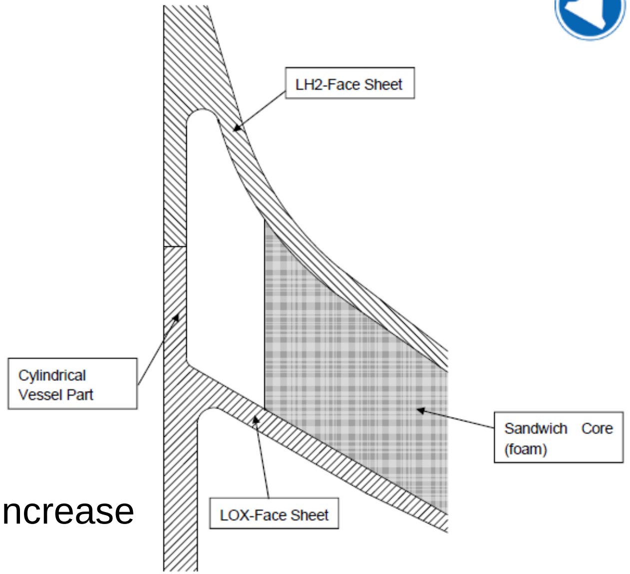
- MT Aerospace with about 11% workshare of Ariane 6
- Design definition authority for metallic aero structures & Tanks
- Risk sharing partner with significant own investment

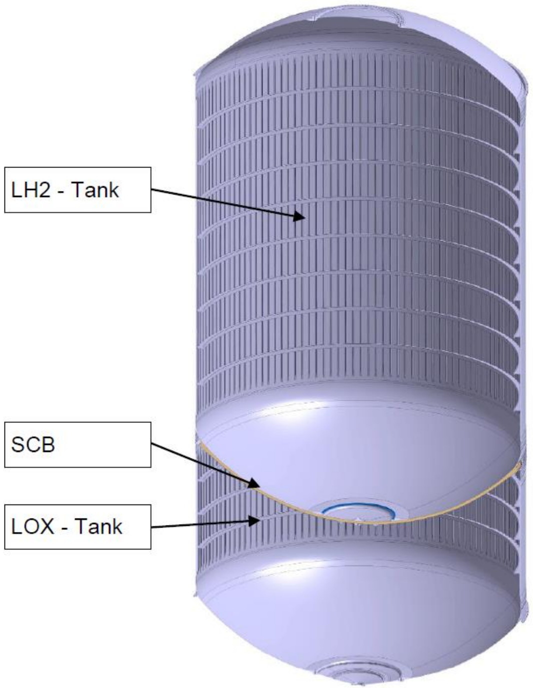


INTRODUCTION

Context

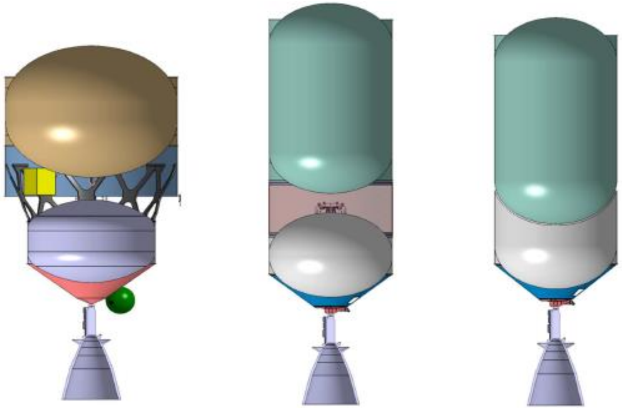
- Launcher development
- Cryogenics
- “medium-term” mission
  - Upper stage
  - GEO mission
  - (Lunar transfer)
- Mass reduction / performance increase





Exercise

- Concept studies
- Technology development
- Alternative materials (maturation)
- Alternative propellants



Cryogenic upper stage of Ariane 6 (ULPM) to GEO

- Assessment of different technological approaches
  - Separated tanks
  - Common bulkhead
  - In-line vs suspended
- Assessment of different materials
  - Aluminum
  - CFRP
- Assessment of different propellants (e.g. Methalox)

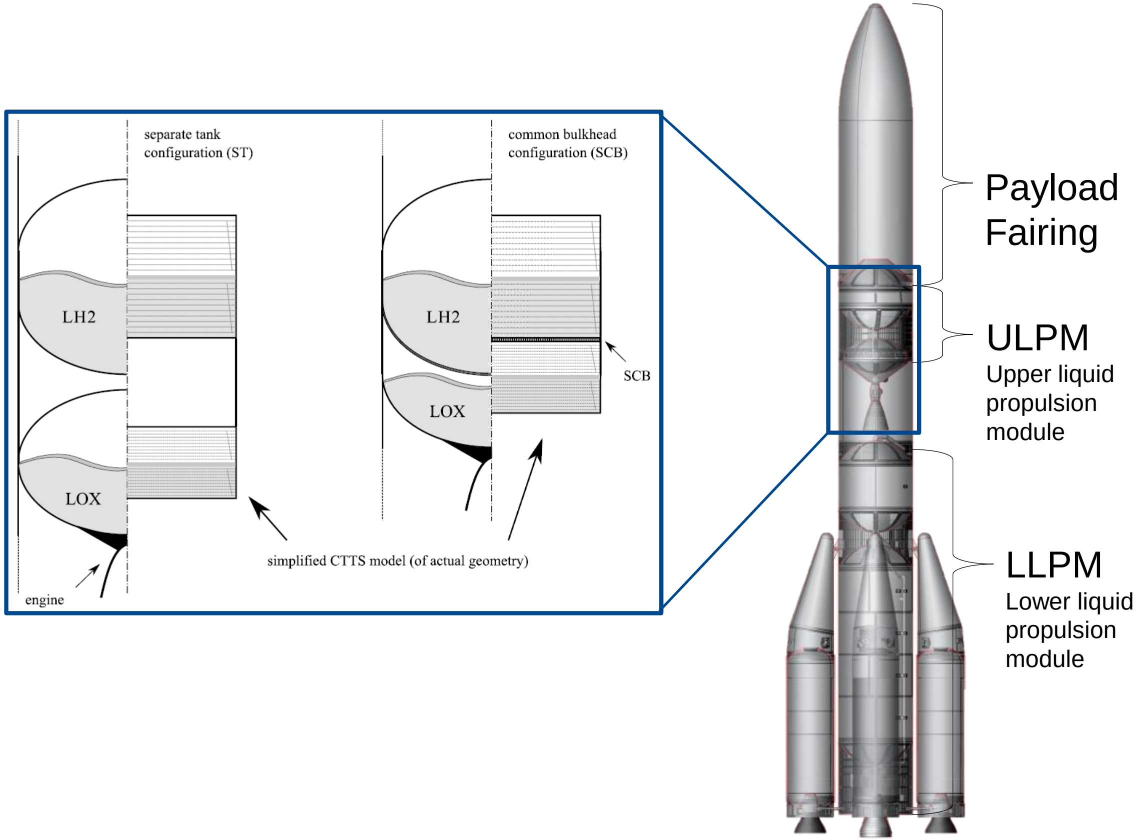


TABLE OF CONTENTS

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Goals

- Assess and compare different technologies
  - Analyze (diss-)advantages
  - Performance
- Optimization
  - Structures / tanks based on mechanical loads
  - Thermal insulation concept
  - Trade evaporation losses for insulation mass

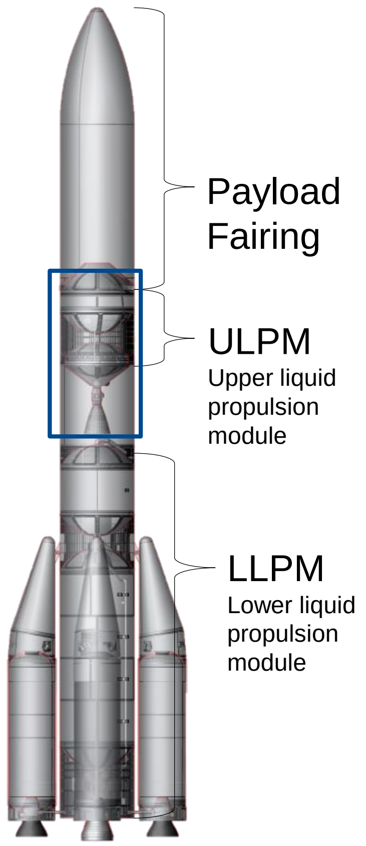
→ Coupled approach

- Appropriate level of detail
  - Geometry
  - Thermodynamics
  - Structural

→ Simplify as much as possible without compromising accuracy of key aspects

- Reasonable computation power requirement and programming effort
  - Workstation suitable
  - Simulation times of entire missions in the order of hours

→ Ability to quickly change models and receive results



MODEL OVERVIEW

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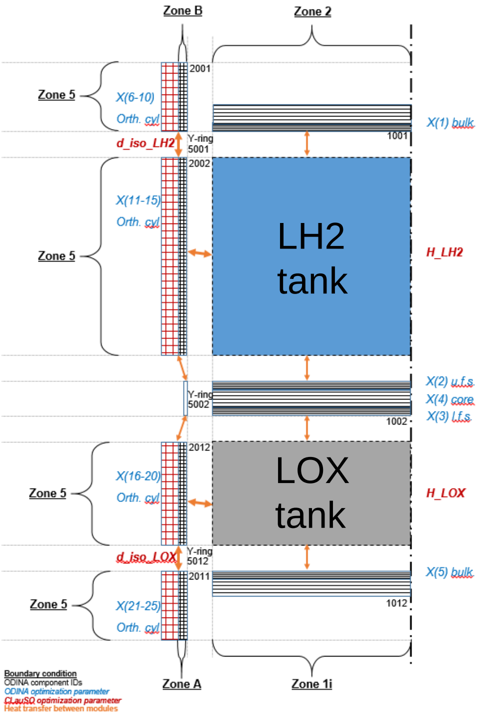
- Mission
  - Trajectory
  - Phases / durations
- Geometry / Structural components
- Mechanical boundary conditions
  - Pressure differentials
  - Fluxes (axial, bending)
- Thermal boundary conditions
  - Atmospheric flight
  - Space flight
  - Coasting
- Material properties
  - Mechanical
  - Thermal
  - Optical

INPUT



OUTPUT

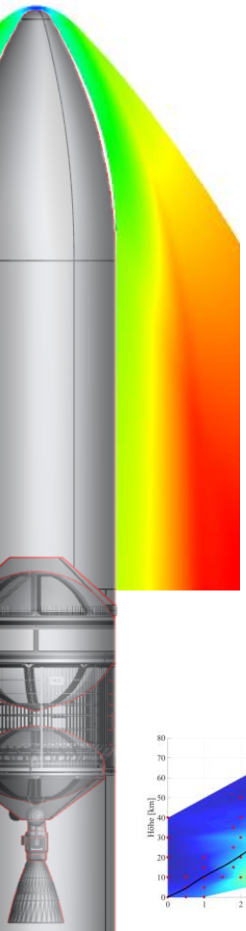
Thermodynamics

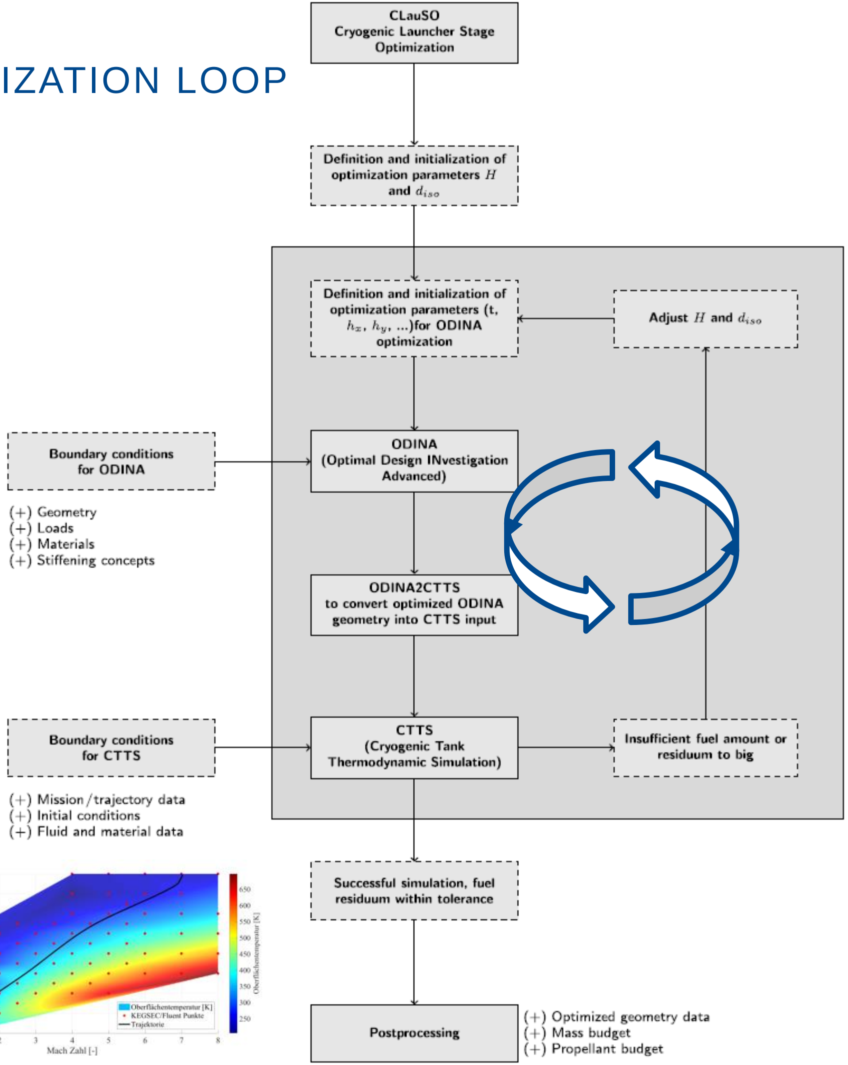
- Tank pressure development
- Heat entry / propellant evaporation
- Optimal insulation thickness
- Optimal tank volumes

Structure

- Preliminary sizing of main components ► mass estimation
  - Bulkheads
  - Cylinders
  - Y-rings
- Effective thermal masses and distances

OPTIMIZATION LOOP





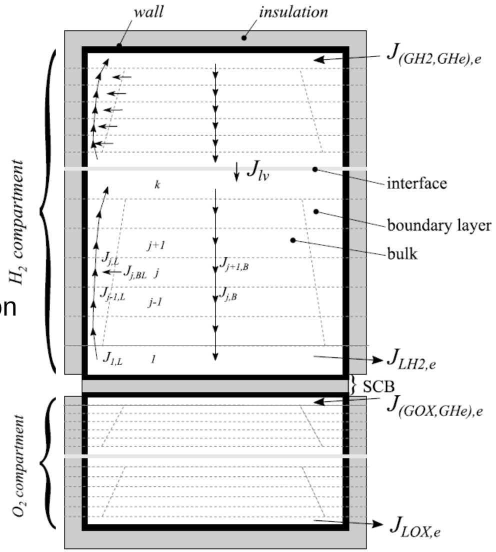
- **Launcher functions important for simulation**
  - **Venting:** controlled release of excess gas
  - **Engine feed:** draining of liquid tank content towards engine
  - **Pressurization:** active regulation of tank pressure during boost phases

- **Reference mission: GEO**
  - Chilldown
  - Pressurization 200s
  - LLPM boost 454s
  - 1. ULPM boost 668s
  - Coasting 19000s
  - Pressurization 50s
  - 2. ULPM boost 105s

MODEL OVERVIEW

Cryogenic Tank Thermodynamic Simulation (CTTS)

- 2D-axisymmetric cylinder approximation of tank
- Division into liquid and gas/vapor phase
- Evaporation or condensation at liquid-vapor interface ▸ energy & mass exchange
- Further division of phases into horizontal layers with boundary and bulk cells
- Natural convection
  - Nusselt correlations
  - Boundary-layer flow
  - Macroscopic circulation flow
- Tank functions
  - Venting
  - Engine feed/depletion
  - Pressurization
- Heat conduction
  - Walls
  - insulation



Optimal Design Investigation Advanced (ODINA)

- Analytical formulas for strength and buckling of
  - Cylinders
  - Bulkheads
- Stiffening concepts
  - Isotropic wall
  - Orthogrid stiffening
  - Sandwich (foam or honeycomb)
- Wall thickness and stiffening concepts mass-optimized for unlimited number of load scenarios
  - Compression / tension flux
  - Differential pressure
- Output
  - Mass
  - Volume
  - MoS

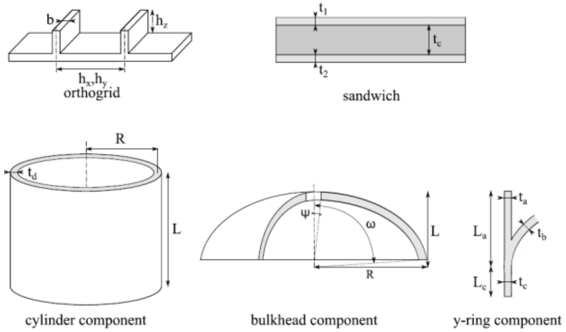


TABLE OF CONTENTS

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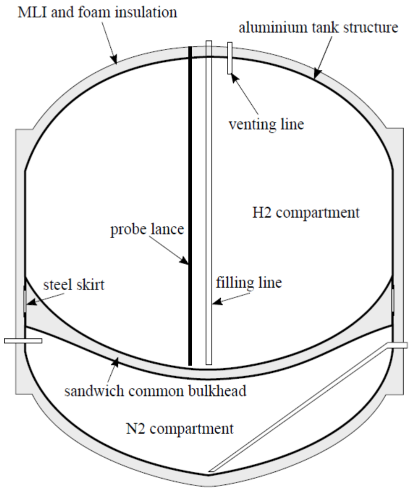
Verification of CTTS conducted with two different test tanks

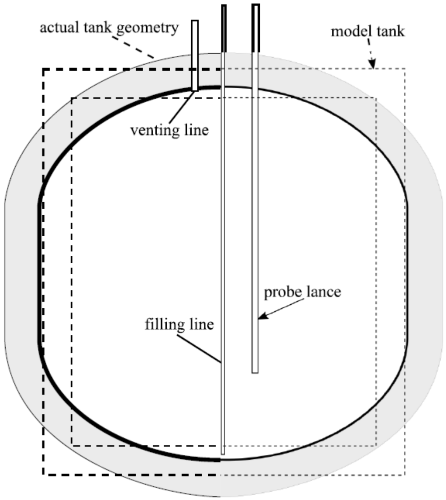
CRONUS

- Tank featuring a sandwich common bulkhead
- Cryo-test campaign with LH2 and LN2 in vacuum chamber



SKK

- Single compartment tank
- Cryo-test campaign with LH2

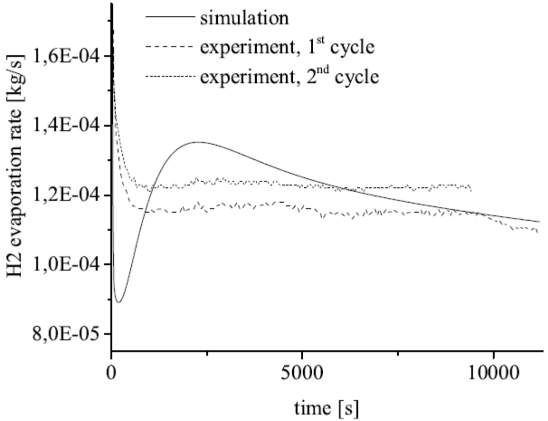


Verification of ODINA

- ODIN -> MT in-house development
- estimation errors range from 3% to 15% depending on
  - structure type
  - general dimensions
  - loads applied
- reflection of analytical formulas
- Correlation factors implemented based on FEA calculations

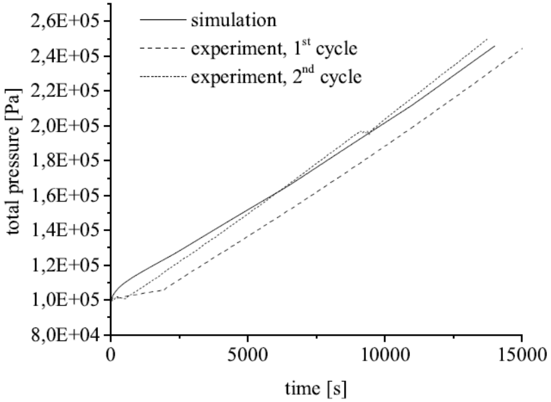
VERIFICATION

- CRONUS test tank (FLPP project)
  - Two test cycles (dashed lines) and the simulation results (solid lines)



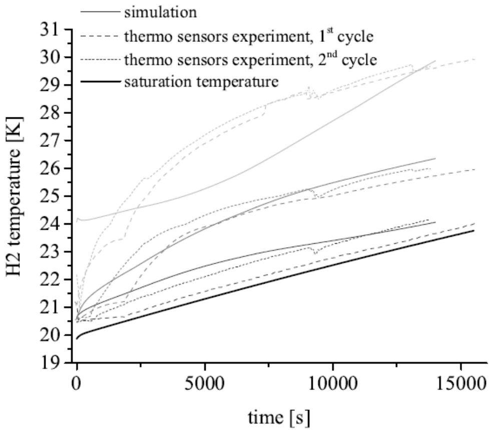
Steady state evaporation rate

… represents the net-heat flow and the correct modelling of evaporation



Tank pressure development

... self-pressurization rate is a result of evaporation and heat entry



Temperature stratification

… indication of correct simulation of macroscopic flows inside the fluid

TABLE OF CONTENTS

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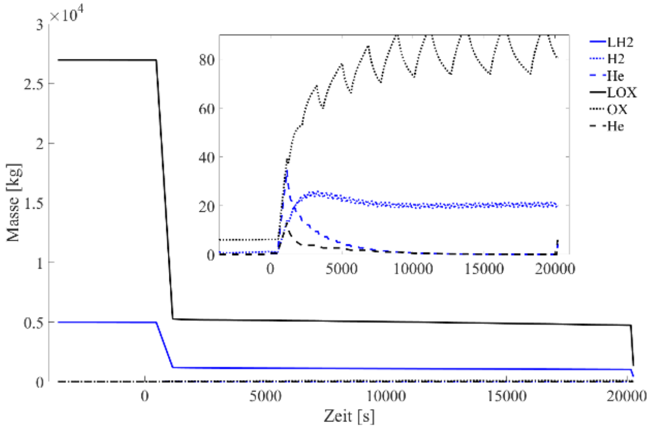
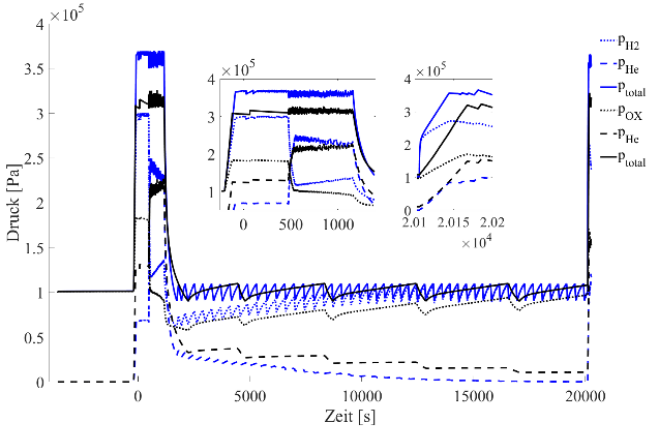
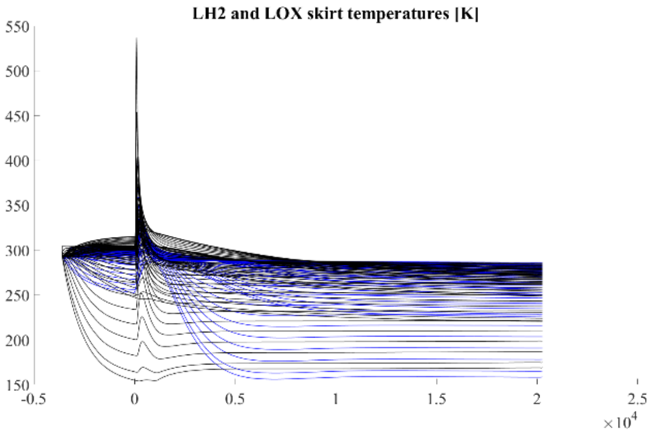
EXEMPLARY RESULTS MISSION ANALYSIS





LH2/LOX tank with SCB

(Sandwich Common Bulkhead)



Progression of …

- Propellant masses (liquid & vapor)
- Tank pressure (incl. partial pressure of vapor & gas)
- Wall & insulation temperatures

EXEMPLARY RESULTS OPTIMIZATION

Variables

- LH2 tank height
- LOX tank height
- LH2 insulation thickness
- LOX insulation thickness

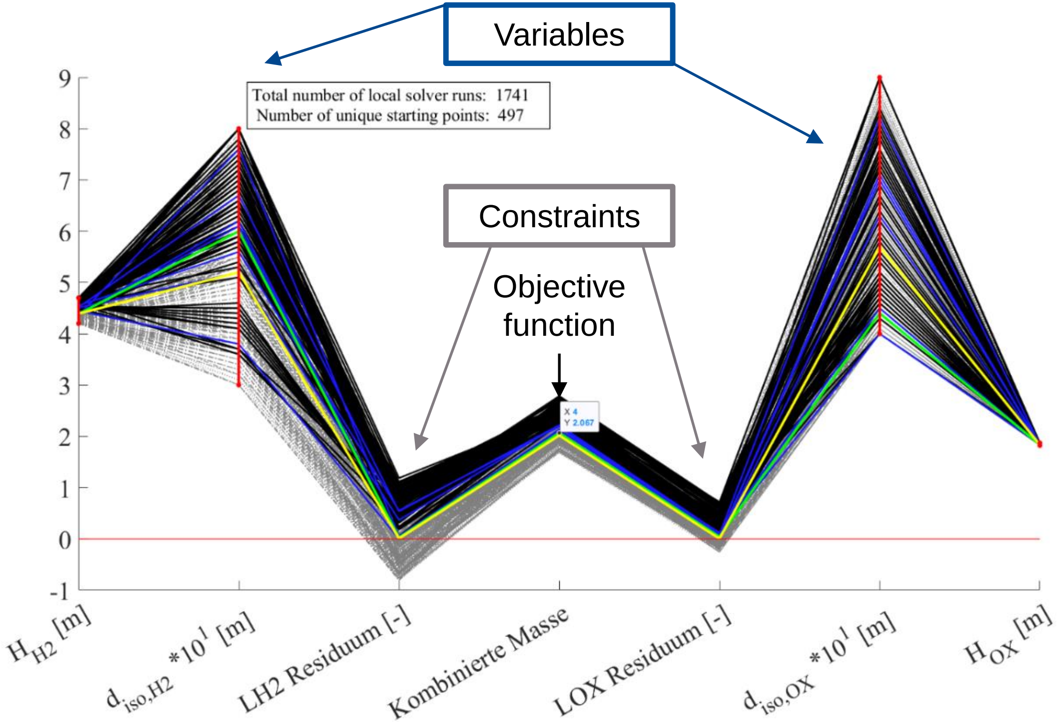
Constraint

- LH2 residual
- LOX residual

Objective function

- Combines propellant, structure and insulation mass

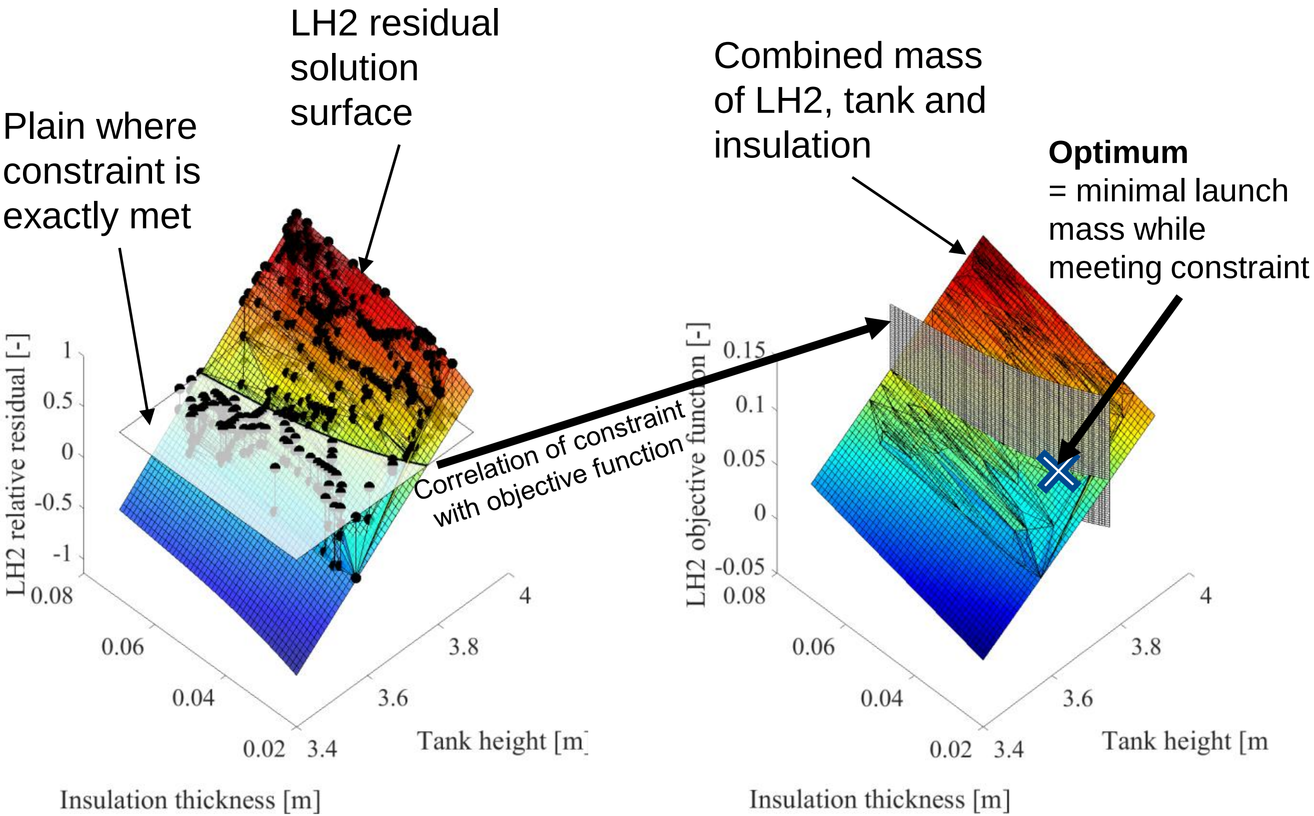
▶ Global optimization with local gradient based solver



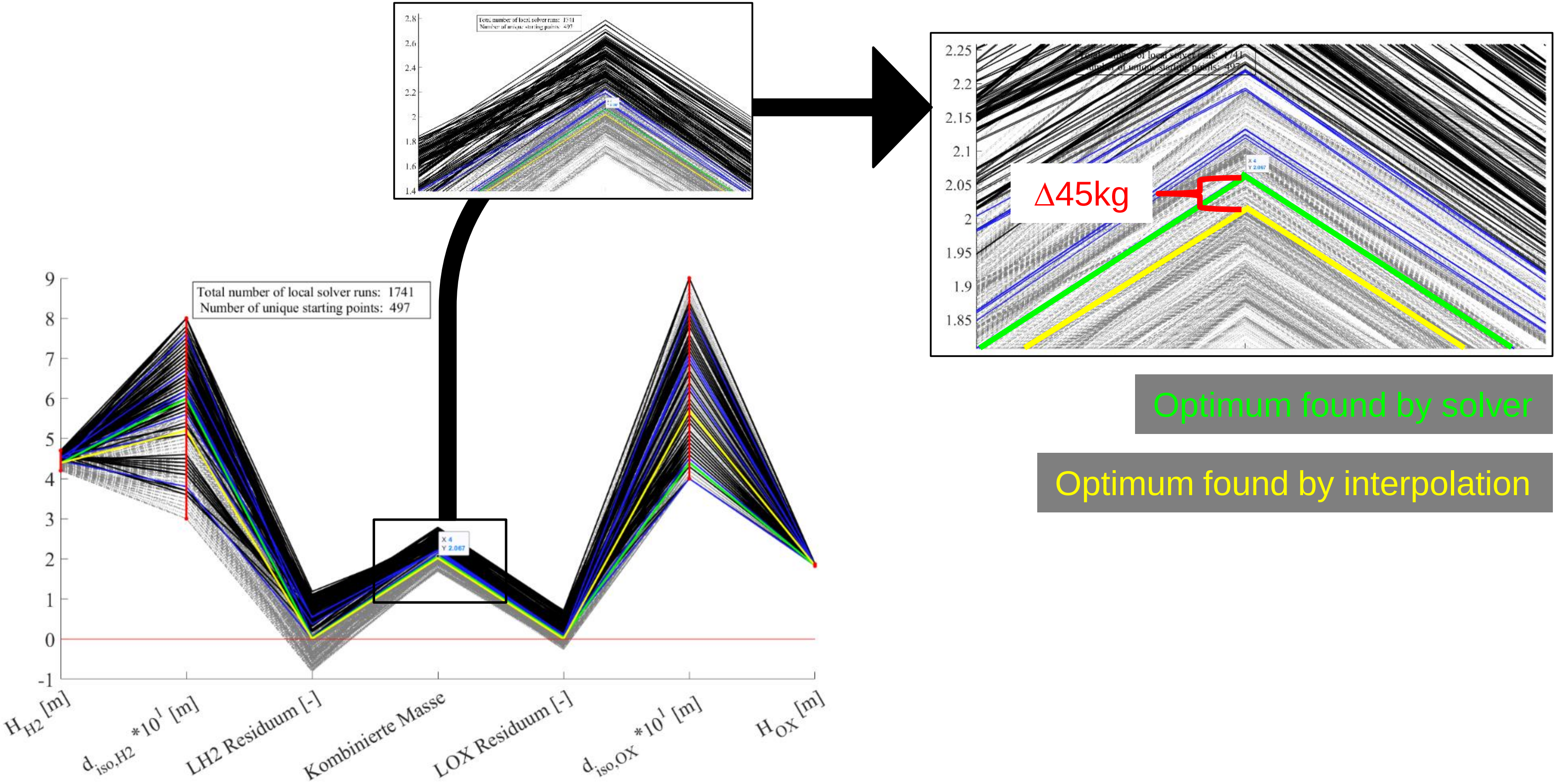
EXEMPLARY RESULTS OPTIMIZATION

Manual enhancement

- Each dot in the graph represents one simulation
- The LH2 residual is dependent on both associated variables (tank height **H_tank**, insulation thickness **d_iso**)
- Intersection curve represents all combinations of **H_tank** and **d_iso,** where the constraint is exactly met
- Optimum will be somewhere along this line
- Transfer of curve onto objective function **OF**
- Looking for minimum of **OF**



EXEMPLARY RESULTS OPTIMIZATION



Optimum found by solver

Optimum found by interpolation

TABLE OF CONTENTS

COMPARISON OF AL AND CFRP

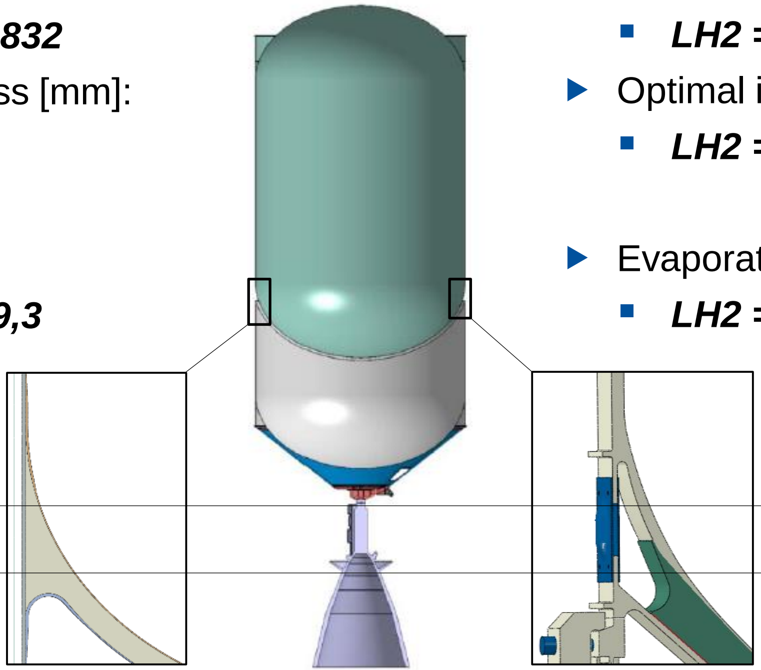
Identical …
- *Dimensions*
- *Mission*
- *Mechanical loads*
- *Thermal loads*

PHOEBUS C3

- SCB core thickness = ***12,0*** mm
- SCB face sheet thickness = ***1,0*** mm
- Optimal tank height [m]:
  - ***LH2 = 4,392; LOX = 1,832***
- Optimal insulation thickness [mm]:
  - ***LH2 = 52; LOX = 57***
- Evaporated mass** [kg]:
  - ***LH2 = 99,6; LOX = 139,3***

SCOUT FS2 SCB

- SCB core thickness = ***11,3*** mm
- SCB face sheet thickness = ***1,7**** mm
- Optimal tank height [m]:
  - ***LH2 = 4,392; LOX = 1,834***
- Optimal insulation thickness [mm]:
  - ***LH2 = 51; LOX = 65***
- Evaporated mass** [kg]:
  - ***LH2 = 107,7; LOX = 166,5***



-8,1%

-19,5%

CFRP VS ALUMINIUM

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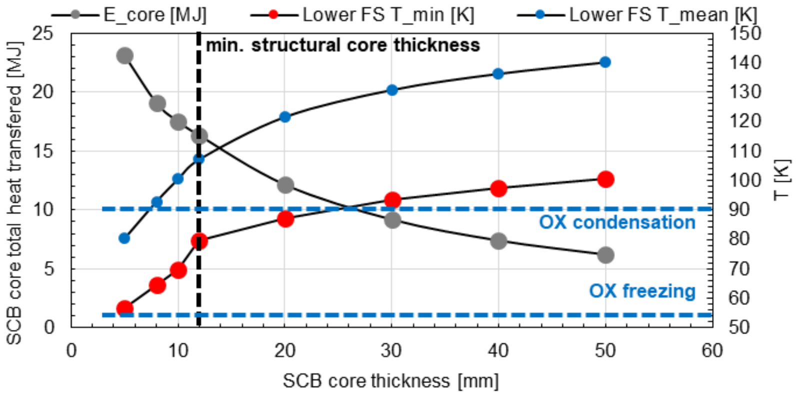
A6 ULPM (upper liquid propulsion module) equivalent stage with a SCB (sandwich common bulkhead)

- Sandwich Common Bulkhead core thickness variation
- Investigation of LOX condensation or freezing

CFRP

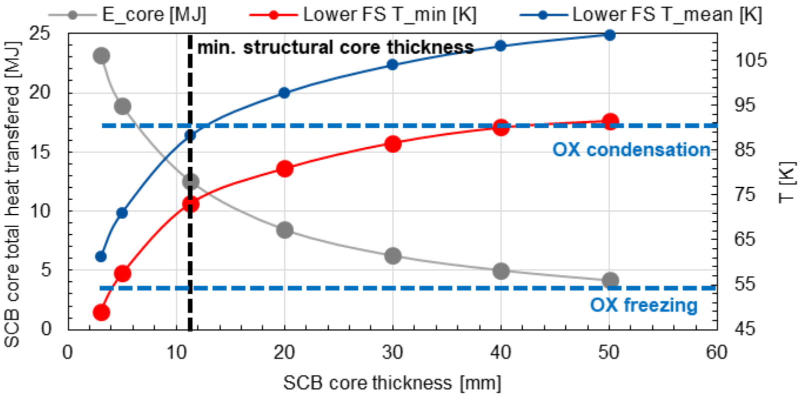
- Due to reduced thermal conductivity of CFRP vs. Al, step at *min. struct. core thickn*. noticeable



Note: all values during coasting from t=1159s to 20106s

Aluminum

- Due to large difference in thermal conductivity (Al vs. foam), SCB core is driving for thermal properties



Note: all values during coasting from t=1159s to 20106s

SCB VS SEPARATED TANKS & AL VS CFRP

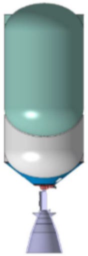
m_{prop}: LH2/LOX d_{iso}: LH2/LOX	**SCB** 	**Separated tank** 
Aluminum	m_{prop}: 4835/26486 kg d_{iso}: 51/65 mm	
CFRP	m_{prop}: 4812/26196 kg d_{iso}: 52/57 mm	m_{prop}: 4861/26215 kg d_{iso}: 38/74 mm

TABLE OF CONTENTS

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CONCLUSION / NEXT STEPS

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Model

- Coupling of thermal and structural aspects
- Good model for studies
  - Not computation performance hungry
  - Relatively fast simulation of entire mission durations
  - Quick results for parameter studies or investigation of different concepts
- Optimization of various parameters possible
  - Structural
  - Thermal
  - Coupled

Benefits of CFRP over Al

- Less dense, less structural weight
- Less heat conductive
  - Reduces parasitic heat fluxes and consequent evaporation losses
  - Requires less insulation effort
- SCB thickness can be easily tailored to optimize LOX cooling by LH2 evaporation
- CFRP is overall beneficial from a thermal-structural system-perspective

CFRC CYLINDER - ANALYTICAL INVESTIGATION

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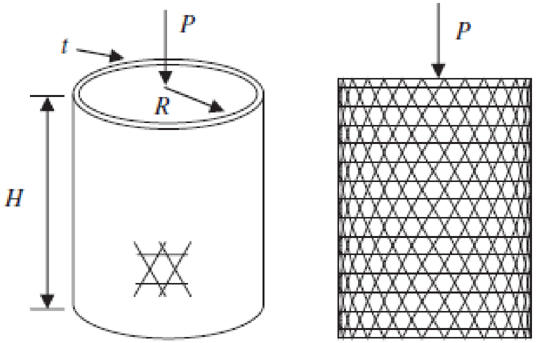
Lattice core sandwich

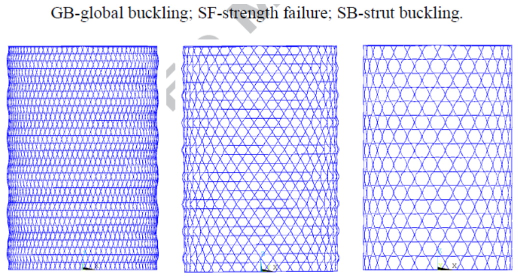
- global buckling
- face sheet mono-cell buckling/dimpling
- face sheet local buckling
- lattice rib crippling



Source: Equivalent analysis and failure prediction of quasi-isotropic composite sandwich cylinder with lattice core under uniaxial compression

Lattice

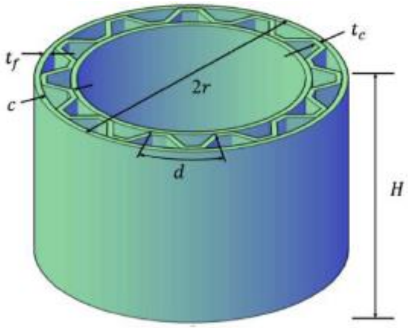
- global buckling
- out-of-plane strut buckling
- in-plane strut buckling
- strength failure



Source: Analysis of failure loads and optimal design of composite lattice cylinder under axial compression

Corrugated core sandwich

- global buckling
- shell buckling
- local buckling
- face crushing



Source: Fabrication and mechanical behavior of carbon fiber composite sandwich cylindrical shells with corrugated cores

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