

Final WORKSHOP



Trailer design to maximise amount of GH₂ transported using Type V tubes

« ROAD TRHYP »

ROAD trailer design – use of Type V thermoplastic tube with light composite structure for HYdrogen transPort

ICP

June 17th, 2026



Safety moment : What should I do if an alarm goes off ?



1/ I HEAR OR SEE A BUILDING ALARM

2/ I am **OUTSIDE** the building:

2/ I am **INSIDE** the building:

3/ I **DO NOT ENTER**,
I go to the closest
meeting point.



3/ I go to the closest meeting point calmly, I do not run, I hold the handrail when using the stairs. (I do not take the elevator).



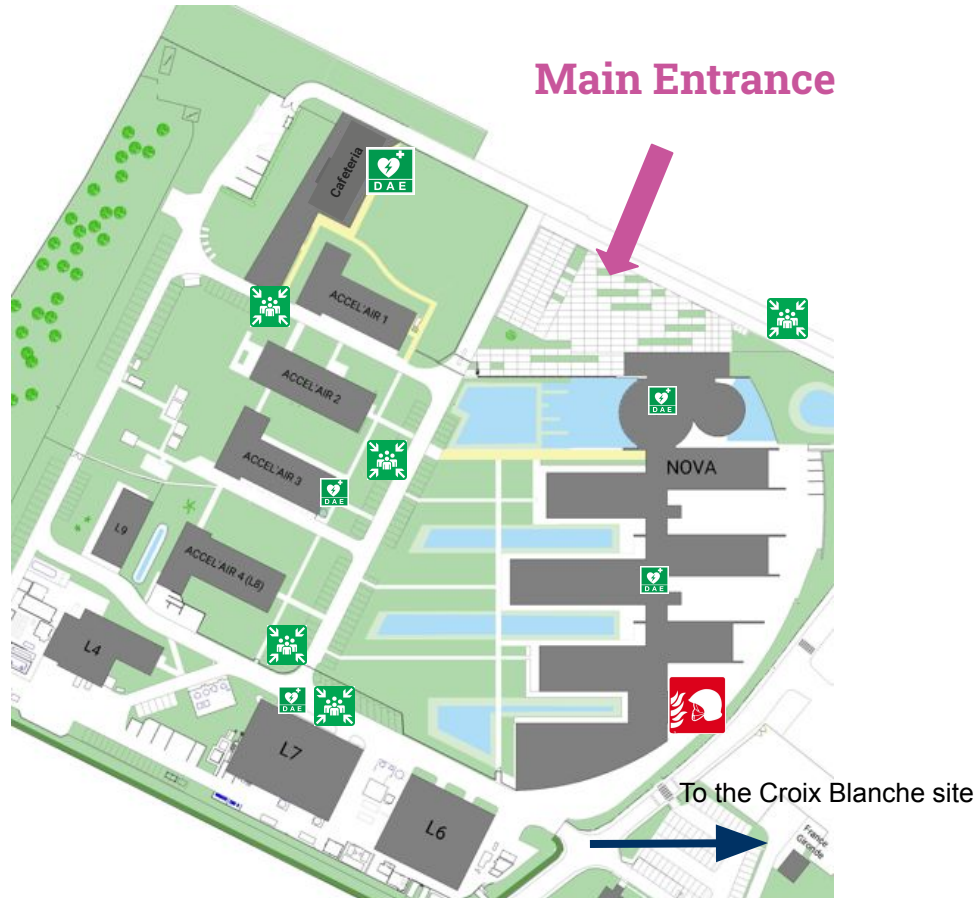
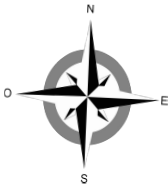
I look after the visitors for whom I am responsible.



4/ I **RE-ENTER** the building only if the **Meeting Point Coordinator** invites me to do so.

Safety moment : What should I do if an alarm goes off ?

ASSEMBLY POINTS - Innovation Campus Paris



Main Campus: 5 assembly points

In case of emergency: 
Call the internal first aid team

French phone: 01 39 56 38 82
Foreign phone: +33 1 39 56 38 82



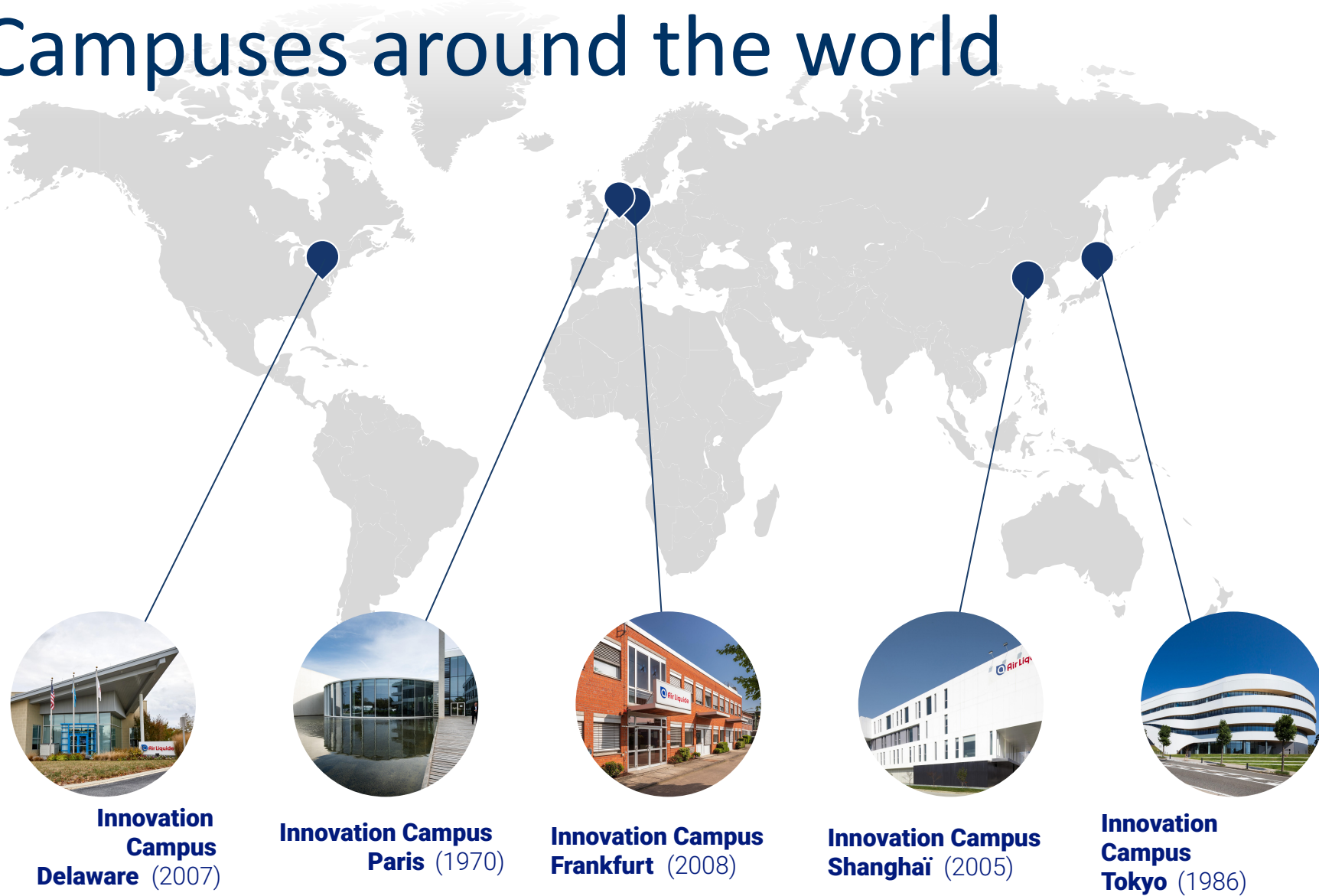
Agenda

- | | |
|------------------|---|
| 10.00 – 10.30 am | Welcome |
| 10.30 – 10.45 am | Presentation of ROAD <u>TRHYP</u> : origin, objectives and partnership |
| 10.45 – 01.00 am | Results : <ul style="list-style-type: none">- Type V cylinder development / performances / industrialisation
<i>Materials, Processing (equipment, energy, waste, ...), Weight saving, Gravimetric index, Recyclability</i>- Advantages from the Usage point of view
<i>Cylinder preparation, Drying, Periodic inspection</i>- Safety & Fire behaviour- Prediction tools for Cylinder temperature management to maximise operating conditions
<i>Preparation conditions - HRS operation</i>- TCO of a dedicated GH2 Supply chain- Conclusion & Perspectives |
| 01.00 – 01.30 pm | Q & A session |
| 01.30 pm | Lunch – Networking – Parts displayed |

WELCOME !

Key Figures

Campuses around the world



~ 500
R&D employees

+ 300
Academics & Industrial Partners

> 50%
R&D projects conducted in partnerships

5
Campuses





INNOVATION CAMPUS PARIS

59 Laboratories



8 Technical
platforms

Gas Safety - Process Engineering -
Computational and Data Science -
Material Qualification - Combustion,
Food processing - Additive Manufacturing
- Gas Analysis



400

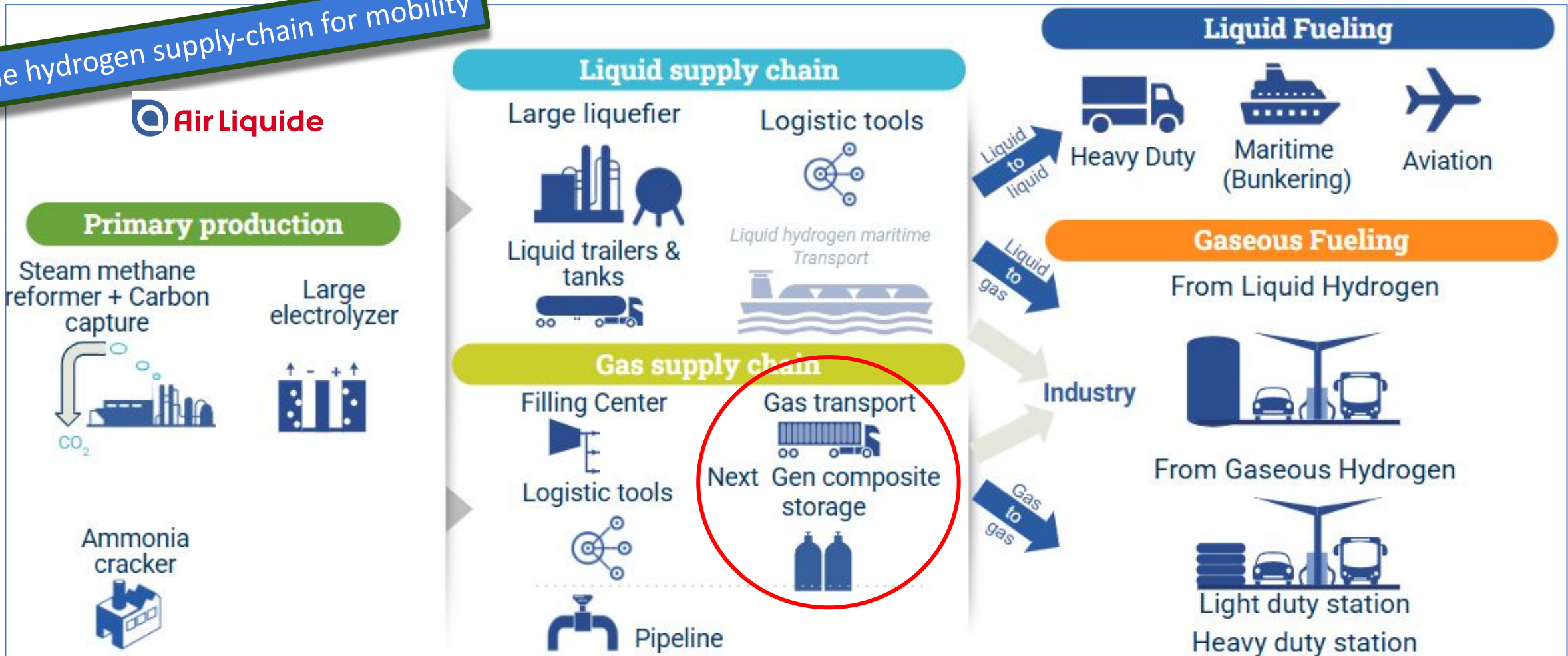
people on the Campus

Discover the campus in [video](#)

The campus also relies on a team based in Krefeld (Germany).

Origin of the project : Why did we start ROAD TRHYP ?

The hydrogen supply-chain for mobility

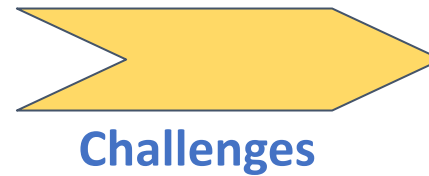


Origin of the project : Why did we start ROAD TRHYP ?

Metallic tubes trailer



Composite tubes trailer



Regulation, standards

Use of EN 17339 Transportable gas cylinders - Hoop wrapped and fully wrapped carbon composite cylinders and tubes for hydrogen

1,5 T of Hydrogen at 700 bar

Hydrogen purity

ISO 14687 / SAE J2719 compliance: < 5 ppm water content

- Polymer absorption
- Drying feasibility
- Vacuum/collapse resistance

Safety

Composite tube & trailer behavior in fire

- Fire: damage, Leak before burst
- TPRD
- Leak management & mitigation

Usage

Type V: smooth the differences with metallic behavior

- Filling/emptying + drying SOP
- Damage detection & inspection

Scope of the CH JU Call and objectives of ROAD TRHYP



Scope of the call :

- To develop and validate a solution to store in a trailer a **minimum payload of 1.2 ton** of compressed Hydrogen
- Working pressure **above 500 bar**
- The **solution should be cost competitive** compared to existing solutions reaching at least a cost of 600-650 €/kg of Hydrogen stored

Objectives of the project :

- # 1: Design **Type V tubes** according to EN 17339 and key performance & usage (filling/unfilling, drying, ...) tests
- # 2: Elaborate a **decontamination methodology** to meet H₂ purity → key parameters to have less than 5 μmol/mol H₂O
- # 3: Demonstrate the **safety of Type V tubes** → Bonfire test & modelling of tube behavior in fire - Safety aspect
- # 4: **Demonstrate that** a trailer made with Type V tubes will achieve the **expected KPIs in 2030** (350 €/kg of GH₂ stored, > 500 bar WP, GC > 5 - 5,3 %) & **improved environmental impact**
 - Trailer & demonstrator design
 - Demonstrator testing to validate key features & modelling validation (filling/unfilling & upfire)
 - **TCO Type IV and Type V comparison**
- # 5: **Formulate the regulatory regulations** aiming at faster deployment of the technology

The Partnership



Development of Type V tubes



Tape optimisation & manufacturing



Design of trailer, participates to the regulation study, eco-design and LCA



Study of the mechanical behaviour of tubes exposed to fire



Wrocław University
of Science and Technology

Cylinder testing



Is in charge of drying & filling/unfilling tests



Is in charge of large scale fire tests and fire modelling



Filling/unfilling tests & modelling, drying tests, standard and regulation study, T.C.O.

ROAD TRHYP : Technical Presentations



ARKEMA

Advanced Thermoplastic Composite Materials for High-Pressure Hydrogen Storage in Trailers



Financé par



GOUVERNEMENT

Liberté
Égalité
Fraternité



Financé par
l'Union européenne
NextGenerationEU



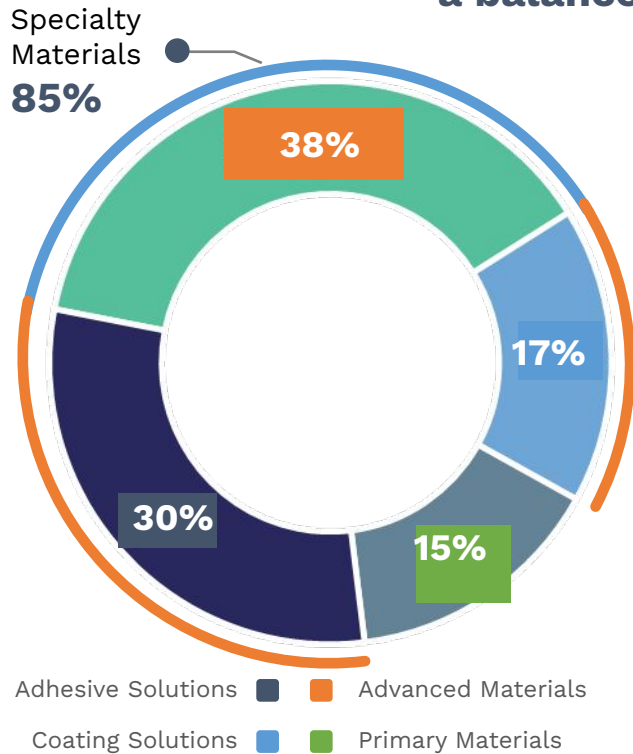
Workshop at Air Liquide, June 17th, 2026



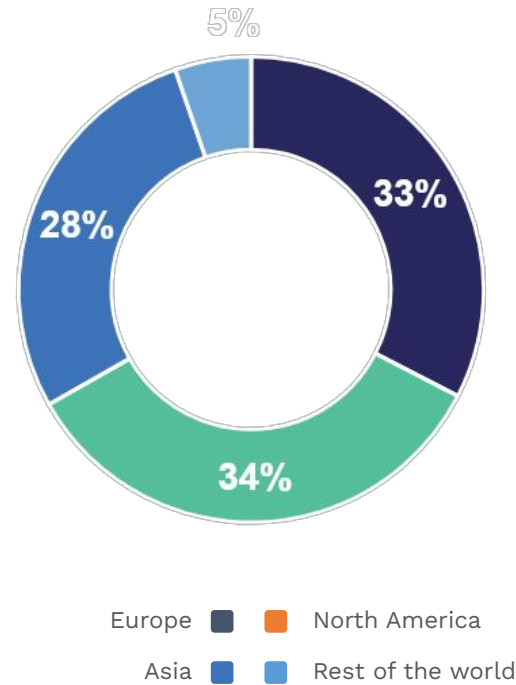
A Global **Specialty Materials** Leader across various **High-Growth Markets**

A leader in Specialty Materials with a balanced geographical footprint

2025 data



€9.1bn sales



We provide solutions for **Composites End Markets**



Transportation



Aerospace



New Energy



Electric & Electronic



Building & Construction



55
countries



20,700
employees



€636m
capex

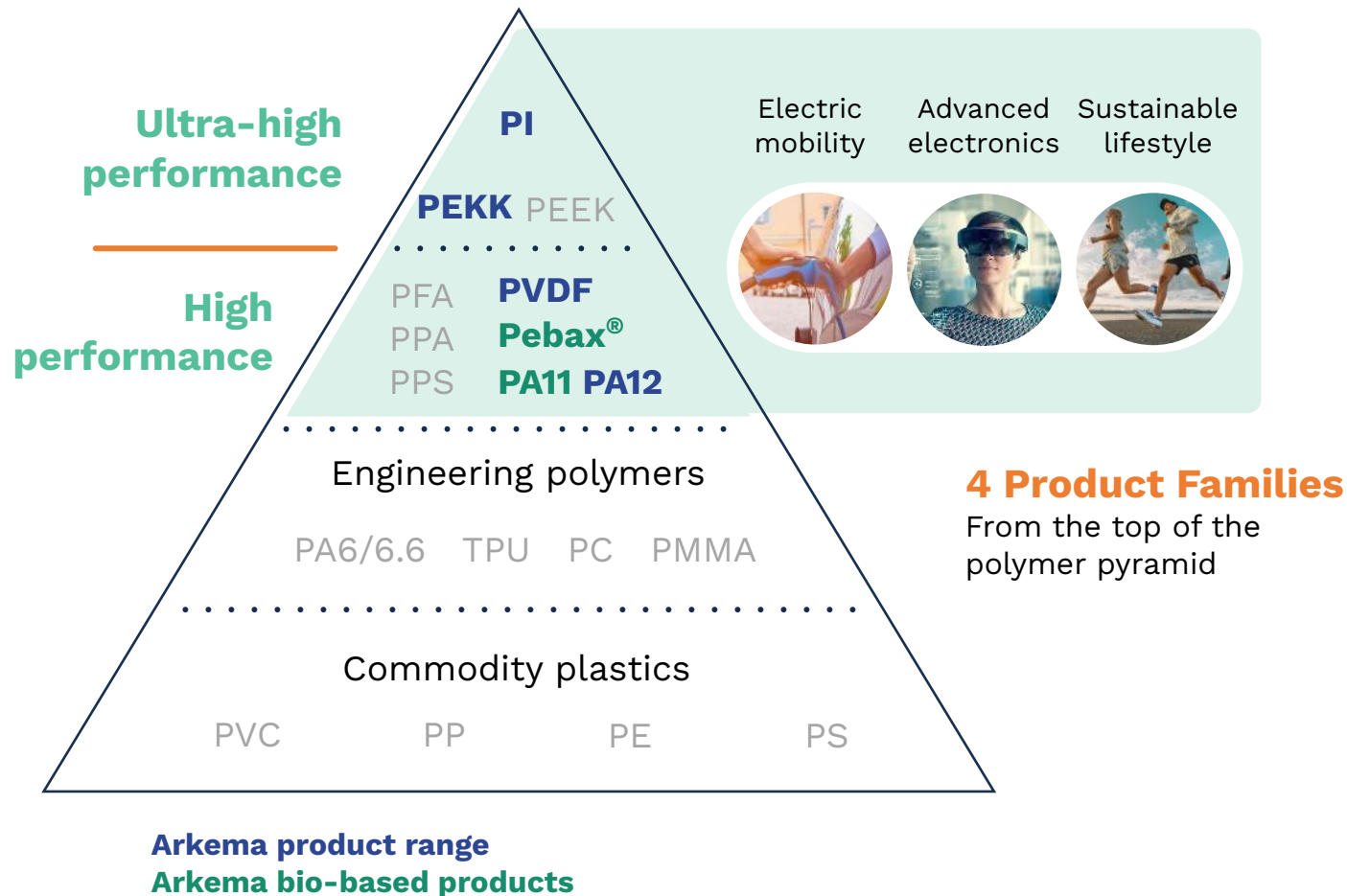


€284m
R&D expenses

Arkema - A Differentiated Portfolio of **High-Performance Polymers**

High Performance Polymers

Driving decarbonization, durability, and circularity



High Performance Polymers

PVDF

Kynar® Fluoropolymers

PA11, PA12

Rilsan®, Pebax®, Rilsamid®, Orgasol® Specialty Polyamides

PEKK

Kepstan® PEKK

Polyimides

Zenimid® PI solutions

From castor bean to advanced polymers – **A miracle of science**



Castor Plant



Castor Bean



Castor Oil



Polyamide 11

Preventing the depletion of natural resources (crude oil)

Castor – The magic bean

The castor bean is actually a **seed**.
Plant it, and more seeds grow.
The circle of life.



No competition with food / feed



Grown mainly in India (Gujarat region) – mainly in the poorest soil



No deforestation



The beans are crushed to make ~45% oil and 55% cake (sold as fertilizer)

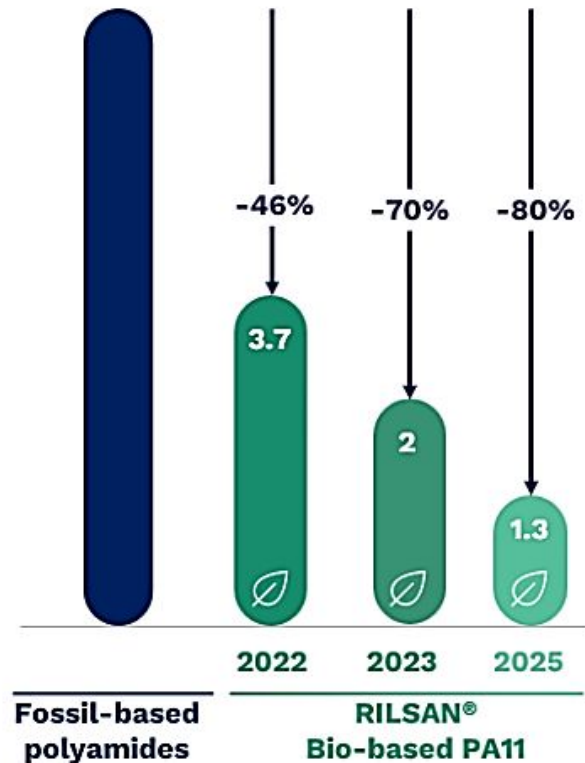


Highly profitable for the farmers (the main reason they grow castor)

Climate Change Impact Reduction and Other LCA Benefits

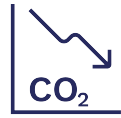
Carbon Footprint

(PA11 comparative data vs standard fossil-based polyamides)
Standard ISO 14040/44 and ISO 14067 (kg CO₂e/ kg)



- **Rilsan® PA11's carbon footprint reaches 1.3 kg CO₂e/kg**

- Applies to the entire global production (not limited to a selection of grades)
- Continuous action plan for further reduction by 2030



- **Agricultural land use**

Castor grows best in marginal soils



- **Water depletion**

Castor takes advantage of the natural rainy seasons



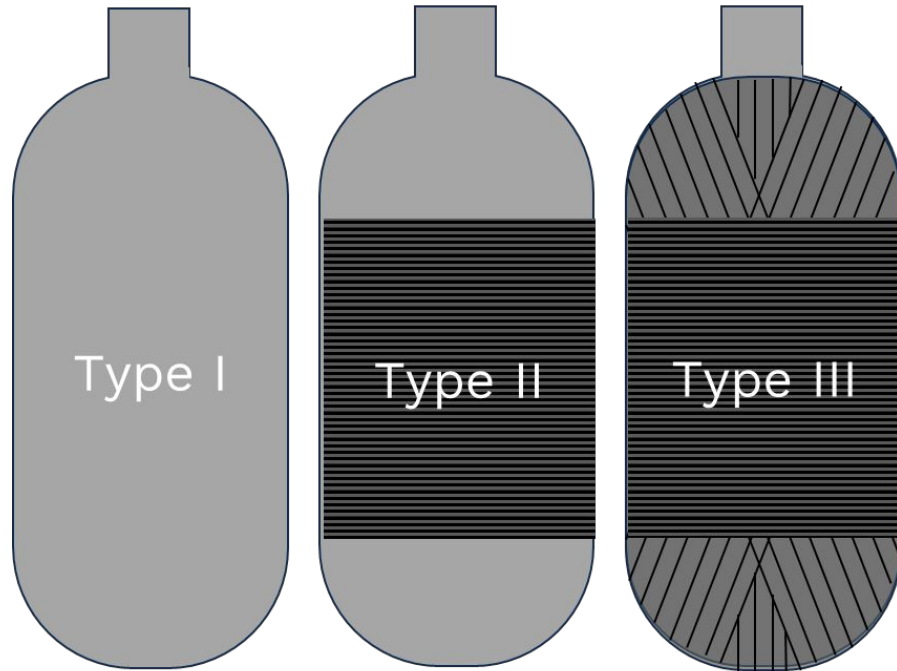
We are now well on track to deliver on our ambition to lower the PCF even further, to 1 kg CO₂e/kg by 2030.

Model for Fossil Materials Based on use of Traditional Energy Sources

A bit of H2 pressure vessel wording

ARKEMA

Metallic Liner



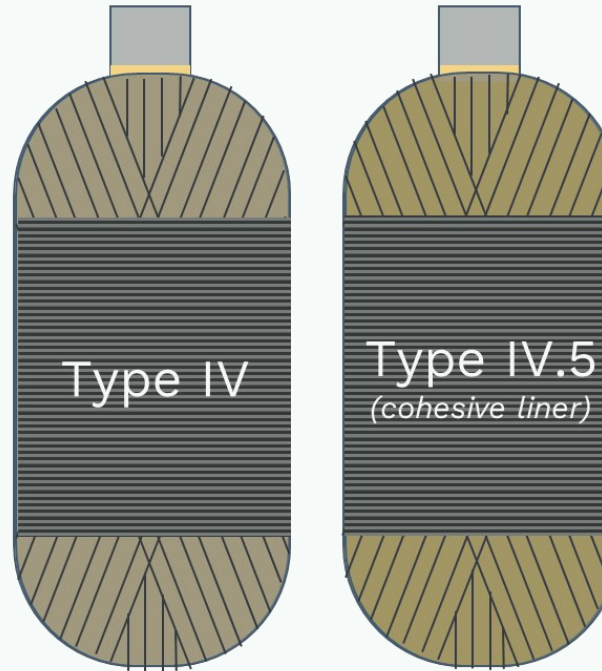
No Fiber winding

Fiber Hoop-winding

Hoop + Hex Fiber winding (full tank)

RILSAN®

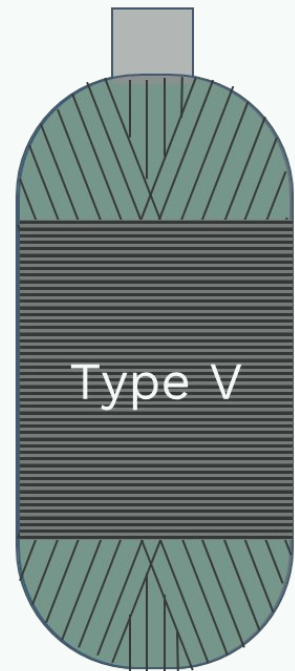
Polymeric Liner



Type IV

Type IV.5
(cohesive liner)

Linerless



Type V

ELIUM® UDX®

UDX®

UDX[®] PA11 tapes: Our **High Performance** Thermoplastic Carbon Tapes



Description

Continuous carbon fibers impregnated with **Rilsan[®] PA11**

Processing

Designed for **Robotized Deposition** or **Hand Lay-up**

Use cases : **Local Reinforcement** + **Overmolding**

Full/hybrid composite part manufacturing

Consolidation : **Temperature** + **Pressure**

Market focus

(Winter) **Sports**, Consumer, **New Energies**, Industrial, Transportation etc.



Main advantages

Light, **Stiff**, **Strong**, **Impact** resistant,

Sustained **performance at low T°**

Very low moisture uptake



> **98wt% bio-based**
Rilsan[®] PA11 matrix

UDX[®] PA11 tapes: How are they **manufactured** ?



Description

Continuous carbon fibers impregnated with **Rilsan[®] PA11**

Impregnation process

One Tow One Tape technology

Multiple bands in parallel

On-line calibration

Sustainability

Dry powder impregnation (**No solvent, no water**)

Coarse powder

No slitting (no material loss)

Energy consumption mostly dedicated to **melt the polymer**

Low melting point biobased polymer (**Rilsan[®] PA11**)

Main advantages

High production speed

High carbon fiber content materials

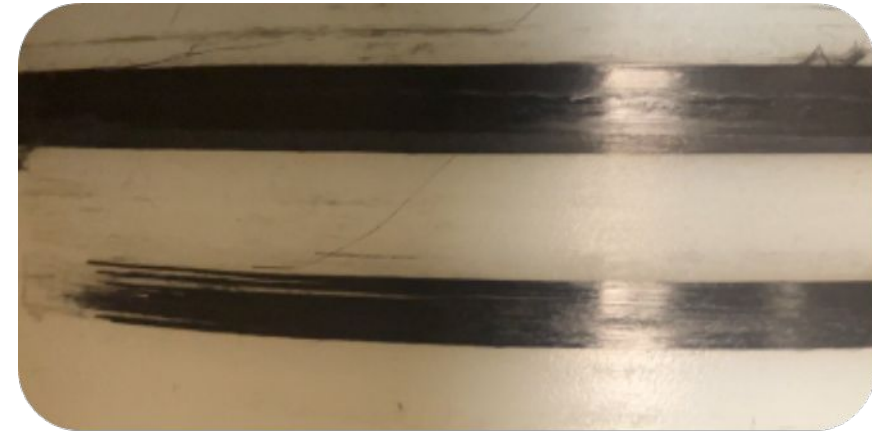
Low FAW (60g/m²) products

Long continuous tape **spools**

Expected benefit using **PA11 barrier layer** & **UDX® PA11 tapes** for **COPV**

→ **Cohesion** between the barrier layer & reinforcing composite layers : A **safer & efficient** solution

- No liner collapse □ drying under vacuum is possible
- No H₂ accumulation between liner & composite
- Higher barrier performance (monolithic structure)
- Overall very low moisture uptake solution

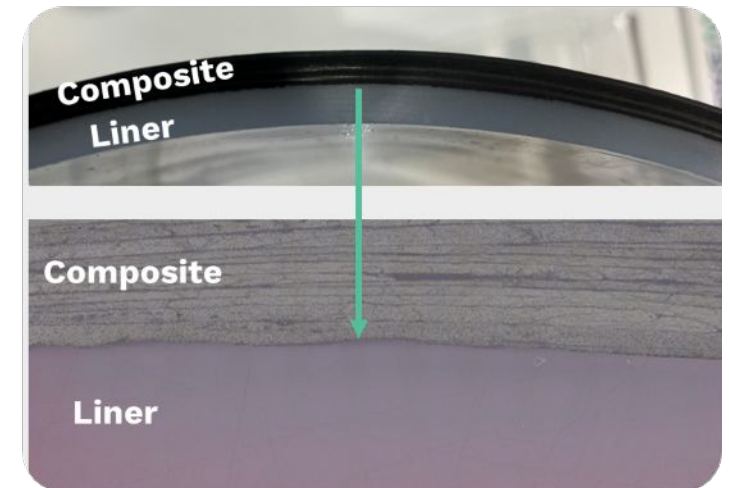


→ **Extended lifetime** of the COPV

- Higher resistance to crack compared to epoxy-based tanks
- Better fatigue behavior

→ A more **environment friendly solution**

- PA11 is a biobased polymer
- Only 2 organic components (PA11 and carbon fibers) □ increasing recyclability solutions



Materials provided in the RoadtrHYp project to Covess

- **Main material characteristics**
- **57%vol** carbon fiber □ **high mechanical performance** (> 2500MPa)
- **No slitting** during tape manufacturing □ no fiber cut □ **unaltered performance**
- **Low viscosity** Rilsan® PA11 □ **high processability** even in in-situ consolidation
- **100% biobased** Rilsan® PA11 resin
- **Very low moisture** uptake □ **constant performance** in real condition of use (moisture & temperature)

- **Tape spool characteristics**
- **Carbon spool length** = initial **carbon roving** (3.5km each)
 - **fewer stops** during tank manufacturing □ **higher productivity** & less defects
- No slitting & no splicing □ no dust, **no defect on the spools**
- **No specific storage** or pre-drying conditions prior to use □ **higher efficiency**



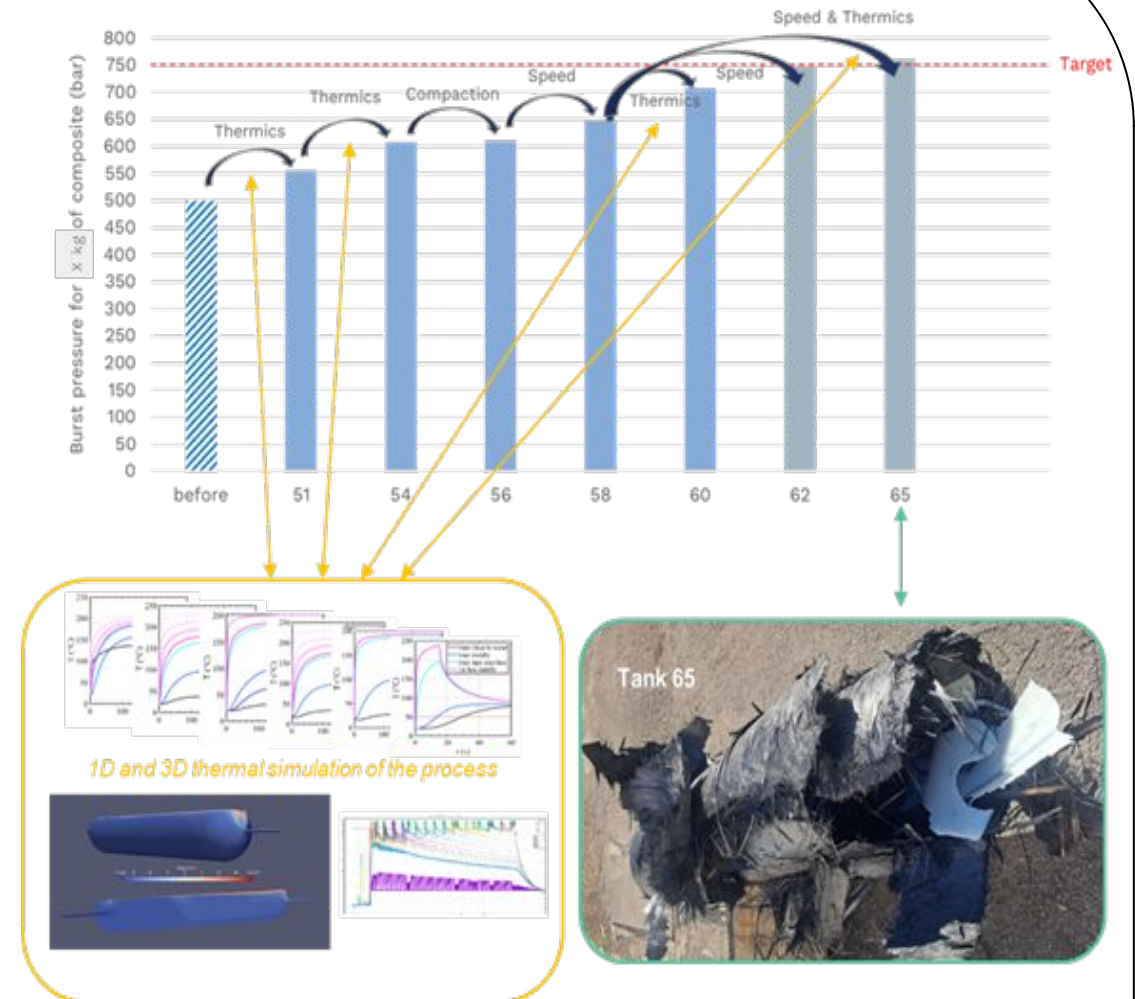
Achievements on type 4,5 tanks (330L PA11 liner EBM)

□ **Burst pressure → Milestone Achieved**

- **Optimization** of the tank manufacturing process with support from **1D and 3D thermal simulation**
- Target **burst pressure > 750bar** achieved (330L for x kg of composite)
- **Repeatability** of performance within standard criteria (variation < 5%)

□ **Liner/Composite Cohesion → Milestone Achieved**

- Optimization of the tank manufacturing process with support from 1D and 3D thermal simulation
- **Optimization of the base component materials** (bosses covered with PA11)
- **Strong liner/composite cohesion** throughout the entire tank



Achievements on type 4,5 tanks (330L PA11 liner EBM)

□ **Ambient & Extreme Temperatures Cycling → Milestones Achieved**

- **Hydraulic cycling at +23°C AND (+65°C / -40°C)** according to EN 17339 standard
- Results:
 - At +23°C : **No leakage or rupture after 21,209 cycles** (test voluntarily stopped) □ Achieved at least 140% of the target set by the standard (15000 cycles)
 - At extremes temperatures : **No leakage or rupture after 5000 + 5000 cycles** in compliance with standard criteria (5000 cycles at each temp)

□ **Burst Pressure After Extreme Temperature Cycling → Milestone Achieved**

- Burst pressure measured on the tank cycled at extreme temperatures according to EN 17339 standard
- **Burst pressure at 702bar >> 591bar (target)** in accordance with standard criteria
- Achieved at least 118% of the target set by the standard

Achievements on type 4,5 tanks (330L PA11 liner EBM)

- Conclusions
- **Arkema PA11 liner & UDX[®] PA11 composite are highly performant materials**
- **Covess manufacturing process is highly consistent**
- It is possible to have a **cohesive liner in a performant tank**
- **A full PA11-based tank can sustain the requirements of standard ISO EN 17339**

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arkema.com

ARKEMA

Type V cylinder development / performances (including usage)

Materials, Processing (equipment, energy waste,..),
weight saving , Gravimetric index , Recyclability



Content



- The Principal of the type V developed.
- The production process
- Major developments which have taken place in covess in this project.
- Major USP's in use of a type 5 compared to the state of the art.
 - Monolithic structure hence vacuum resistance.
 - Intrinsic high safety benefits
 - Fatigue performance
 - Barrier performance
 - Low Ecological footprint - Recyclability
 - Unique replaceable connectors - covess patented design.
 - Higher temperature performance

Type 4

Type 4.5

Type 5



Outer reinforced layer



Liner
No cohesion



Co-melted
Liner



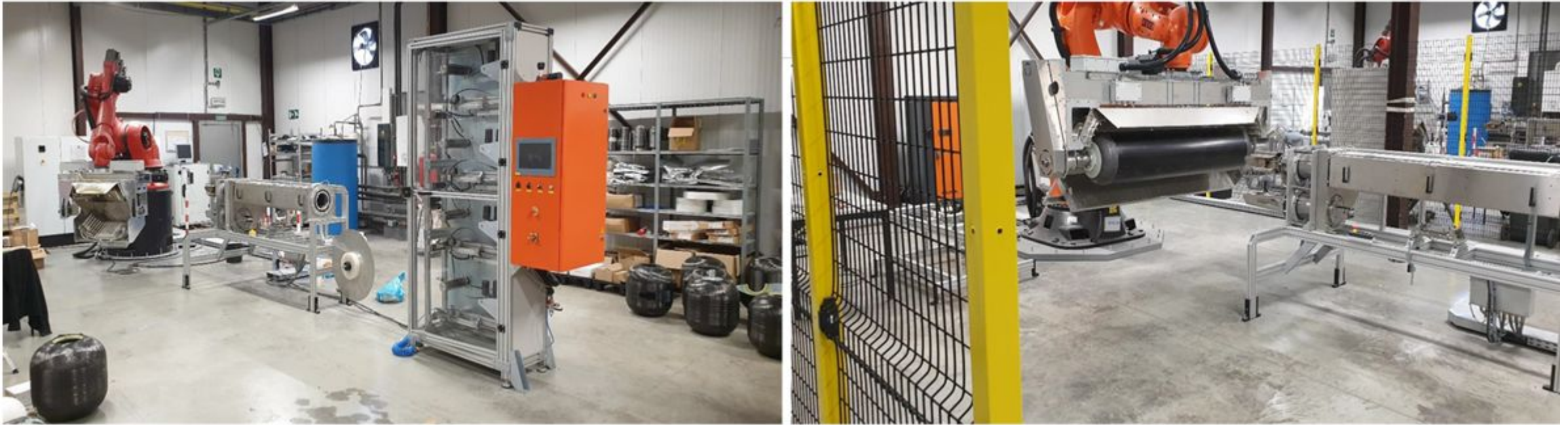
Similar base polymer for both layers cohesively "bonded/melted" into a unique thermoplastic monolithic composite structure



Co-melted
barrier



The production process



The process can be best described as a 3D composite printing process -1 steps process



A 3D composite printing process

- Covess process is a thermoplastic (TP) Unidirectional (UD) tape winding process with a direct consolidation no post curing step needed for a thermoset solution
- Over the years a significant Patent portfolio has been developed and is further expanding all the time covering all parts of this process.
- During Roadthryp the process hardware and software has been continuously improved



The production process cntd.



Preheating the tape into melt



UD tape bobbin tensioning device
Detailed tension control for every bobbin

Infrared oven multi feedback loop with camera's

- Detailed temperature control is present, for each layer of the tank, over multiple zones.
- Current winding speed for the prototype line is in average 15 m/min - industrialisation will increase the tape laying speed upto 60 m/min.

Past en recent high pressure developments

In the period 2014- 2016 similar technology, first high-pressure achievement with type 5/60liter based on PA

During the Roadthryp-project 2023 – Q2 2026 below vessel of 330liter was produced

Failure at 444 Bar

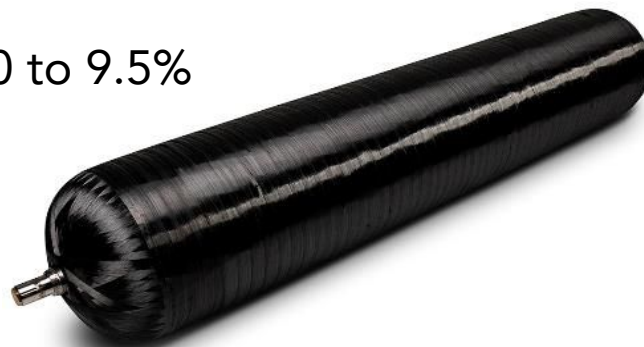
G.I = 3.2%



Weight 27 kg



G.I = 9,0 to 9.5%



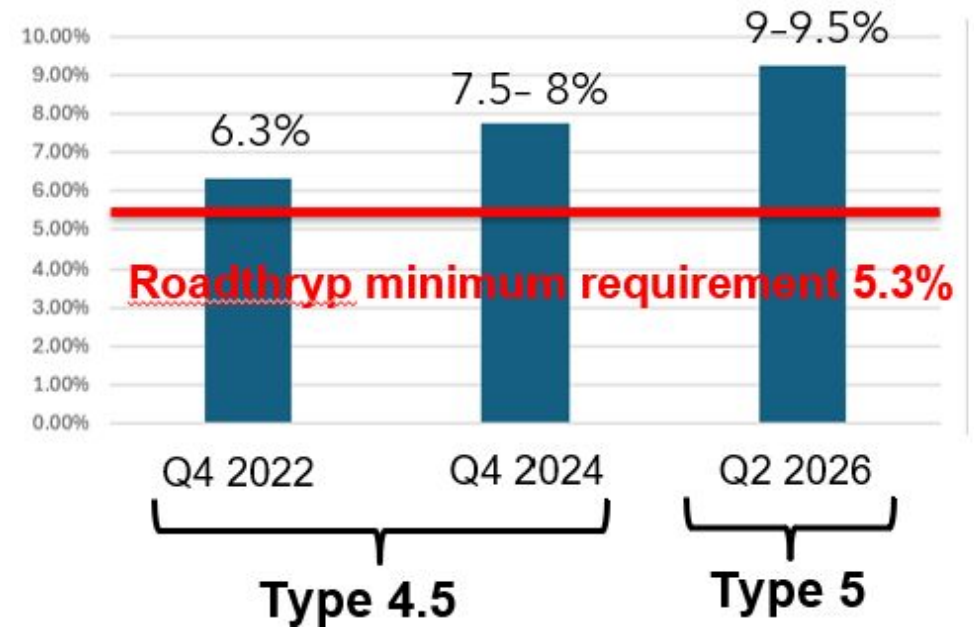
Mid term true potential.
G.I. > 10

Factor 2.89 increased Storage efficiency (G.I. index)



Latest Burst failure at 825 Bar (320 WP)

Gravimetric Index (G.I.)



Improved inner barrier developed

- **Allowing for a constant thin barrier layer over the entire cylinder independent of the length off the cylinder**



Replaceable Connectors developed - Covess patented boss design.

- Inner thread damages of the boss, does not anymore mean the end of live for the tank.



Inner Boss nipple can be replaced.

Some recent high pressure developments

- Example of a 320 WP vessel - 350 L towards a G.I. 9-9.5% - further weight optimisation possible

350 liter tank Burst testing type 5 2026 (320 Bar working pressure, minimum burst pressure 756 Bar)									
				Tape (kg)	barrier (kg)	total weight tank (kg)	BP (bar)	GI WP related	GI BP related
70	PA11	04-Jun	Alu 7 bosses /O ring	75,79	5.22	87.21	825	9.0	9.6

- Reproducibility in burst performance of a 380 WP vessel - 350 L

350 liter tank Burst testing type 5 2026 (380 Bar working pressure, 897 minimum burst pressure)							GI WP related	GI BP related	
				tape (kg)	film (kg)	BP (bar)			
56	PA11	19-Mar	Alu 7 bosses /O ring	95.13	5.32	957	8.4	8.90	
57	PA11	23-Mar	Alu 7 bosses /O ring	98.38	5.35	918	8.2	8.30	
63	PA11	16-Apr	Alu 7 bosses /O ring	95.46	5.34	945	8.4	8.70	
64	PA11	20-Apr	Alu 7 bosses /O ring	94.38	5.32	918	8.5	8.60	
average burst value last 4 tanks spread below 4.5% in burst behaviour						935	Average gravimetrix index values last 4 tanks	8.4	8.6

Recent very high pressure developments

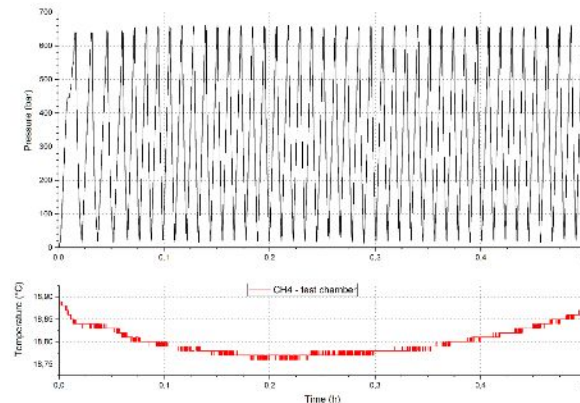
- 3 test vessels have been manufactured with a burst pressure of 1300 Bar, Test pressure upto 650 -720 Bar

150 liter vessel produced for further testing exit Qc test pressure tested at 650 -720 Bar				Tape (kg)	Barriere (kg)	Test pressure (bar)	
37	PA11	06-Jan	steel bosses	97.3	2.93	669*	Used cycle testing
38	PA11	08-Jan		98.4	2.91	654*	Used for Bonfire testing
39	PA11	12-Jan		95.4	2.89	718*	Used for high speed filling testing
41	PA11	05-Feb		97.5	2.77		Vessel packed with thermocouples for thermal simulations
* Test pressure tested part of exit QC ** With a burst pressure of ca.1300 Bar							



Resistance to pressure cycles at ambient temperature – test 6 (ATPC test) according to EN17339

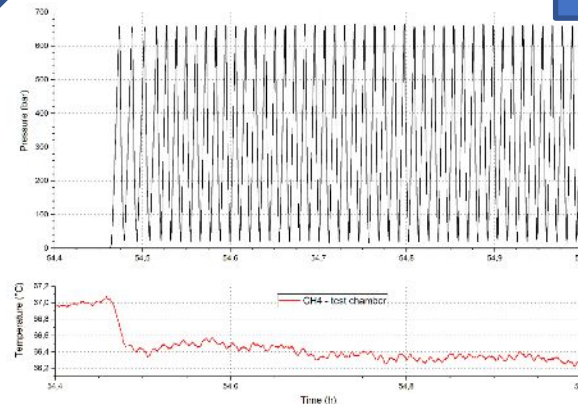
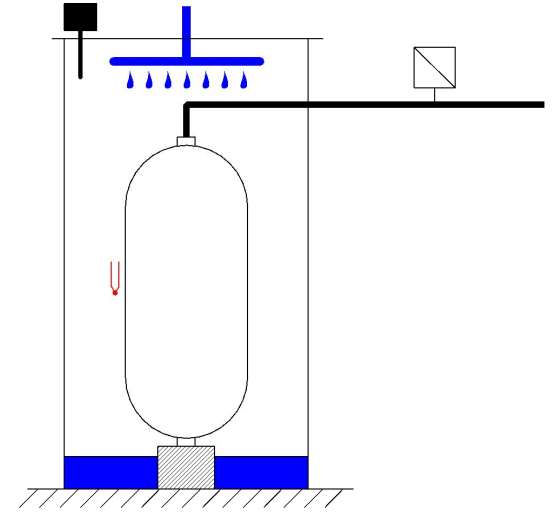
- Test results: >15000 cycles at 30 ÷ 650 bar
- Test was done in 3 rounds (AT + HT +LT): each >5k Pressure Cycles
- Test of tank #037 was done at WRUST facility



Extreme temperature cycle test – high temperature acc. EN17339

- Pressure: 30 ÷ 650 bar
- Conditions: Temp >65 °C, RH ≥95%
- Test of tank #037 was done at WRUST facility

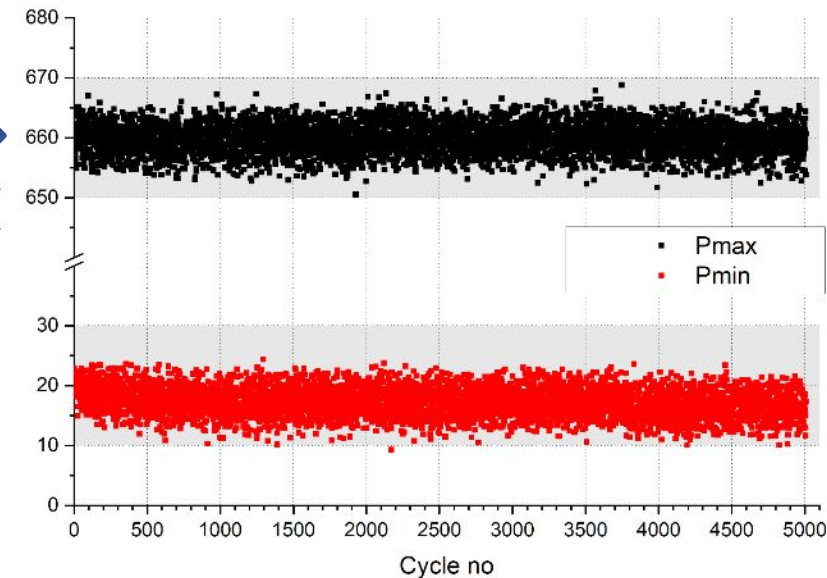
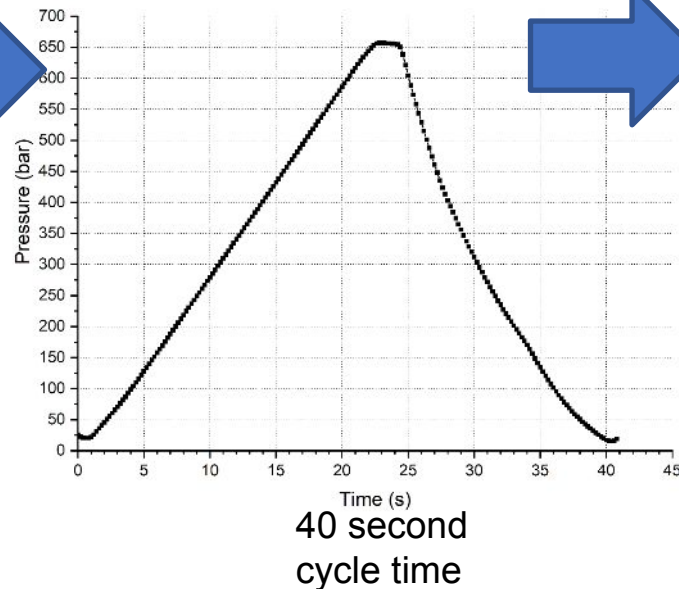
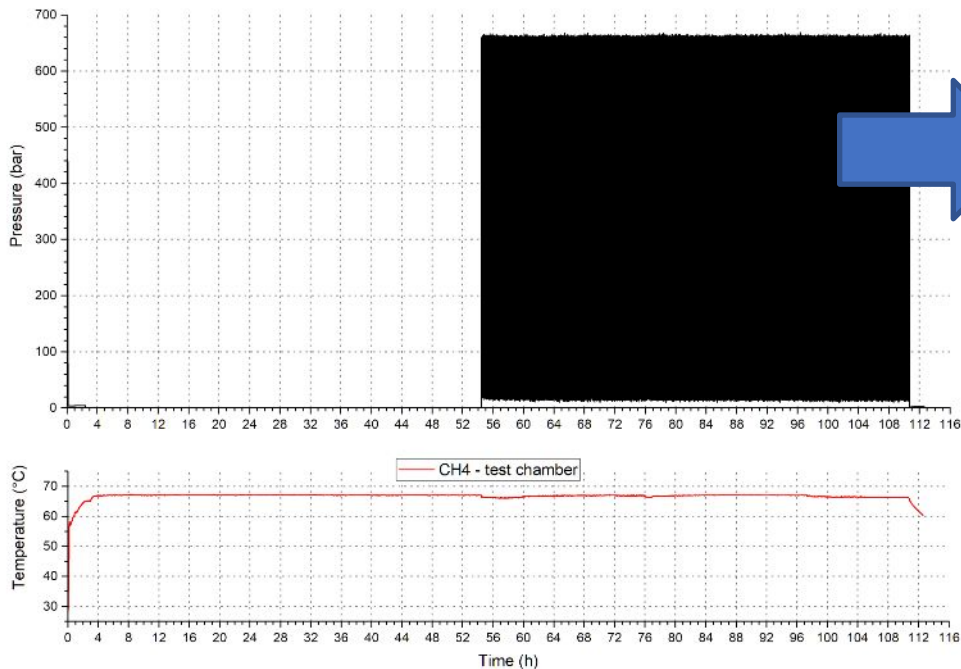
- Pmin: <30 bar
- Pmax: >Pmax at 65°C (650 bar)
- Temperature: >65 °C
- Relative humidity: ≥95%



Extreme temperature cycle test – high temperature – acc. to EN17339

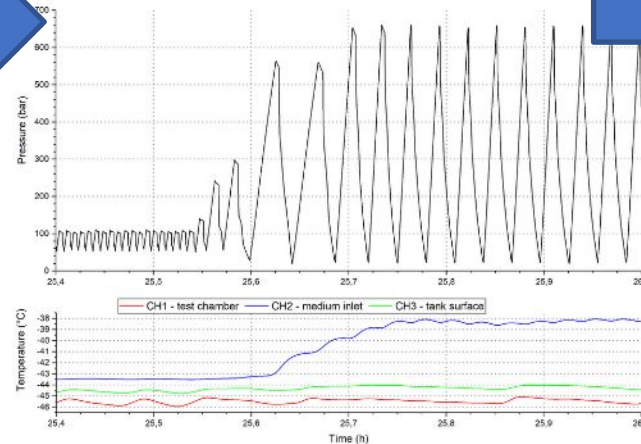
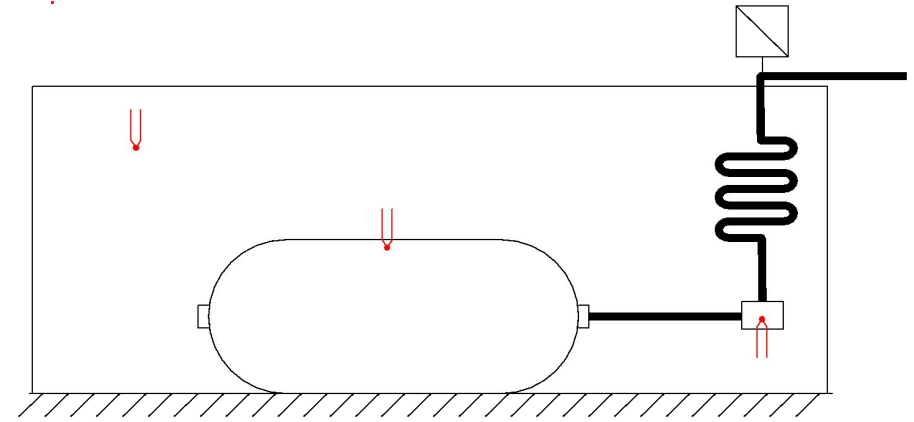
- Test results for the HT phase:

	N total	Mean	Standard Deviation	Minimum	Maximum		Mean	Minimum	Maximum
						Temperature (°C)	66,7	66,0	67,2
Pmax (bar)	5008,0	659,8	2,5	650,5	668,8				
Pmin (bar)	5007,0	17,3	2,4	9,3	24,4				



Extreme temperature cycle test – low temperature

- Pressure: 30 ÷ 650 bar
- Conditions: Temp <-40 °C
- Test of tank #037 was done at WRUST facility

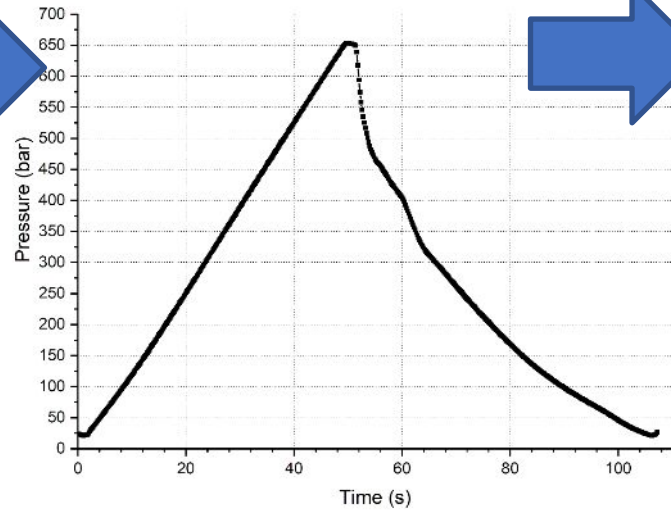
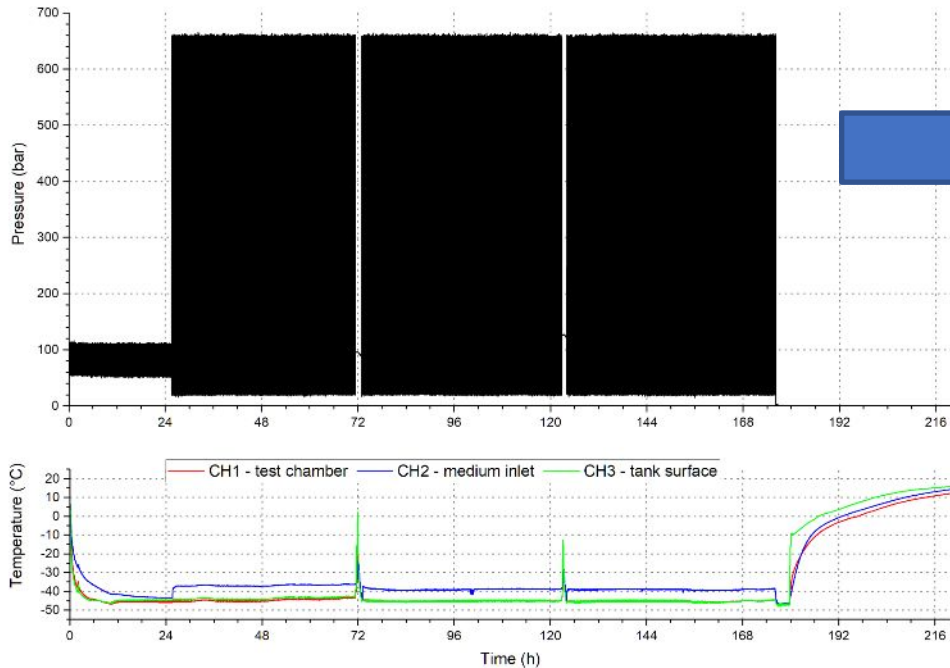


Extreme temperature cycle test – low temperature

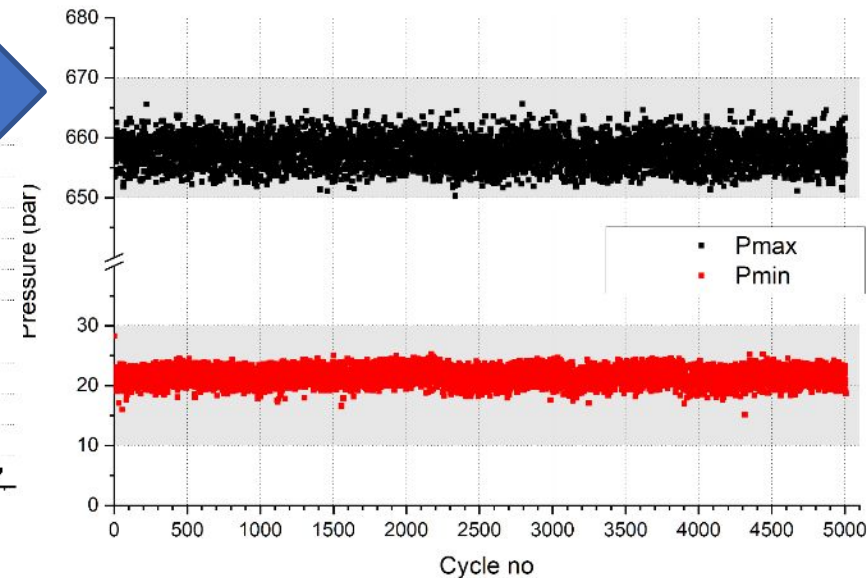
- Test results for the LT phase:

	N total	Mean	Standard Deviation	Minimum	Maximum		Mean	Minimum	Maximum*
Pmax (bar)	5003,0	657,6	2,4	650,3	665,6	Test chamber (°C)	-44,8	-47,7	-21,0
Pmin (bar)	5004,0	21,5	1,4	15,1	28,3	Medium inlet (°C)	-38,3	-46,7	-23,6
						Tank surface (°C)	-44,5	-47,9	2,0

* - during de-icing procedure



100 s cycle time



Exposure to elevated temperature – test 7 (AccSR test)

Basic test requirements (according to EN 17339/2020):

- Test pressure for AccSR: $>P_{max}$ at 65 °C (650 bar)
- Temperature: 70 ± 5 °C
- Relative humidity: $>50\%$
- Number of hours: 1000 h (or 2000 h)
- Burst pressure after AccSR



The AccSR test is ongoing

USP identified for our high pressure type 5 applications and some consequences in use.



USP's of the COVESS type 5 tank process technology compared to Type 4:

No curing process

- No curing means no additional micro-voids introduced in the micro-structure.
- No issues like a curing gradient over the cross section of the reinforced tank structure

Consequences:

- A low void structure < 3 %
- Lower variability in performance + better expected fatigue performance.
- Better barrier performance very low permeation rate
- Higher impact performance

Consequences for the transportation application

- Longer live time expected in use. For the current low-pressure type 5 commercial applications 150.000 pressure cycles and full retention of the burst pressure after cycling is really basic performance.
 - Ambient and Extreme temperature cycling done on 1 very high pressure 150 liter and high temperature creep testing (test 7) ongoing

USP identified for our high pressure type 5 applications and some consequences in use.



Consequences:

- Integrated fused inner liner (type 4.5) barrier (type V) – no collapse / blistering possible
- Better barrier performance very low permeation rate
- Vacuum resistance
- Higher reliability because less assembly arrangement

Consequences for transportation en production:

- Faster decontamination\drying possibilities demonstrated in Roadthryp
- Faster filling demonstrated in Roadthryp, in 4 min, 150 liter tank filled upto 550 Bar with hydrogen.
- Vessels do need only very low pressurization level when not in use.
i.e. behaving much more like steel tanks, but 5 times lighter.

Other USP 's cntd.



- Lightweight result (Gravimetric index (G.I.) 9 – 9.5 %). Burst pressure data are now fully validated. First cycle testing done on type 5 including extreme temperatures. very low ecological footprint solution + recyclability + e.g. use of Biobased polymers like PA 11

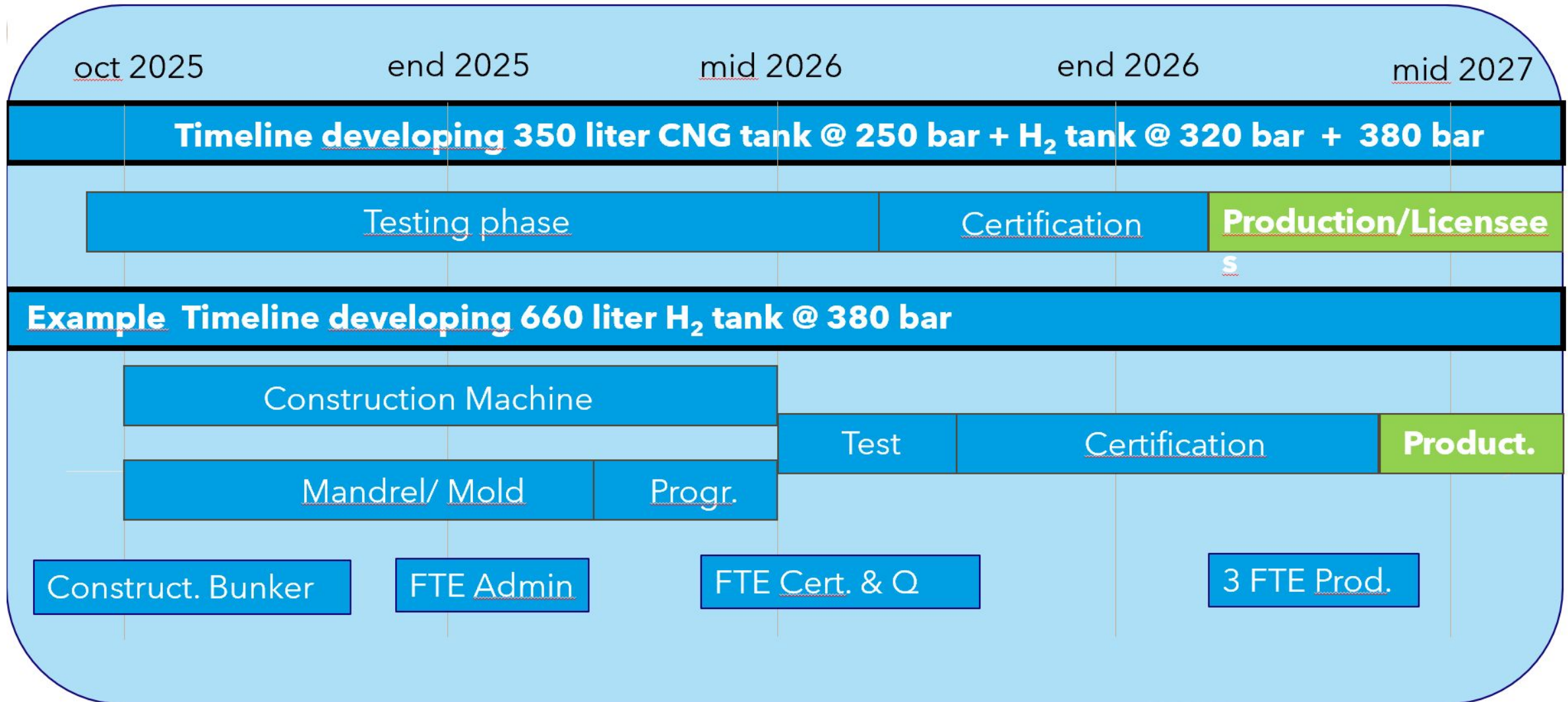
Outlook for the near future:

- Potential further improvement areas for the following generation tanks are already identified.
- Our Type V tanks will be the lightest compressed gas tank in the market
- Very high safety features possible i.e. explosion proof design possibilities also referred to as self-venting tanks. Recent Roadtrhyp results clearly confirms this.
- Replaceable connectors (Patented Unique covess boss design) already cycle tested +extreme temperatures

Consequence for the transportation market:

- Faster acceptance in the market for the use of Hydrogen as an Energy carrier

Timeline commercialization



Thank you for your attention



Type 1 - ~~2~~ - ~~3~~ - ~~4~~ - 5

Type 5 outperforms 'm all !!!



Advantages from the Usage point of view

Evaluation of Type V Carbon/PA11 COVESS cylinder:

- Cylinder preparation at Packaged Gases Production Plant at Hauconcourt, Air Liquide plant (France)
- Design of Experiments with ENVITEST/AIR LIQUIDE in Poland to evaluate best factors for cylinder Preparation
- Conclusions

Usage: Design of Experiment method

Objective: identify the most efficient way to decontaminate (drying) a type V cylinder after hydraulic test

- Global objective → pure gas specifications (14 impurities targeted)
Cylinder preparation is key to avoid any initial gas contamination
Most important contamination : water after hydraulic pressure test !
- 12 factors identified at initial step
 - ◆ Impact on decontamination evaluation
 - ◆ Cost and Industrial evaluation
 - ◆ Experimentations
 - Hauconcourt
 - ◆ Testing with ENVITEST

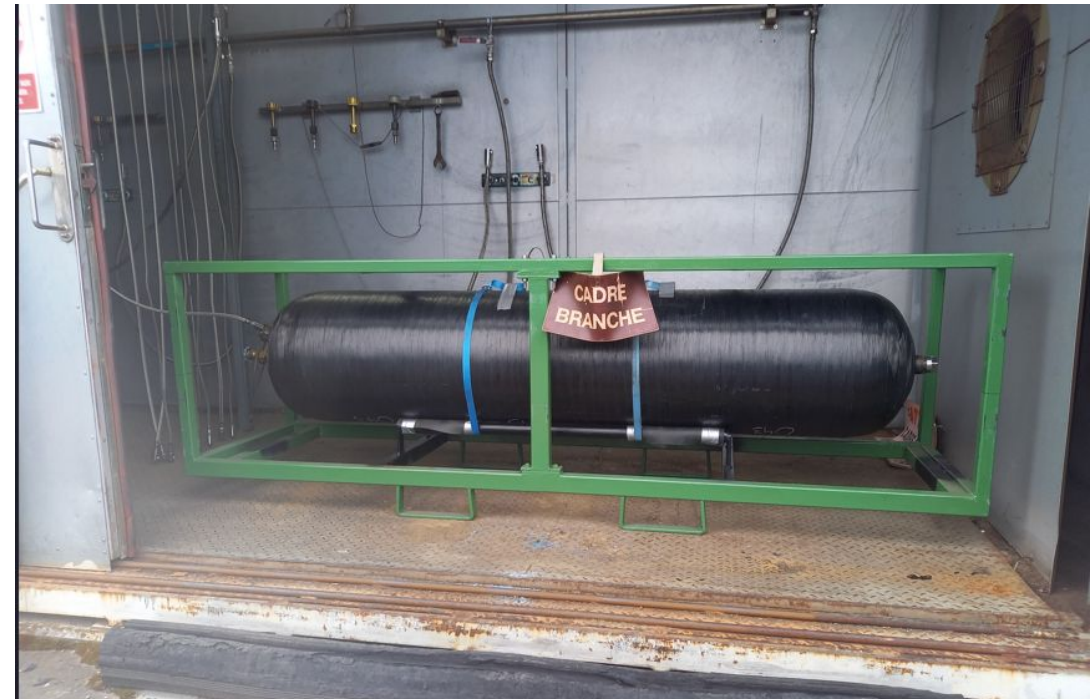
Usage: Design of Experiment method → 1st experimentations

Hauconcourt (France) experimentation :

→ Industrial conditions as for type I



Oven for cylinders & bundles

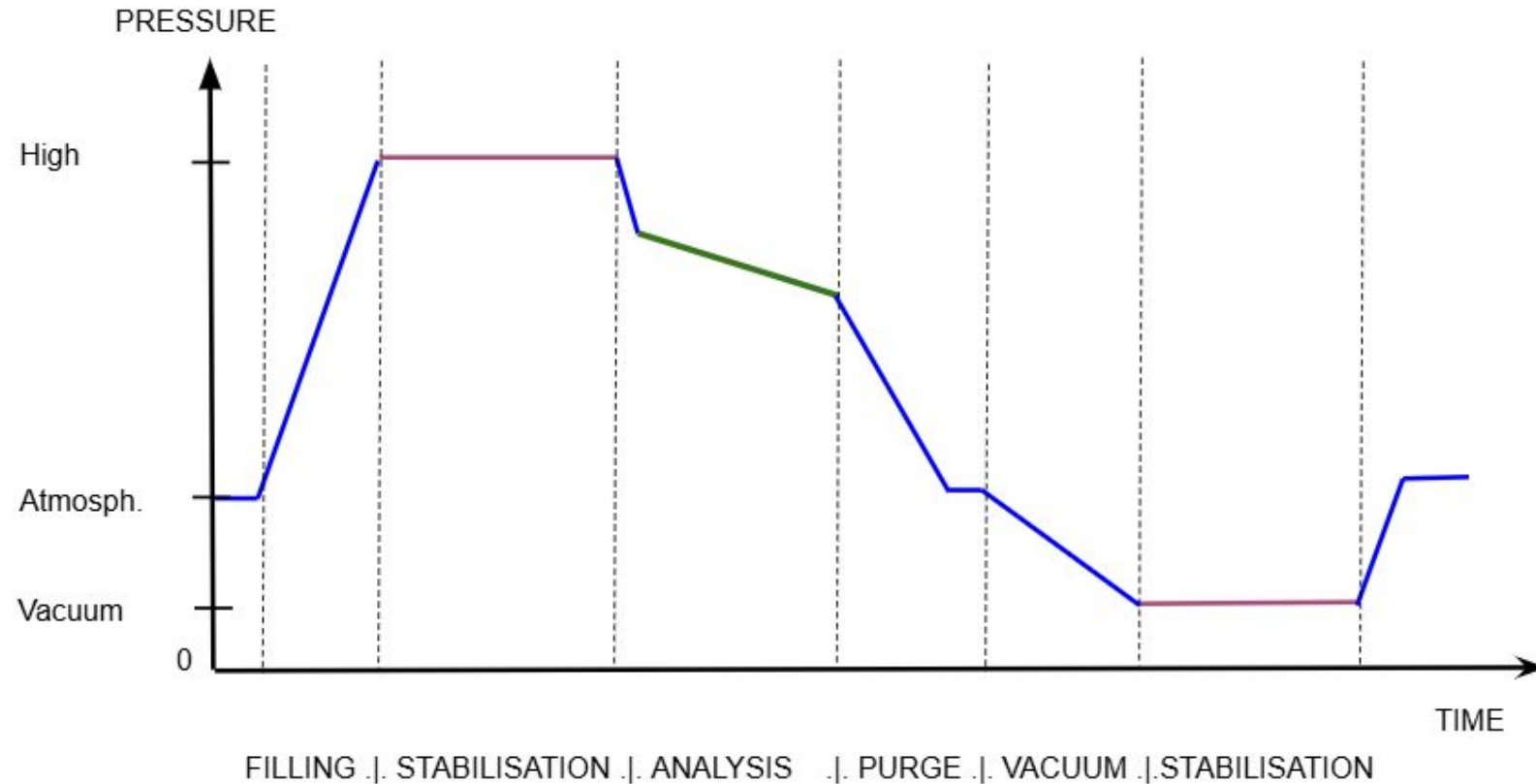


Covess Type V cylinder with its support and connection to gas manifold into the oven

Usage: Design of Experiment method → factors selection

Gas Cycles:

- Dry gas
 - Gas pressure
 - Gas vacuum
 - Dwell time at pressure
 - Number of cycles
- +
- Gas Temperature
 - Cylinder Temperature



Usage: Design of Experiment method → factors selection

Results at Hauconcourt:

- No observation of liner collapse at temperature $> 100^{\circ}\text{C}$ and vacuum at 0.05 bar abs
- Compliance of the cylinder with gas industrial conditions (Drying system at Hauconcourt)
- Heat (of the cylinder) and Vacuum effects on water desorption and diffusion
- Not stable level of water inside the Composite Cylinder Volume
- Significant amount of water inside the Composite Cylinder ($\gg 5 \mu\text{mol/mol}$) increasing with temperature and vacuum

Usage: Design of Experiment method → factors selection

Conclusions for the Design Of Experiment at ENVITEST facility:

- Key factors:
 - Cylinder temperature
 - Vacuum time
 - Number of cycles
- Response:
 - $H_2O_{(g)}$ molar fraction in dry gas
 - \Leftrightarrow Water amount extracted
- Modeling → statistical
 - $\text{mass}_{H2O_removed} = f(\text{factors}, \text{factor_interactions})$



$$Y = a_0 + a_1F_1 + a_2F_2 + a_3F_3 + a_{12}F_1F_2 + a_{13}F_1F_3 + a_{23}F_2F_3$$

Usage: Design of Experiment method → factors selection

Design Of Experiment at ENVITEST facility:

- Factor interactions design

TEMPERATURE	VACUUM DURATION at each cycle		
CYLINDER	30 minutes	90 minutes	Total_Trials
20°C	1 trials	3 trials	4 trials
80°C	3 trials	3 trials	6 trials
Total_Trials	4 trials	6 trials	10 trials

Number of trial per factor levels combination

TEMPERATURE	VACUUM DURATION at each cycle		
CYLINDER	30 minutes	90 minutes	Total_Cycles
20°C	9	27	36
80°C	27	27	54
Total_Cycles	36	54	90

Number of cycles done per factor levels combination (9 cycles per trial)
Note: just 2,3,4,5,6,7,8,9 cycles are computed.

Usage: Design of Experiment → reference State before factor testing

At each trial → hydraulic test initial + protocol of liquid water elimination
→ After hydraulic test + protocol → same **reference state of the cylinder** before testing

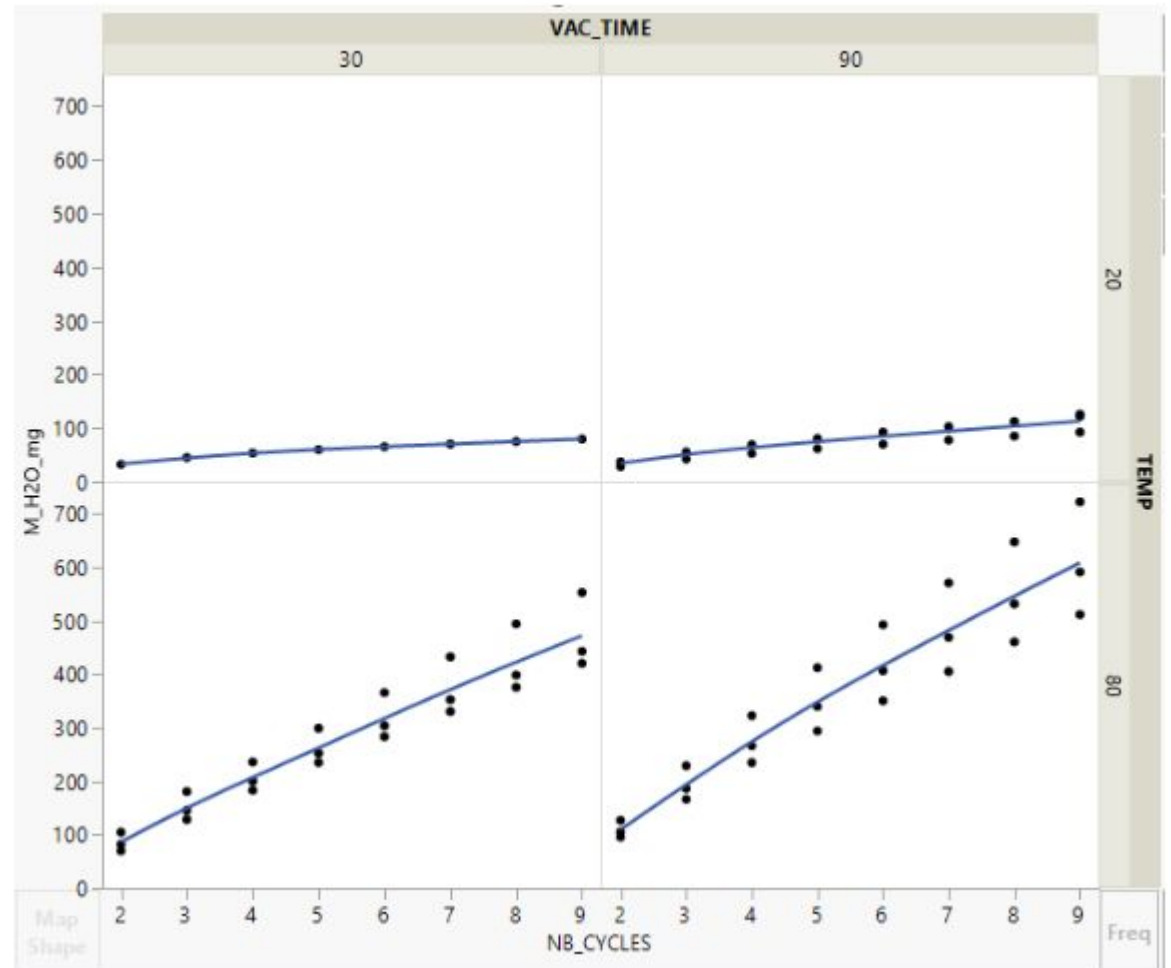


Weight controls

Usage: Design of Experiment method → results exploration

At each trial → hydraulic test initial + protocol of liquid water elimination

- Impact of cylinder temperature
- Vacuum time less significant
- Variance of replicates



Usage: Design of Experiment method → computed results

- First analysis of the 3 factors confirms that they are significant
- Cylinder temperature explains 62% of total variance

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
NB_CYCLES	1	1	728861.4	126.7816	<.0001*
TEMP	1	1	1327395.7	230.8934	<.0001*
VAC_TIME	1	1	72140.2	12.5484	0.0007*

Contribution of the factors to the total amount of water removed (variance analysis)

Factor	Contribution (%)
TEMP	62.4%
NB_CYCLES	34.2%
VAC_TIME	3.4%

Fisher test results evaluating a significant contribution of the 3 factors to the response (total amount of water removed).
[probability value inferior to 0.05 (5% risk)]

Contribution of the 3 factors : cycles number (34%), cylinder temperature (62%) and vacuum duration (4%) to the total amount of water removed.

Usage: Design of Experiment method → computed results

Computing factors and their interactions →

Modeling (statistical) is relevant (Fisher test) and all parameters are confirmed as relevant too

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
NB_CYCLES	1	1	702350.7	432.8273	<.0001*
TEMP	1	1	1257748.4	775.0939	<.0001*
VAC_TIME	1	1	60841.9	37.4941	<.0001*
NB_CYCLES*TEMP	1	1	284358.2	175.2372	<.0001*
NB_CYCLES*VAC_TIME	1	1	11920.8	7.3463	0.0084*
TEMP*VAC_TIME	1	1	18960.6	11.6846	0.0010*
NB_CYCLES*TEMP*VAC_TIME	1	1	2712.8	1.6718	0.2002

$$\begin{aligned} \text{mass_H2O} = & -311,596133 + 41,657945 \text{ CYCLESNB} + 4,449482 \text{ TEMP} + 0,978619 \text{ VACTIME} \\ & + 0,935977 * (\text{CYCLESNB} - 5,5) * (\text{TEMP} - 56) + 0,201683 * (\text{CYCLESNB} - 5,5) * (\text{VACTIME} - 66) \\ & + 0,019125 * (\text{TEMP} - 56) * (\text{VACTIME} - 66) \end{aligned}$$

Analysis of Variance				
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	2374033.4	395672	241.6116
Error	73	119547.5	1638	Prob > F
C. Total	79	2493580.9		<.0001*

Usages: conclusion

Conclusion of cylinder preparation & drying :

- Cylinder Preparation: Composite Cylinder type V is equivalent to Cylinder type I
- Drying of type V after hydraulic pressure test is feasible
 - $< 5 \mu\text{mol/mol}$ at 20 bar, 65°C
- **Temperature of Cylinder** is the most important factor
- Vacuum facilitates the drying process
- **Number of cycles : optimisation** with Cylinder Temperature and Vacuum
- Advantages of type V for :
 - cylinder preparation → Temperature mainly
 - trailer preparation → Temperature & Vacuum

Large scale: Behaviour of type V tubes exposed to fire

□ *Partners involved: Efectis & Air Liquide*

□ *Main objectives of this task are to :*

- Perform fire resistance tests
 - An intermediate test for validation and de-risking reasons
 - The final test on the tube developed in the project
- Simulate the planned standardised fire tests
 - To be used as boundary conditions for thermomechanical simulations

Large scale tests – Setup

- Test Standard: inspired from EN 17339
 - Tube considered as per Type IV
- Fire source engulfing the main part of cylinder
 - Without direct aggression of the TPRD if present
- Fire shall produce within 2 min a temperature of at least 590°C
 - Measured within 25 mm under the bottom of the tube

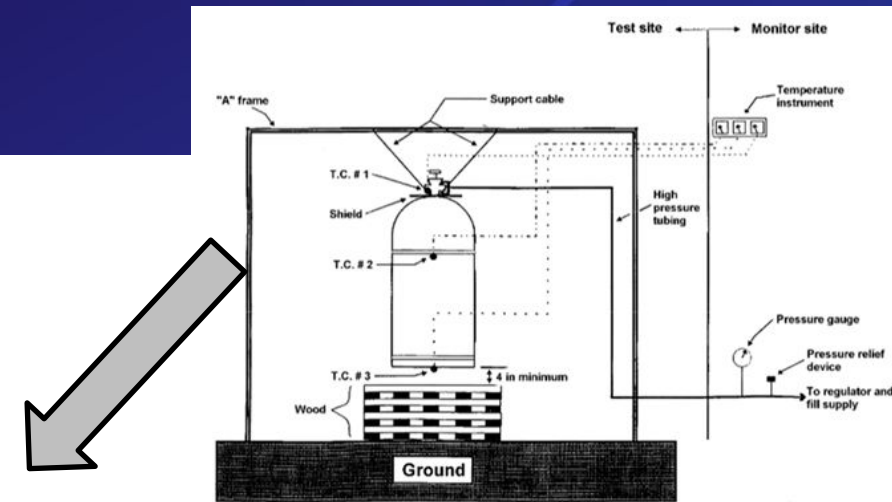
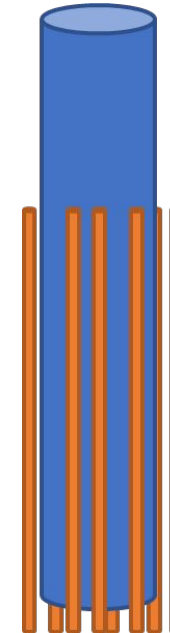
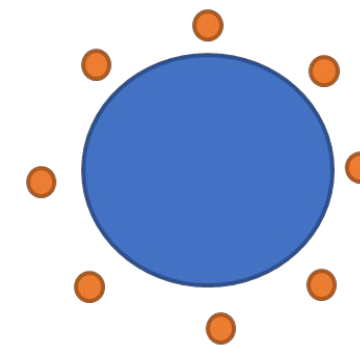


Figure B-1—Wood bonfire test method A



- Safety - Robustness
- Representativity - Reproducibility - Technical content
- Schedule - Budget

Large scale tests – Setup

- Cylinder installed vertically
 - Bottom part of the cylinder at 100 mm above fire source
 - Design of the supporting system for the tube
- Engulfment by means of gas burner
 - Design of the arrays of gas burners

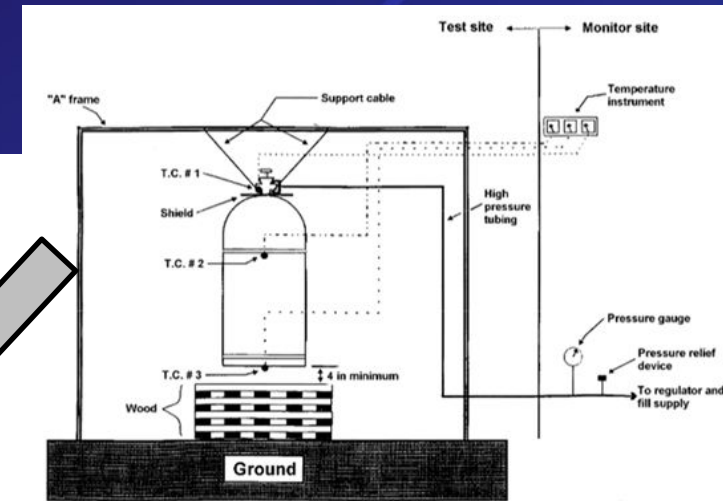
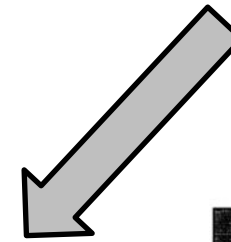
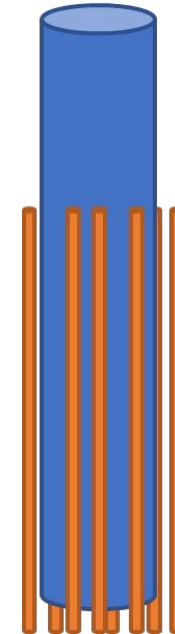
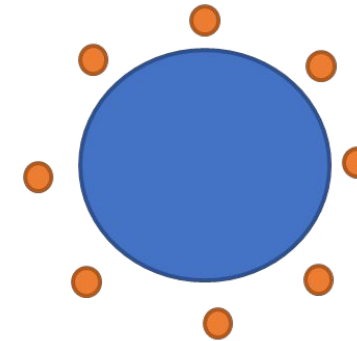


Figure B-1—Wood bonfire test method A



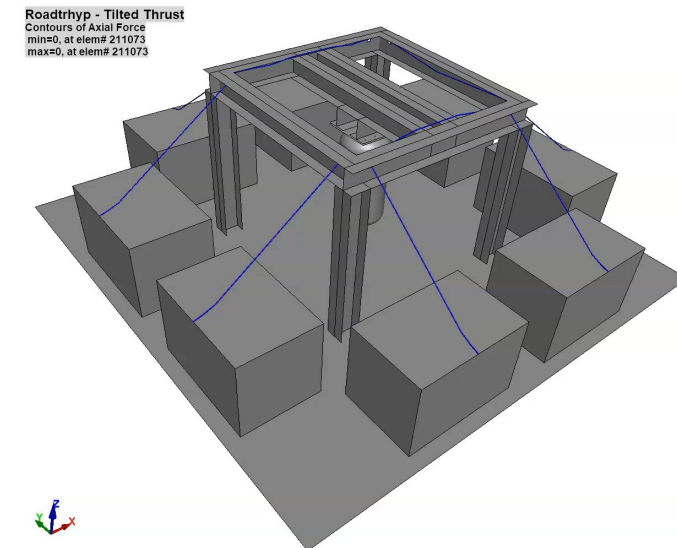
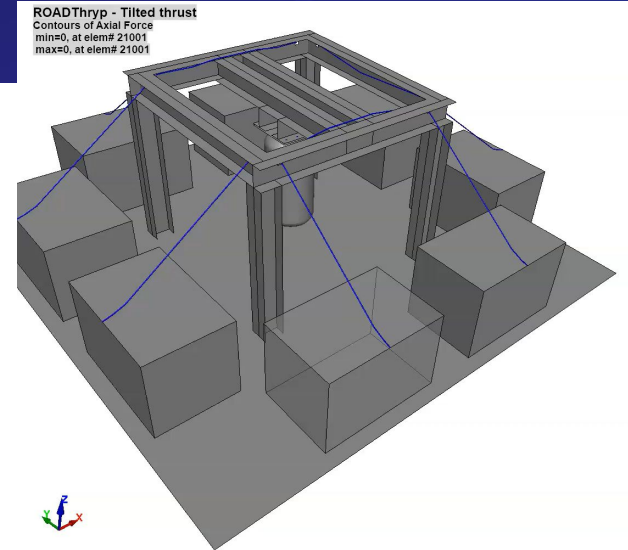
- Safety - Robustness
- Representativity - Reproducibility - Technical content
- Schedule - Budget

Design of the supporting system & burners

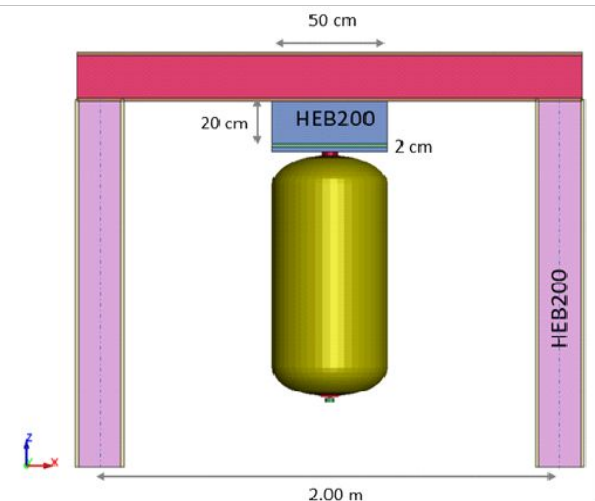
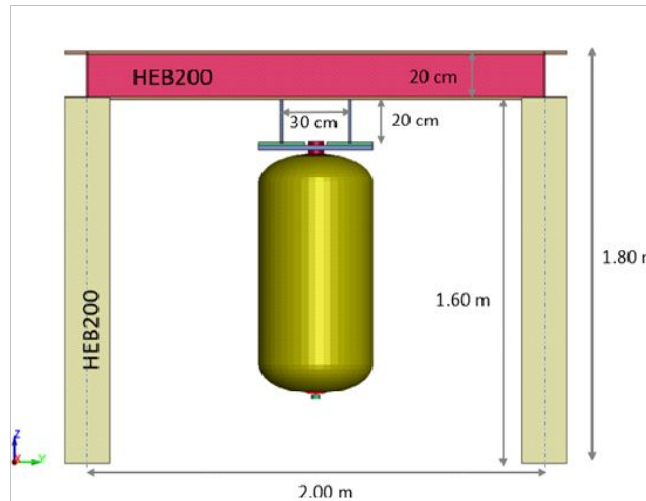
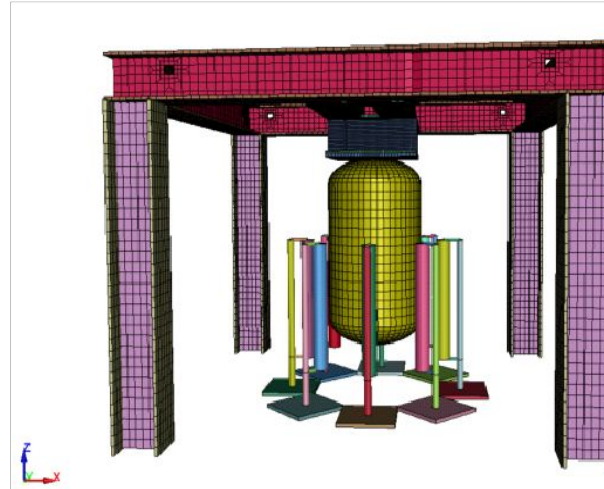
- Adaptation of the test setup for the type V cylinder developed within the project:
 - *Vertical position - large volume - high pressure hydrogen*
- Dedicated supporting system to ensure:
 - Mechanical stability
 - Minimum disturbance to the fire exposure
 - Maintaining the cylinder in position in case of partial tank failure during fire exposure : management of possible “rocket”

Design of the supporting system & burners

- Non-Linear Finite Element analysis of the system for different failure conditions with LS-DYNA
 - Various failure schemes considered
 - Various location and subsequent thrust direction due to uncertainties of HP release
 - Crash of tank to the supporting system
- Final arrangement (iterative process)
 - Steel table : direct support of the tank
 - Steel high strength cables : limit possible uplift of the table
 - Concrete blocks : weights to restrain cables
 - Concrete walls : to manage possible fragment in case of burst



Design of the supporting system & burners



Large scale tests performed

Tests	Object	Objectives	Completed on
1 st test	Intermediate derisking / preliminary test	<ul style="list-style-type: none"> • Mock-up of the 150 L tank without pressure • Calibration of fire source to meet expectations • Optimization of the instrumentation • Full thermal response thanks to calibration with empty steel tube including internal instrumentation 	December 2025
2 nd test	single tube	<ul style="list-style-type: none"> • Real 150 L tank without pressure • Additional instrumentation inside the tank envelope • Validation of thermo-mechanical tank response: Leak Before Burst ability 	February 2026
3 rd test	single tube	<ul style="list-style-type: none"> • Real 150 L tank with H2 @564 bar working pressure • Validation of thermo-mechanical tank response: Leak Before Burst ability 	March 2026

1st & 2nd tests: derisking / preliminary tests

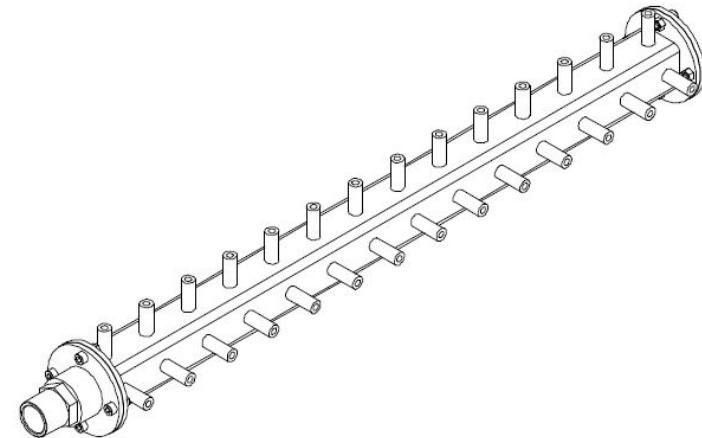
- Tubes with a reduced volume (150 L) compared to the target cylinder (330 L)
 - Only the height is different
- Test performed at Efectis St-Yan test site
- Test Standard: inspired from EN 17339
 - Tube considered as per Type IV



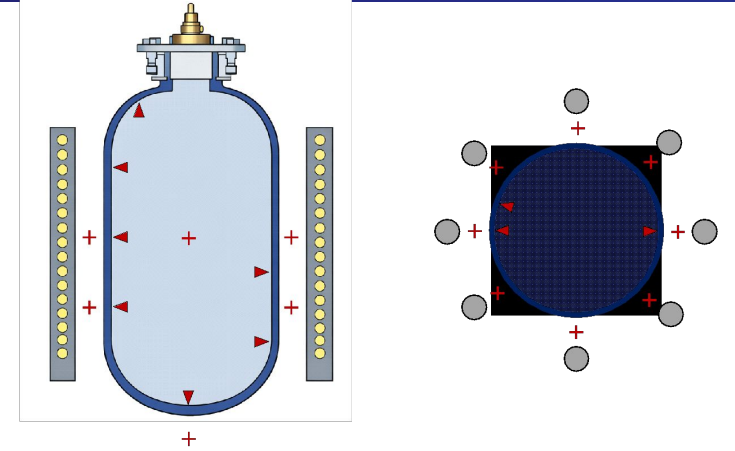
Tests	Object	Objectives
1 st test	Intermediate derisking / preliminary test	<ul style="list-style-type: none">• Mock-up of the 150 L tank without pressure• Calibration of fire source to meet expectations• Optimization of the instrumentation• Full thermal response thanks to calibration with empty steel tube including internal instrumentation
2 nd test	single tube	<ul style="list-style-type: none">• Real 150 L tank without pressure• Additional instrumentation inside the tank envelope• Validation of thermo-mechanical tank response: Leak Before Burst ability

Selection of the fire source

- Timber crib ? Pool fire ? Burner ?
 - *Preference for modifiable burner*
- Efectis is equipped for the bon fire test of Compressed Hydrogen Storage Systems, according to ECE R 134



1st test: Preliminary fire test / derisking



- Modifiable burner and steel dummy cylinder for the calibration

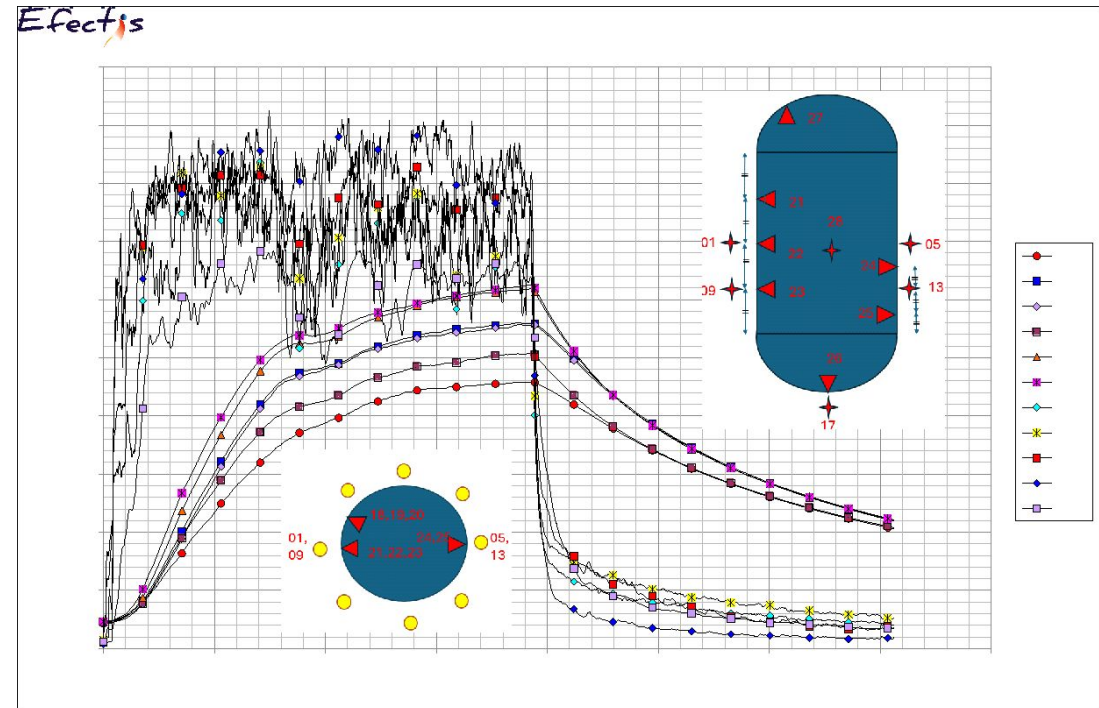
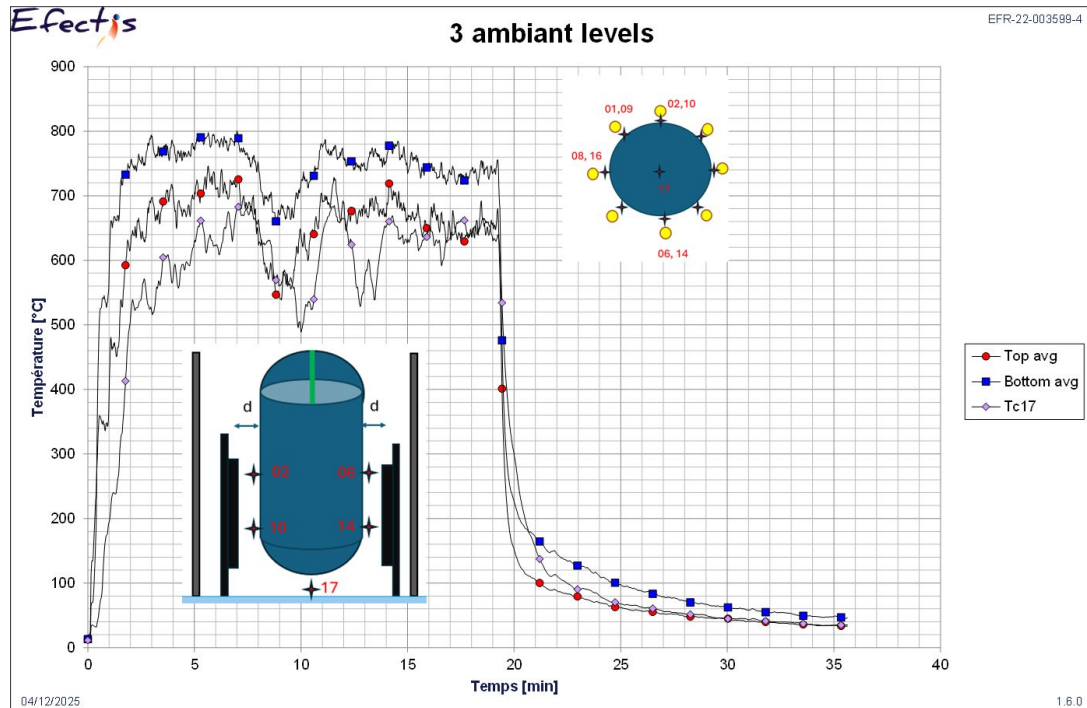
1st test: Preliminary fire test / derisking

- Tests performance: several trials and decision to add a bottom burner ramp



1st test: Preliminary fire test / derisking

- Temperature requirements are met / validation of the burner
 - ***The 1st calibration test validates the proper design of the burners***



2nd test: Preliminary fire test / derisking

- **Real 150 L tank** without pressure - single tube
 - Objectives:
 - Validation of the thermo-mechanical tank response
 - Which will evaluate Leak Before Burst ability
 - Boundary and thermal conditions for simulations (WP 5.3)
 - Same test set-up as 1st test
 - Additional thermocouples installed within the cylinder without H2
 - From Pprime protocol / to be used for thermomechanical simulations



Bottom

Top



Bottom



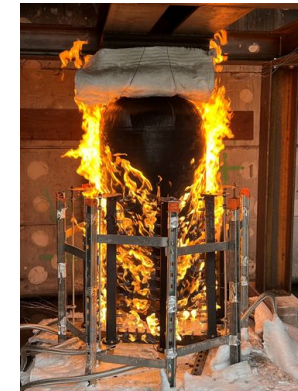
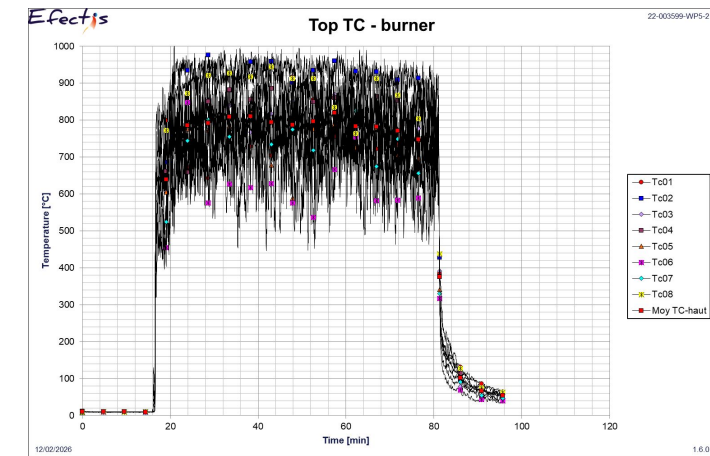
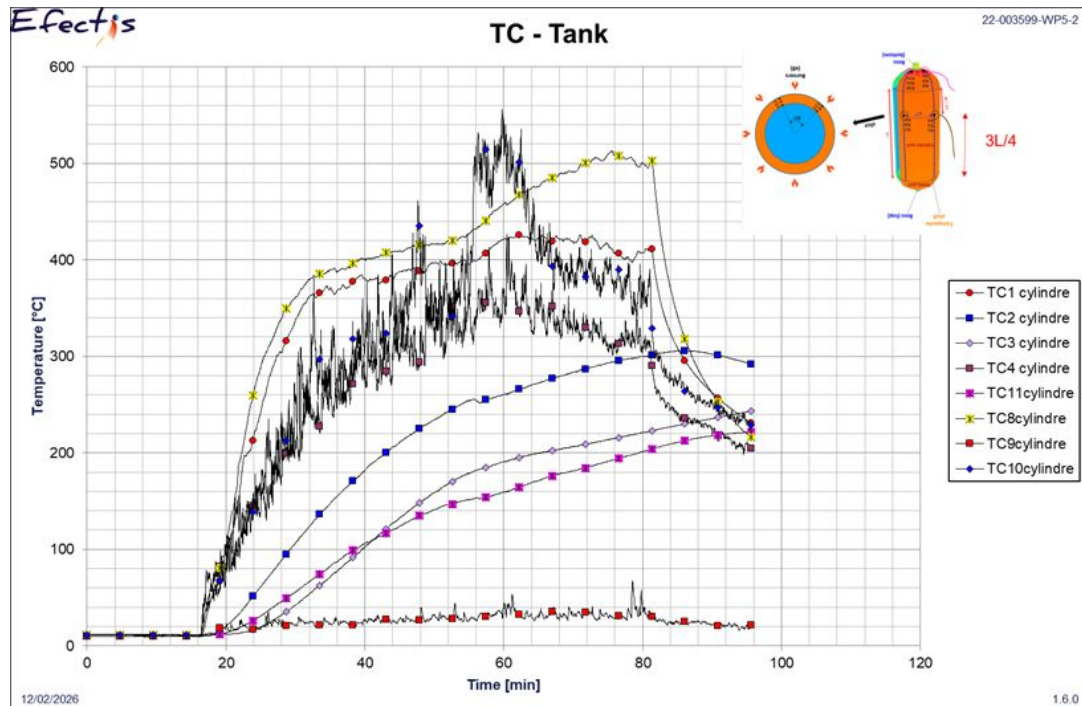
Top



Top

Large scale tests – 2nd test: Preliminary fire test / derisking

- Internal wall temperature:
 - Strongly governed by heat transfer through the structure
 - Between 250 and 500°C evaluated after 1h of test



During the test



After the test

Additional thermocouples at several locations and different depths within the tank envelope during its manufacture

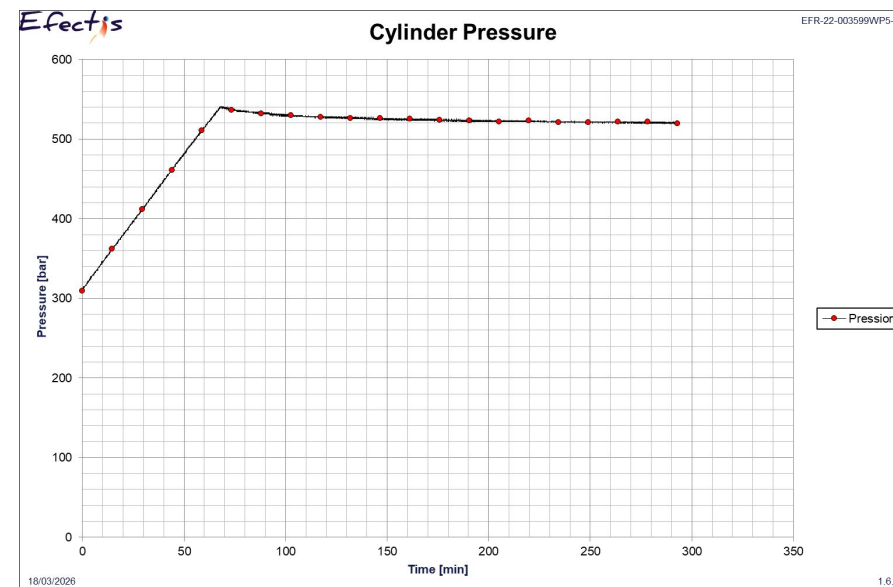
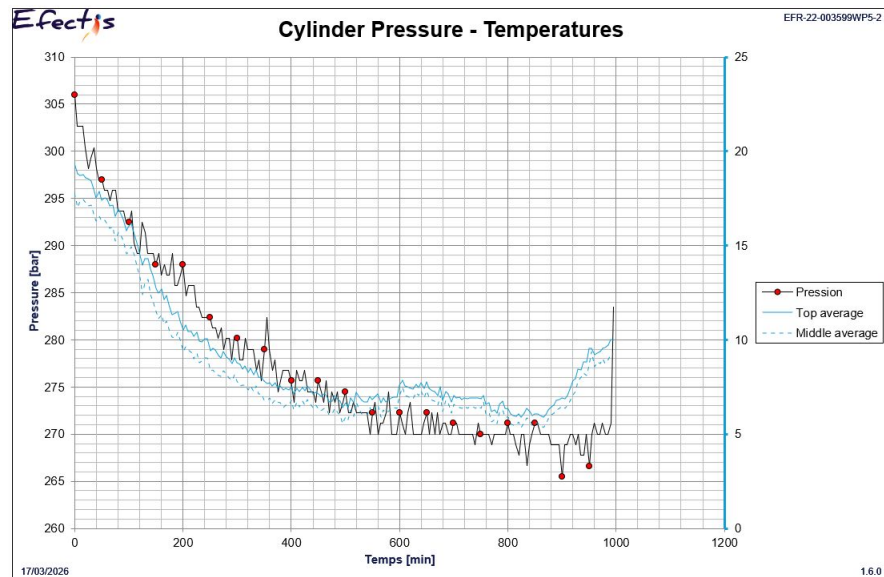
Large scale tests – Final bonfire test

- 3rd test: final test - Single tube
 - **Real 150 L tank with H2 @564 bar** working pressure
 - Verification of thermo-mechanical tank response: Leak Before Burst ability



Final bonfire test

- **Pressurization of the tank - hydrogen filling**
- Before the fire test, pressurization of the tank in two stages:
 - **1st: 300 bar** – 1 day before the test, allowing for the identification of any potential hydrogen leaks overnight - pressure dropped from 305 bar to 270 bar, a decrease of 11% over 15 hours mainly explained by ambient temperature variation
 - **2nd: 520 bar** - after stabilization with no leaks or defects observed



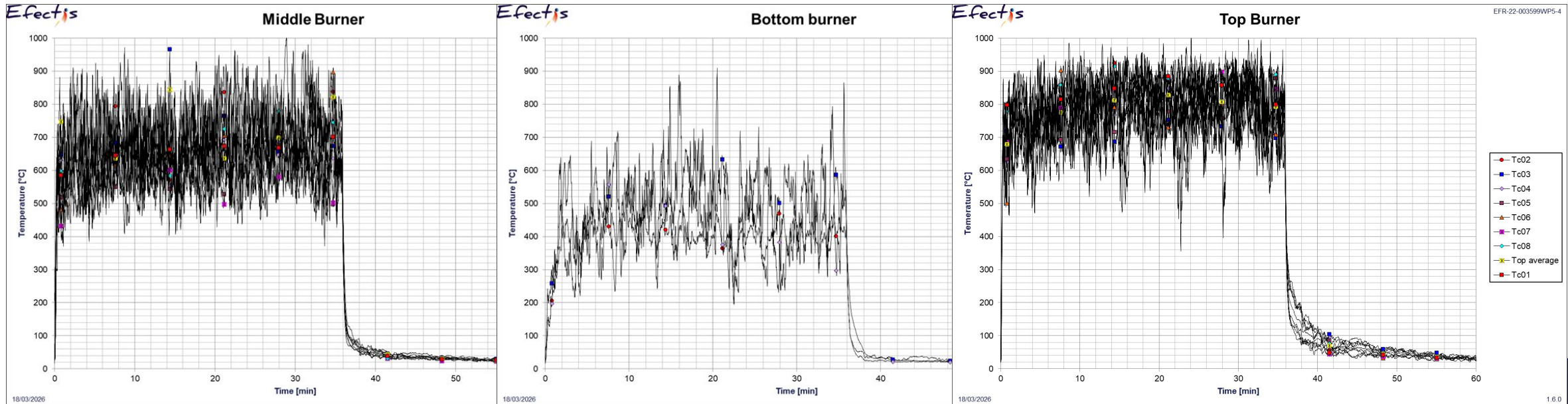
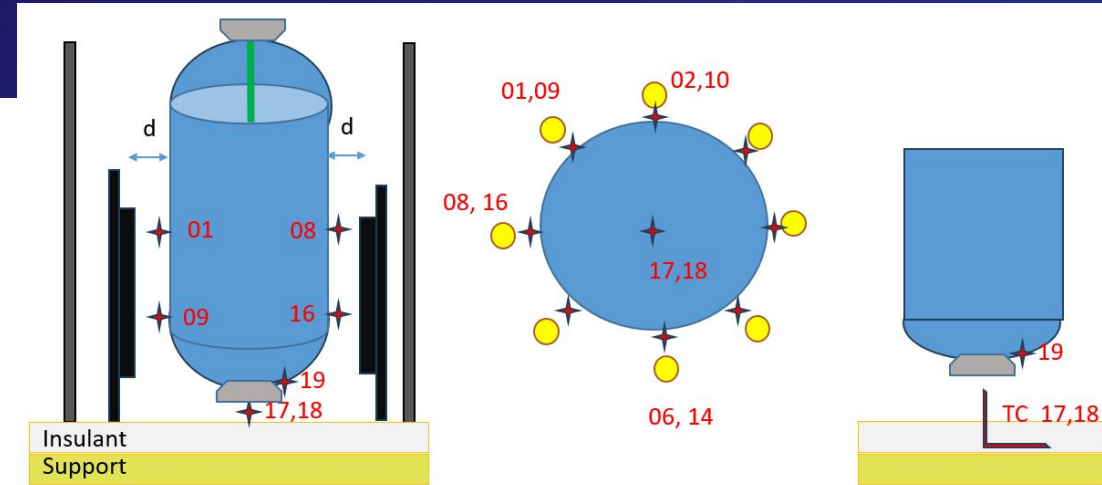
Final bonfire test

- Flame engulfment of the entire height, at the exception of the upper part
- No hydrogen leaks observed during the whole duration of the fire test



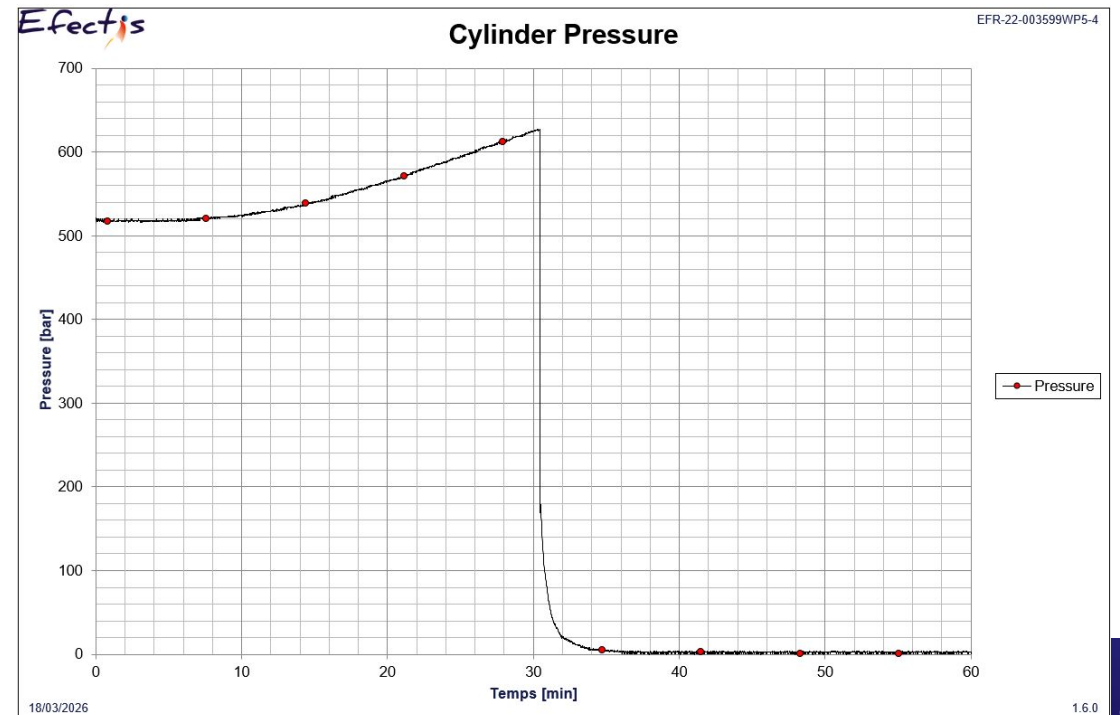
Final bonfire test

- Results:
 - *Temperature requirements are met*



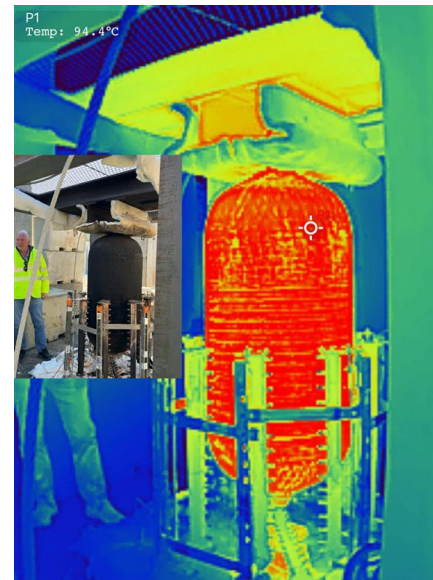
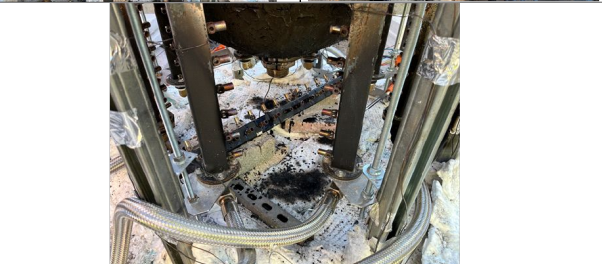
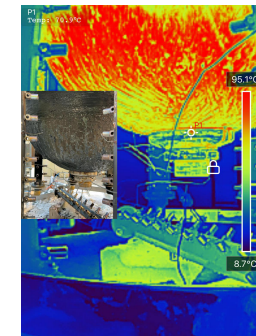
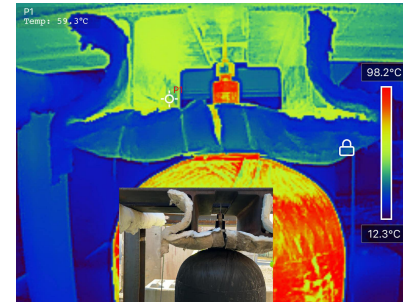
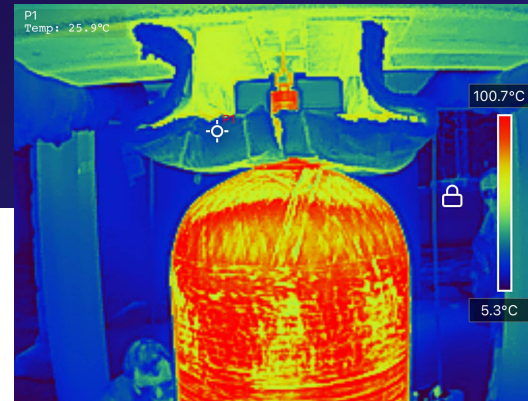
Final bonfire test

- Pressure inside the tank:
 - Remained constant during the first 10 minutes
 - Then increased linearly at a rate of 6 bar/min up to 628 bar
 - burst disc ruptured
 - At the end of the test: 654 bar
- No leak before burst
 - During 33 min of fire test



Final bonfire test

- After the test:
- Exterior of the cylinder:
 - No signs of perforation
 - Lower portion of the tank: thermal decomposition
 - Drips observed beneath the cylinder
- Interior of the cylinder:
 - Surface deformed
 - Whitish appearance only up to a certain height

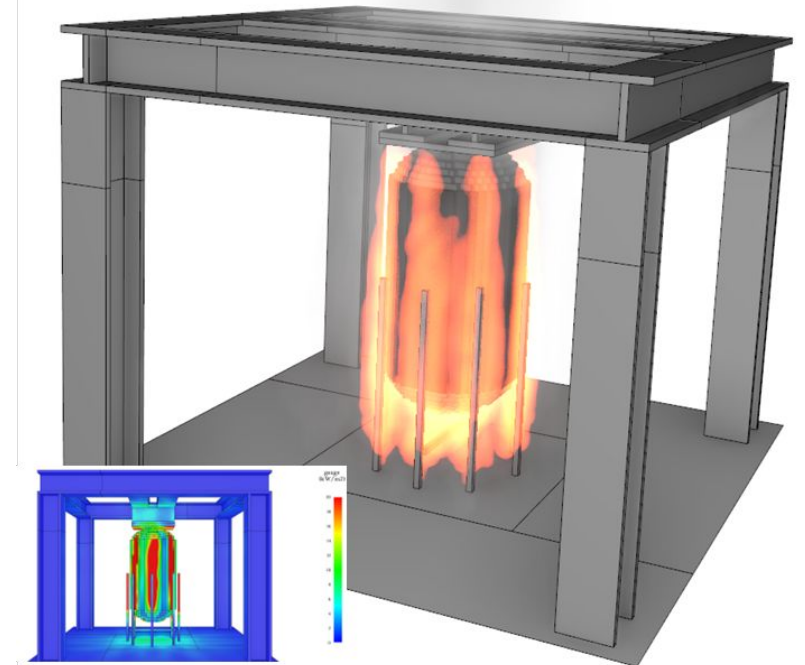
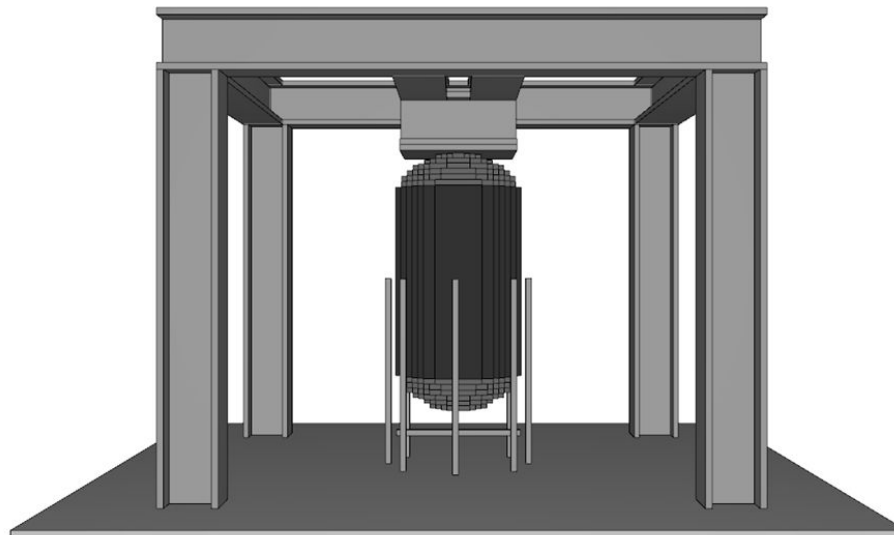


Large scale tests – Numerical modelling

- Numerical simulation performed by Efectis □ inputs for Pprime
 - Mainly to assess thermal boundary conditions (fire / tank)
 - Simulation of the designed burners array
 - Validation based on the tests results (calibration tests 1 & 2)
 - Evaluation at different heights on the 150 L tube:
 - Surface temperature, heat fluxes, convective heat transfer coefficient
 - □ Inputs for thermomechanical simulations of the tank behaviour

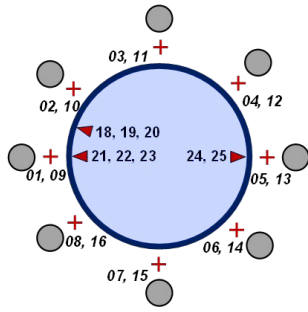
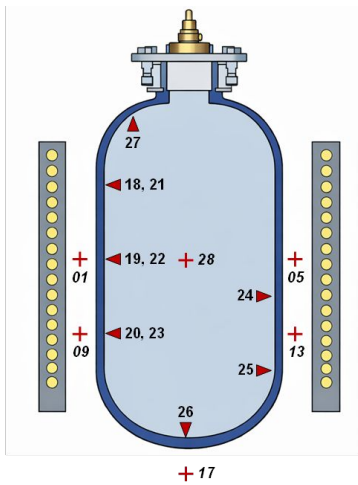
Numerical modelling

- Numerical simulations of the calibration test n°1
 - CFD code FDS
 - Geometry, structure, solid elements
 - Combustion, fire / flames
 - Instrumentation, thermal loads

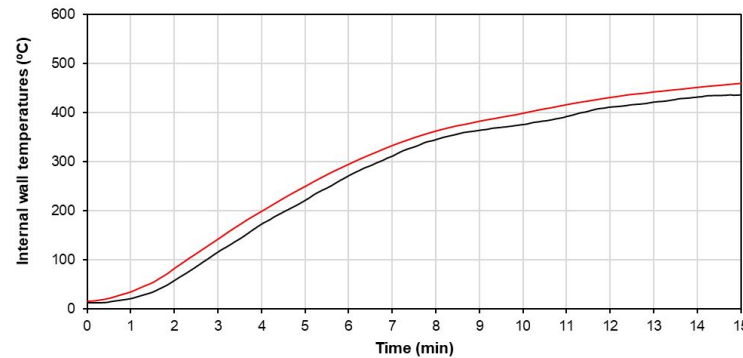


Numerical modelling

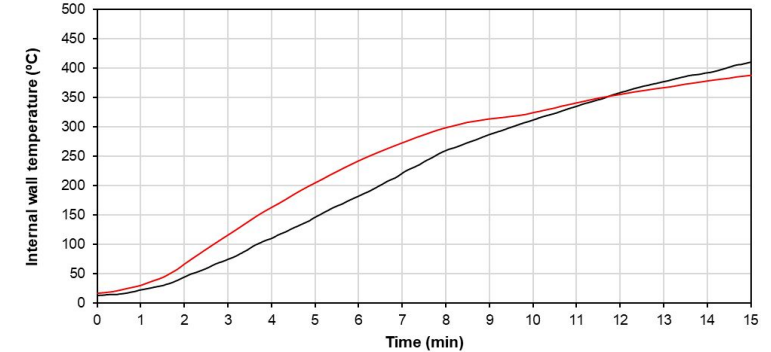
- Comparison numerical (red) / experimental (black) results
 - Wall temperature



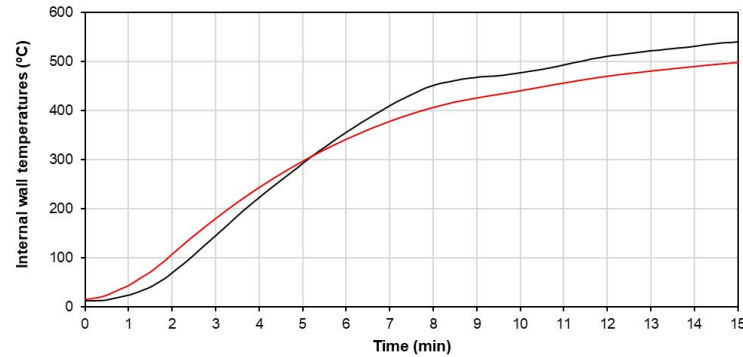
Upper part



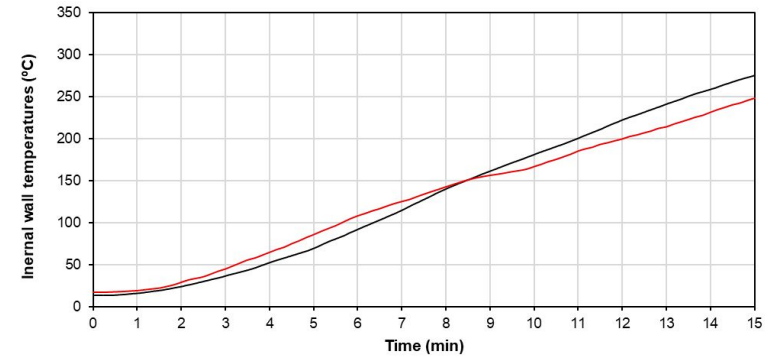
WT26 (bottom position)



Lower part

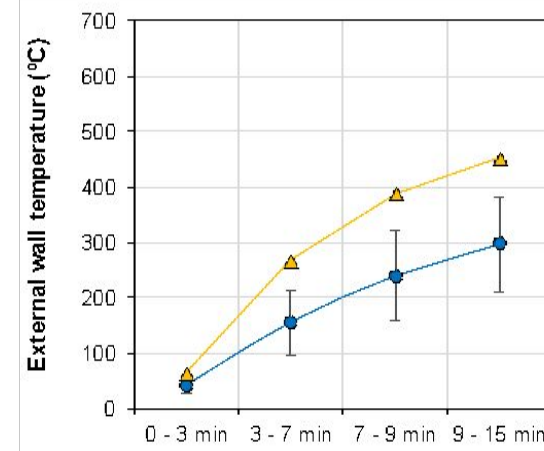
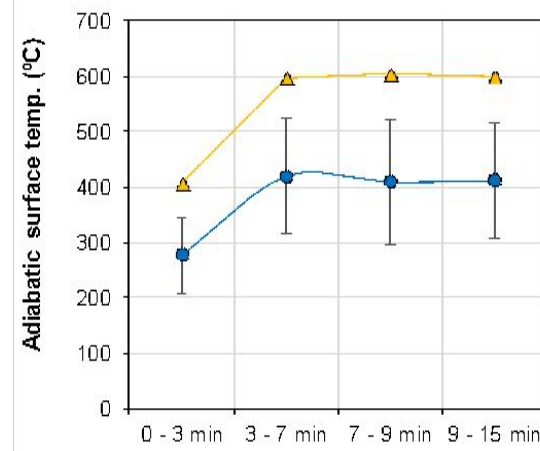
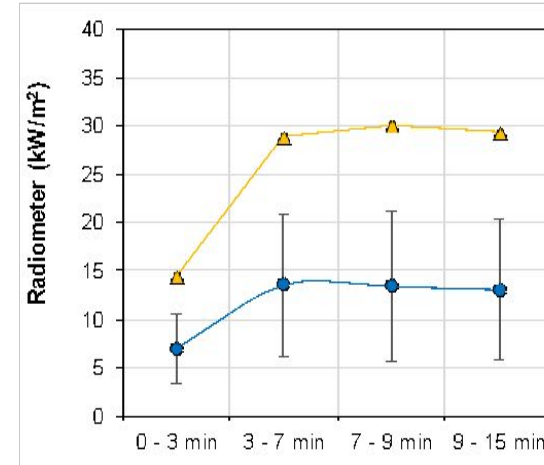
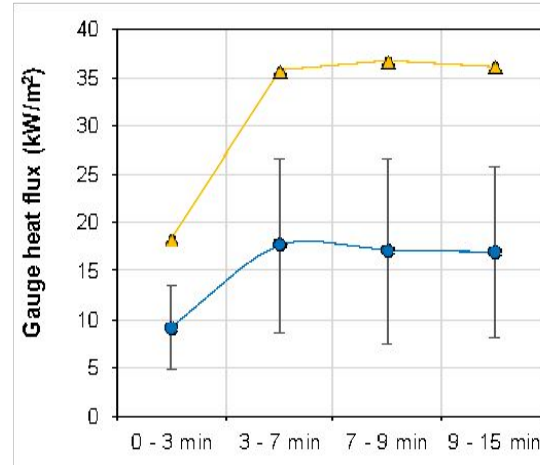
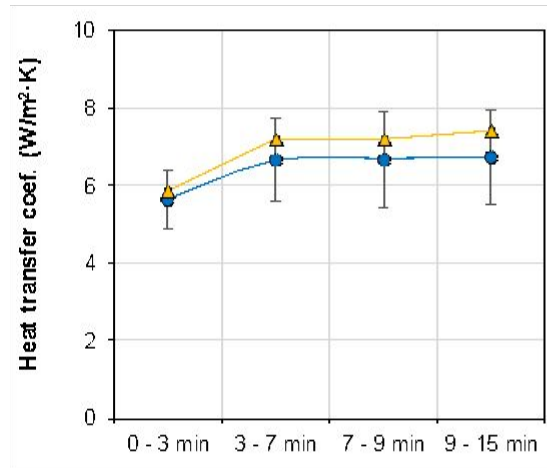


WT27 (top position)



Numerical modelling

- Numerical results
 - Boundary conditions



Mechanical behaviour of tanks exposed to fire

- *Partners involved: Pprime, Efectis, COVESS*
- *Main objectives of this task are to :*
 - Determine material properties of C/PA11
 - Simulate mechanical behaviour of Type V tanks in fire

Lab scale tests of the mechanical behavior of tanks

Safety concerns:

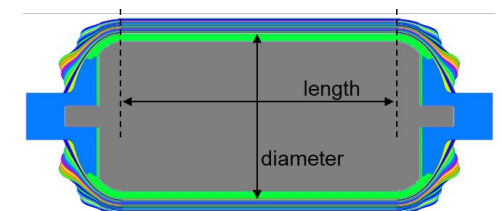
- *How would a single composite tank for gH2 storage react when it is engulfed by fire ?*
- *Is it possible to reliably simulate the behavior of a tank during a fire?*

A multiscale problem:

- **Understand the material behavior:**
 - Measure the performance of the composite material.
- **Understand the structural behavior:**
 - Develop a numerical tool capable of accurately representing the geometry and the in-situ conditions of a storage tank engulfed by fire.
 - Predict the tank failure and compare to bonfire tests.



Numerical model for the tank composite lay-up



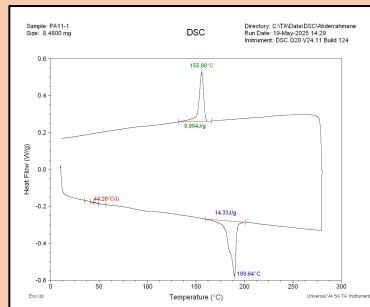
Lab scale tests of the mechanical behavior of tanks

Sample scale: understanding the material behaviour

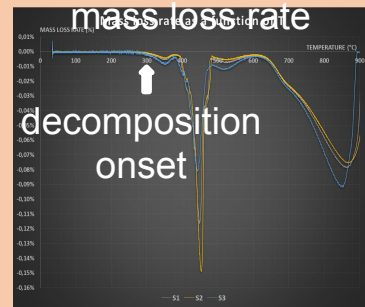
- Thermal degradation of the PA11 matrix.

Thermal degradation

DSC / TGA tests



DSC cycles for
C/PA11



TGA in air for
C/PA11



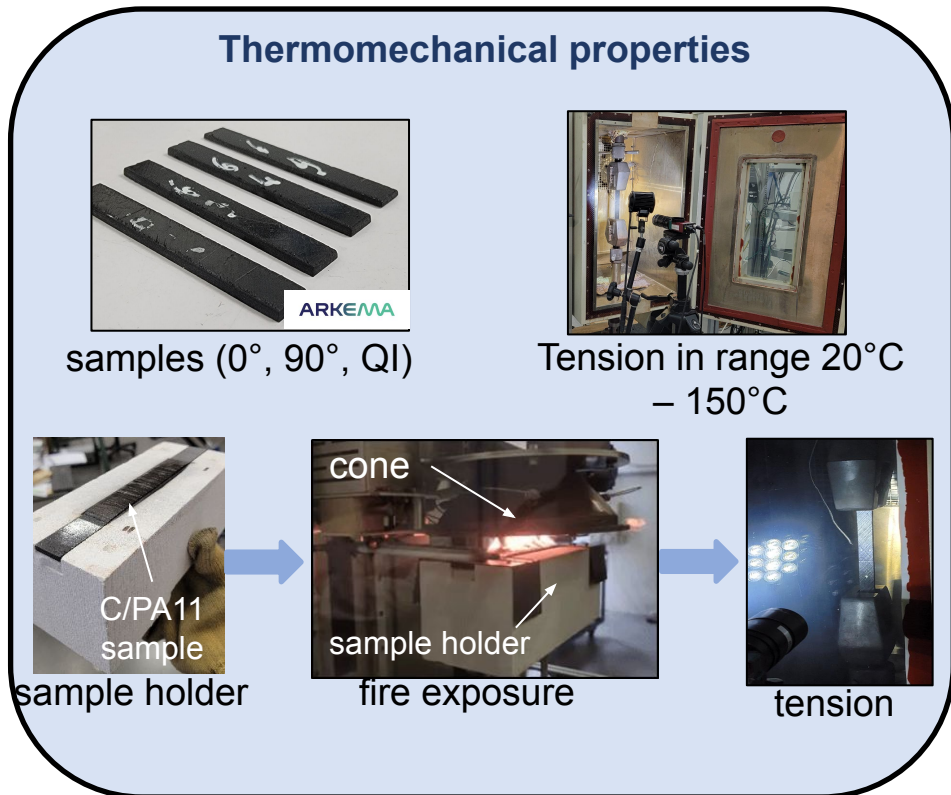
Outputs

- **characteristic temperatures** of the material
 - glass transition
 - melting
 - decomposition onset
 - ...
- **decomposition steps** of the thermoplastic resin at high temperatures

Lab scale tests of the mechanical behavior of tanks

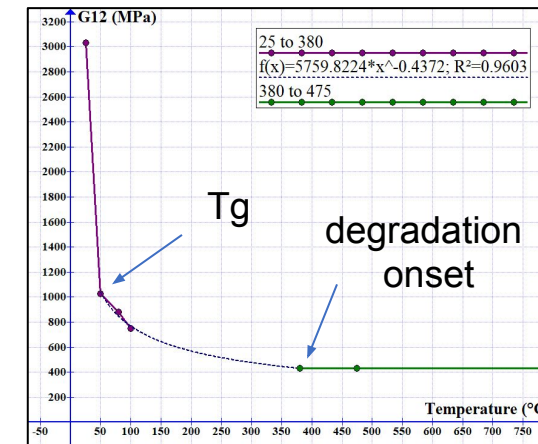
Sample scale: understanding the material behaviour

- Thermomechanical properties of the C/PA11 composite.



Outputs

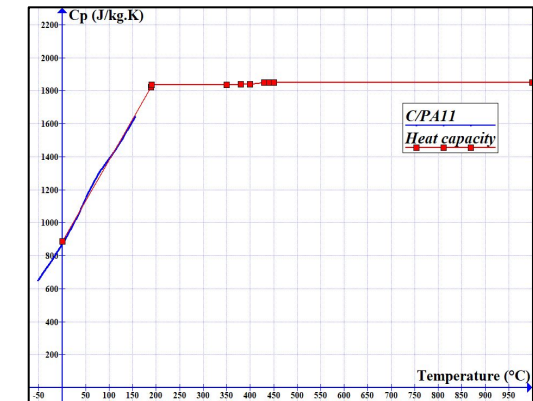
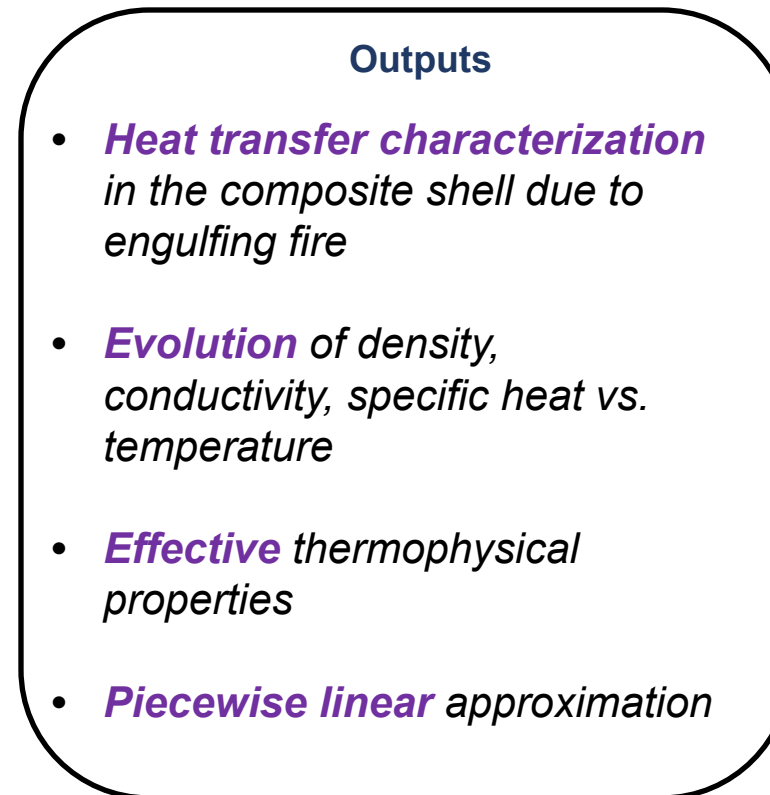
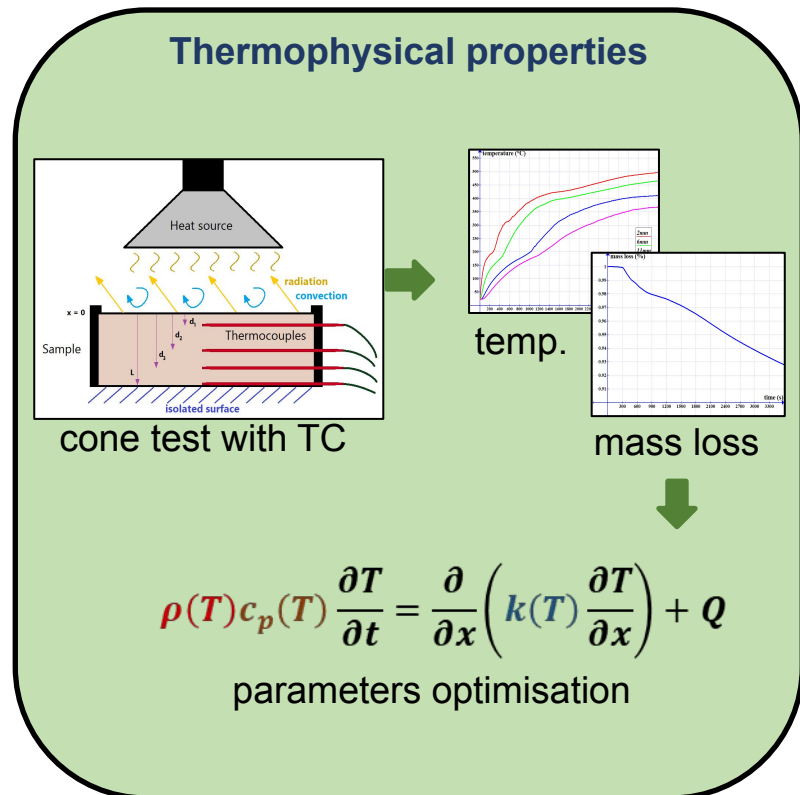
- *Effect of temperature and degradation on mechanical behaviour*
- *Decrease of longitudinal, transverse, shear stiffness, as soon as T_g is reached*
- *Only ~1/3rd of the room- T stiffness is kept at 100°C*
- *Drastic drop of stiffness at degradation onset*



Lab scale tests of the mechanical behavior of tanks

Sample scale: understanding the material behaviour

- thermophysical properties of the composite.



Simulation of the thermomechanical behavior of tanks

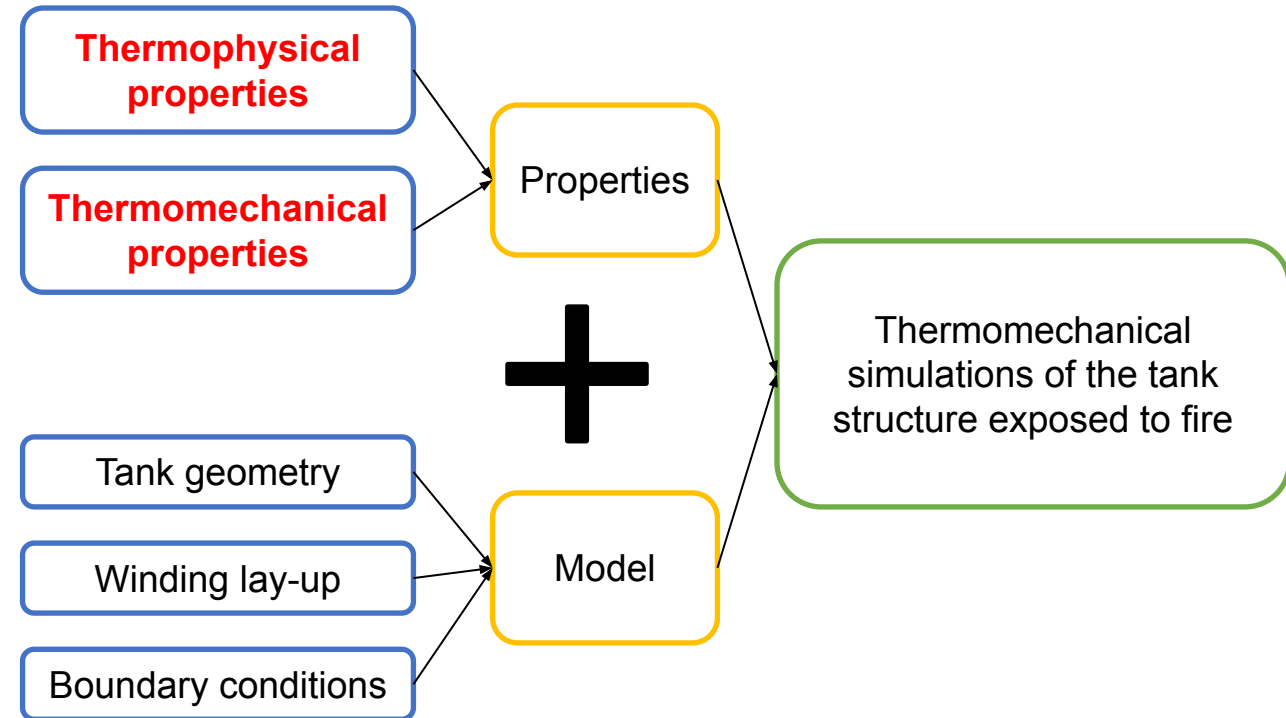
Structure scale: simulation of tank in fire

❖ *Data collected from the experimental campaign aiming to identify key properties of the material as well as how these properties are affected by the thermal degradation emanating from the fire that engulfs the structure.*

❖ *Obtained directly from TCM code developed by PPRIME*

❖ *Obtained directly from winding process by COVESS*

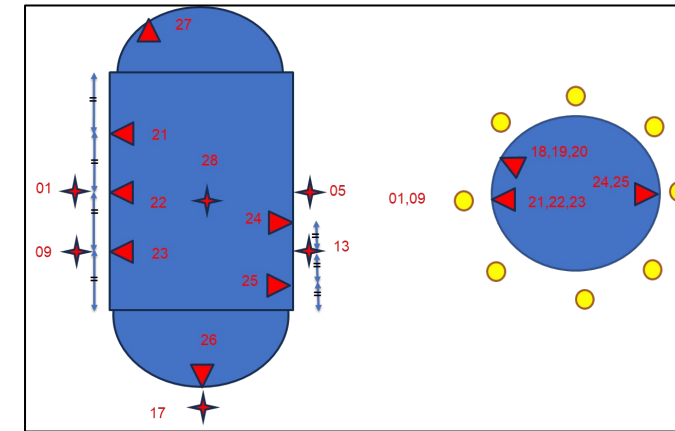
❖ *Obtained from bonfire test on steel tank by Efectis*



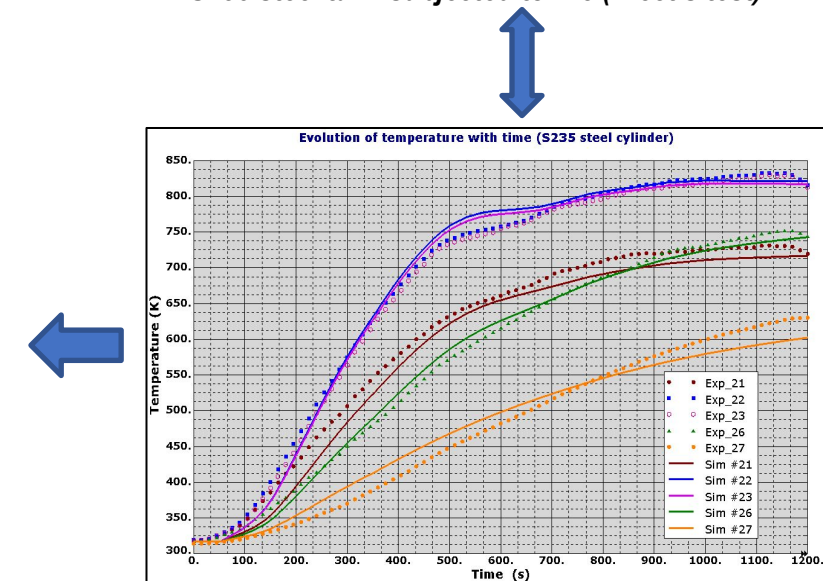
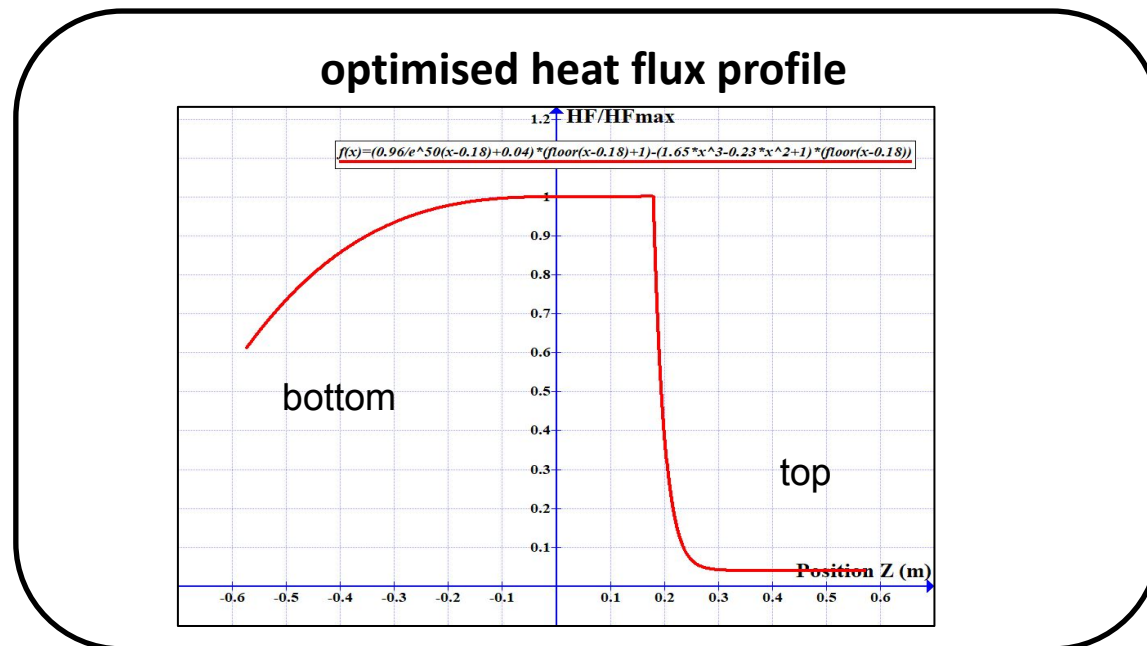
Simulation of the thermomechanical behavior of tanks

□ Identification of boundary conditions

- FE simulation of the S235 steel mock-up cylinder subjected to fire
- Geometry of the tank obtained from Efectis
- Thermophysical properties obtained for S235 steel (literature).



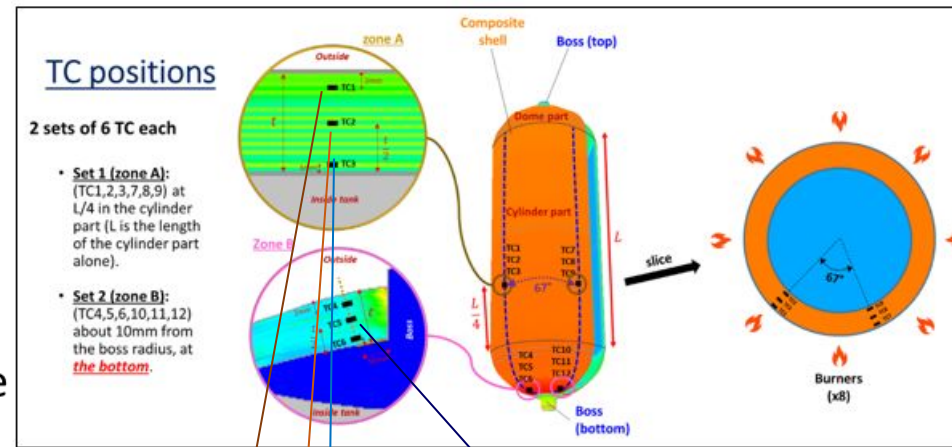
S235 steel tank subjected to fire (Efectis test)



Tank simulation (thermal response)

Simulation of the thermomechanical behavior of tanks

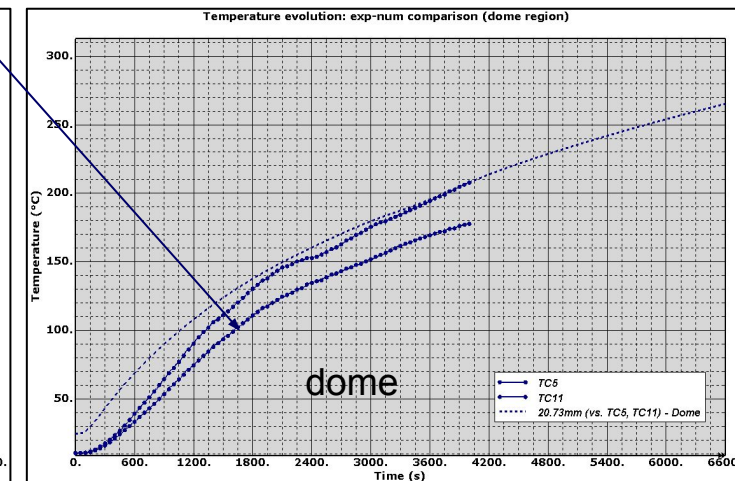
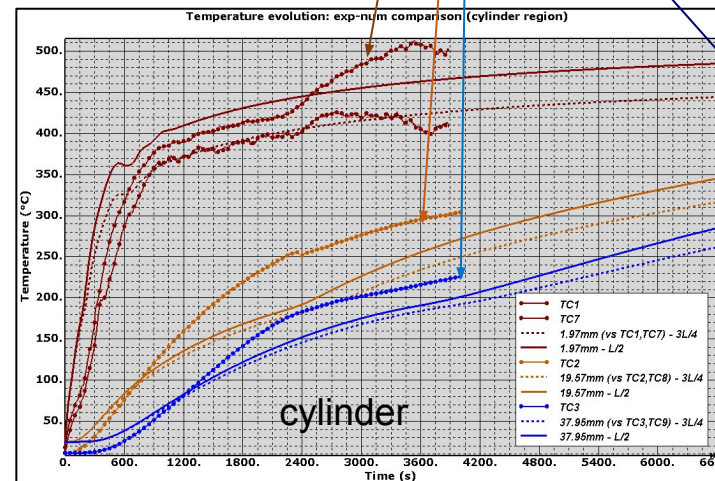
- Validation of material properties and boundary conditions
 - Test on composite tank with no pressure
 - Tank instrumented with thermocouples at different depths (1.97mm, 19.7mm, 37.9mm)
 - A number of thermocouples did not record the temperature but **6 gave useful data!**



Test conducted by Effectis

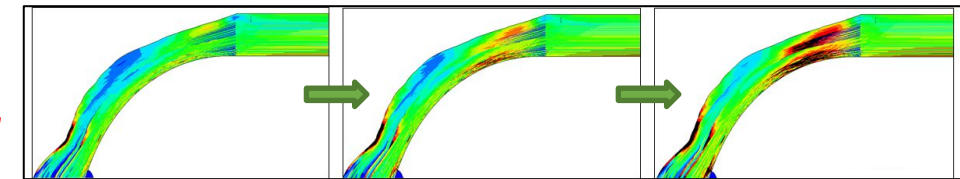
- Some discrepancies
 - exact position of the TCs unknown
 - heat flux changed

Overall, good agreement!



Simulation of the thermomechanical behavior of tanks

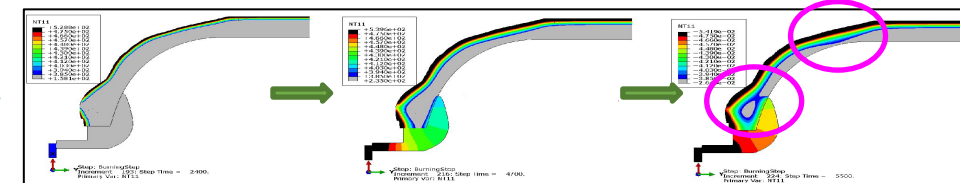
- Simulation of bonfire test on pressurized tank
 - Geometry (mandrel + winding sequence)
 - Properties (thermophysical, thermomechanical)
 - Internal pressure: **700 bar**, $T_{ini} = 25^\circ\text{C}$
 - Heat flux and convection => mock-up test
 - Emissivity: $e = 0.92$, $T_\infty = 25^\circ\text{C}$
 - Polar boss: steel (42CrMoS4+QT)
- **Leak / burst criteria**
 - **Burst** (first fiber failure criterion) :
when fiber stress reaches 1620MPa (fitted to burst test)
 - **Leak – lower bound** (melting criterion) :
melting front crosses the entire thickness
 - **Leak – upper bound** (decomposition criterion) :
decompositon front crosses the entire thickness



Rapid development of fiber failure in the dome



Evolution of the melting front in the composite tank



Evolution of the decomposition front in the composite tank

Simulation of the thermomechanical behavior of tanks

Results of simulation

Leak – lower bound

the melting front develops in the lower part of the dome region

30 minutes: lower bound of leak reached!

Leak – upper bound

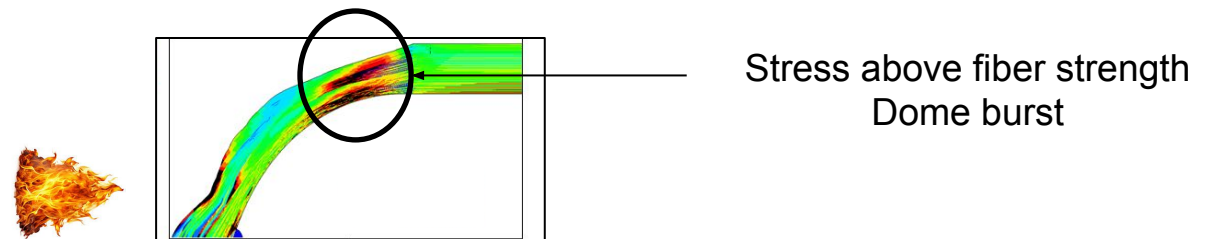
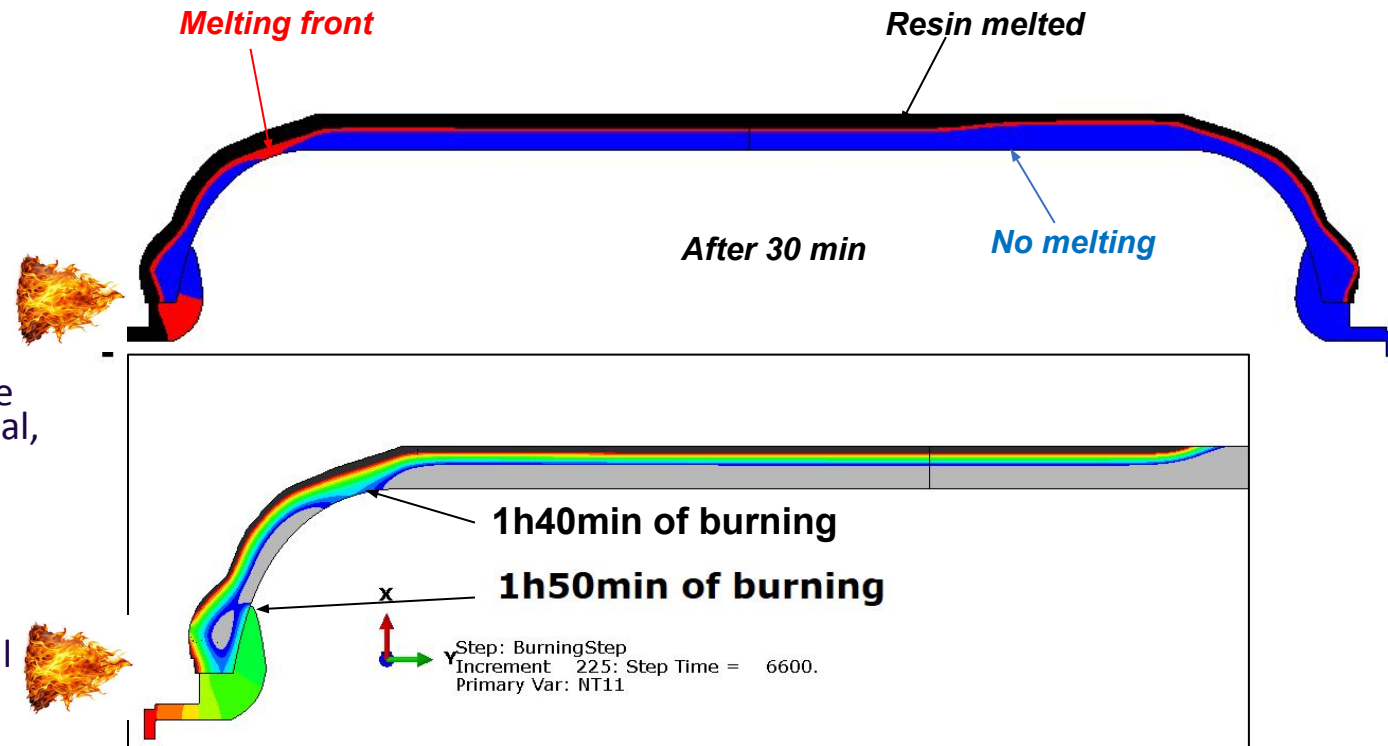
the decomposition front develops in the lower part of the dome region AND close to the boss (whatever the material, steel or aluminum)

1h40min: upper bound of leak reached!

Burst

The fiber strength is reached in the dome (due to thermal decomposition and mechanical weakening)

1h43min: burst criterion reached!



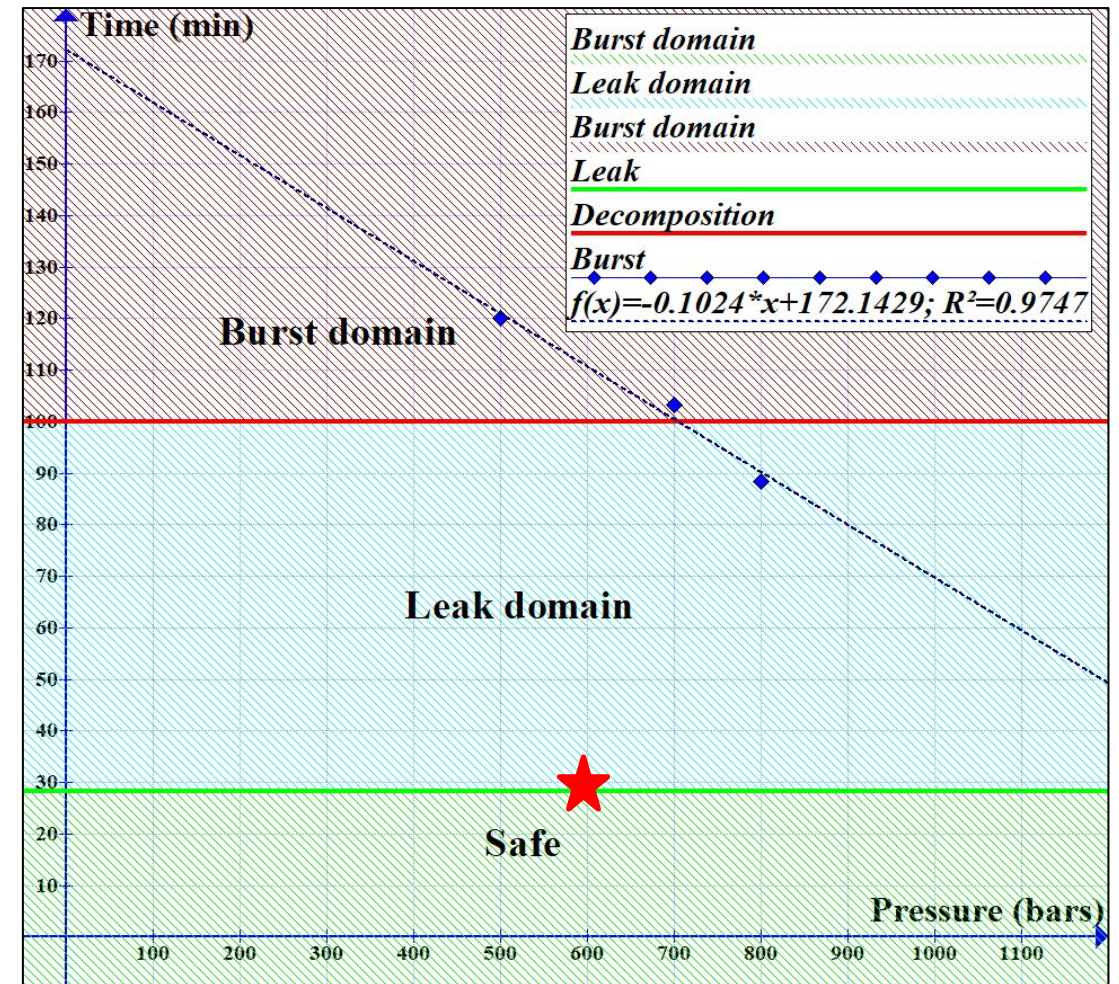
Simulation of the thermomechanical behavior of tanks

□ Results of simulation: influence of inner pressure

- The internal pressure does not influence the leak criteria (both lower and upper bounds) as they only depend on the thermal response of the composite tank.
- The higher the internal pressure, the quicker it would take the tank to reach burst.
- Below 700 bars: **burst will not occur before leak**.
- Beyond 700 bars: **leak is still likely before burst**, but there is small chance it might burst before.

At 550 bar, no leak / burst before 30 minutes

□ consistent with Efectis' bonfire test ! ★



Conclusion & perspectives

Adaptation of the test setup for the type V cylinder developed within the project

- In terms of design of the supporting system for the tube regarding:
- Vertical position - large volume - highly pressurized hydrogen

Preliminary tests / burner calibration □ *validates the proper design of the burners*

- Propane mass flow rate can be easily adjusted □ To define appropriate temperature value - uniformity – flame height around the tested tank
- Gas temperatures rise rapidly - reach values typically ranging between 650 and 850°C
 - Confirm that the experimental setup generates severe thermal conditions around the cylinder
 - Flame height not directly impinging the top part of the tank
 - Confirm the ability of the designed fire source to produce within 2 min a temperature of at least 590°C
 - Measured within 25 mm under the bottom of the tube (required by the test standard)

Dedicated supporting structure specifically designed:

- Ensure mechanical stability, minimum disturbance to the fire exposure
- Maintaining the cylinder position
- Even in the event of leakage or partial structural degradation during fire exposure



Conclusion & perspectives

Final bonfire test conclusion:

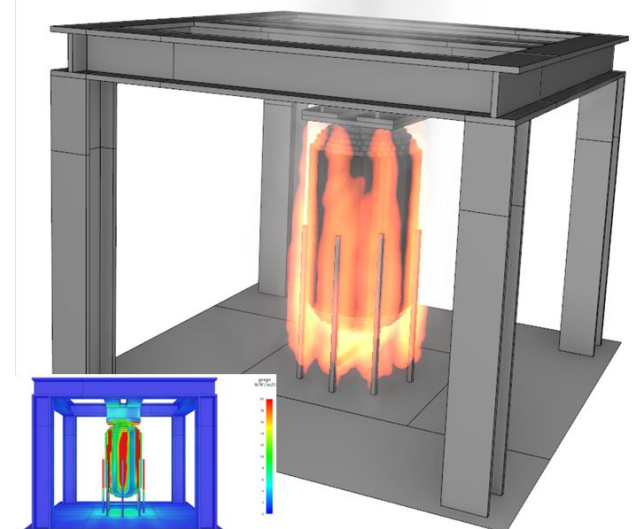
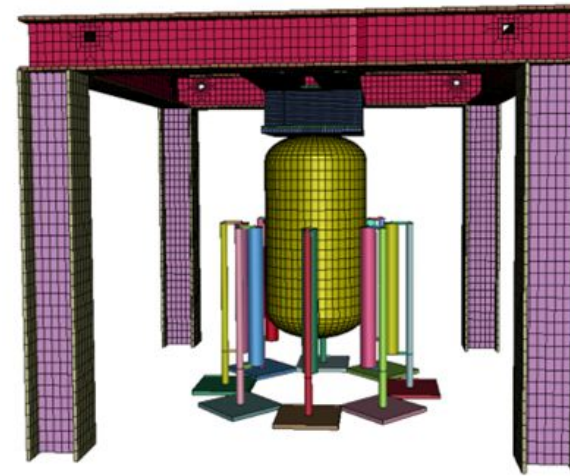
- Adequacy of the fire facility designed
- Demonstrates the ability of the type V tank developed to withstand a bonfire test during 30 minutes
 - Without any leakage or unsafe behaviour
 - No leak before burst behaviour observed / verified
- Pressure inside the tank:
 - Constant during the first 10 minutes - Then increased linearly up to 628 bar
 - Until burst disc ruptured
- After the test: no signs of perforation



Conclusion & perspectives

Challenging technical issues of the project lead to the following findings:

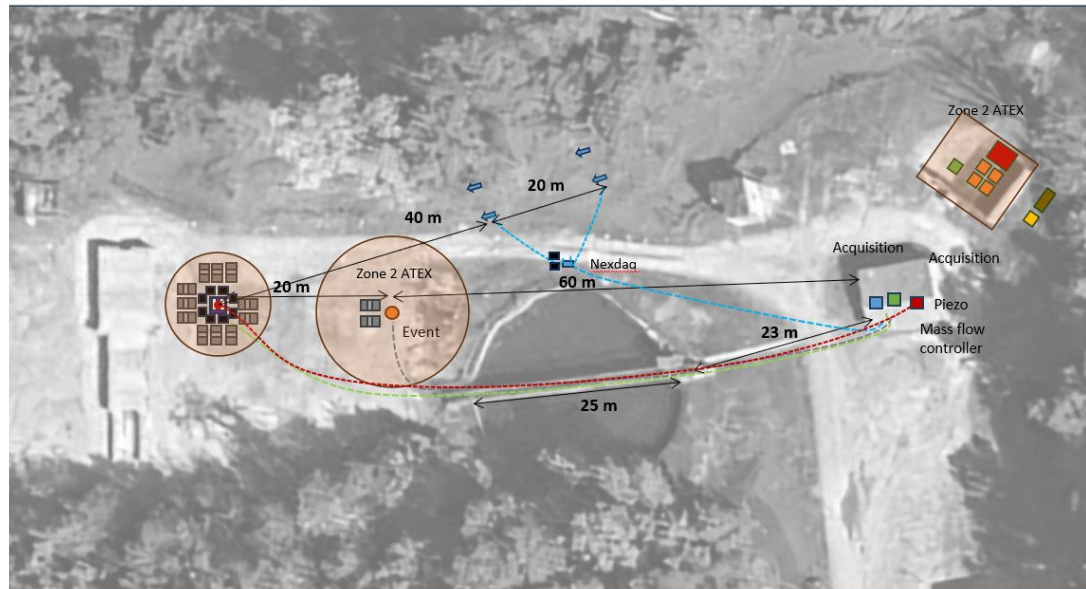
- Numerical tool available to design:
 - Any structural support for cylinder fire test
 - The burner configuration for any cylinder size/shape
- Modulable burners able to adapt to different size and shape



Conclusion & perspectives

Challenging technical issues of the project lead to the following findings:

- Remote control (~ 100 m) and monitoring of H₂ filling, propane burner ignition and feeding
- Remotely monitored instrumentation for both fire and blast phenomena



Prediction tools for Cylinder temperature management to maximise operating conditions

The objective of the modeling tool OneSOFIL once validated is to optimise the filling protocol while respecting the temperature constraints of the tank material:

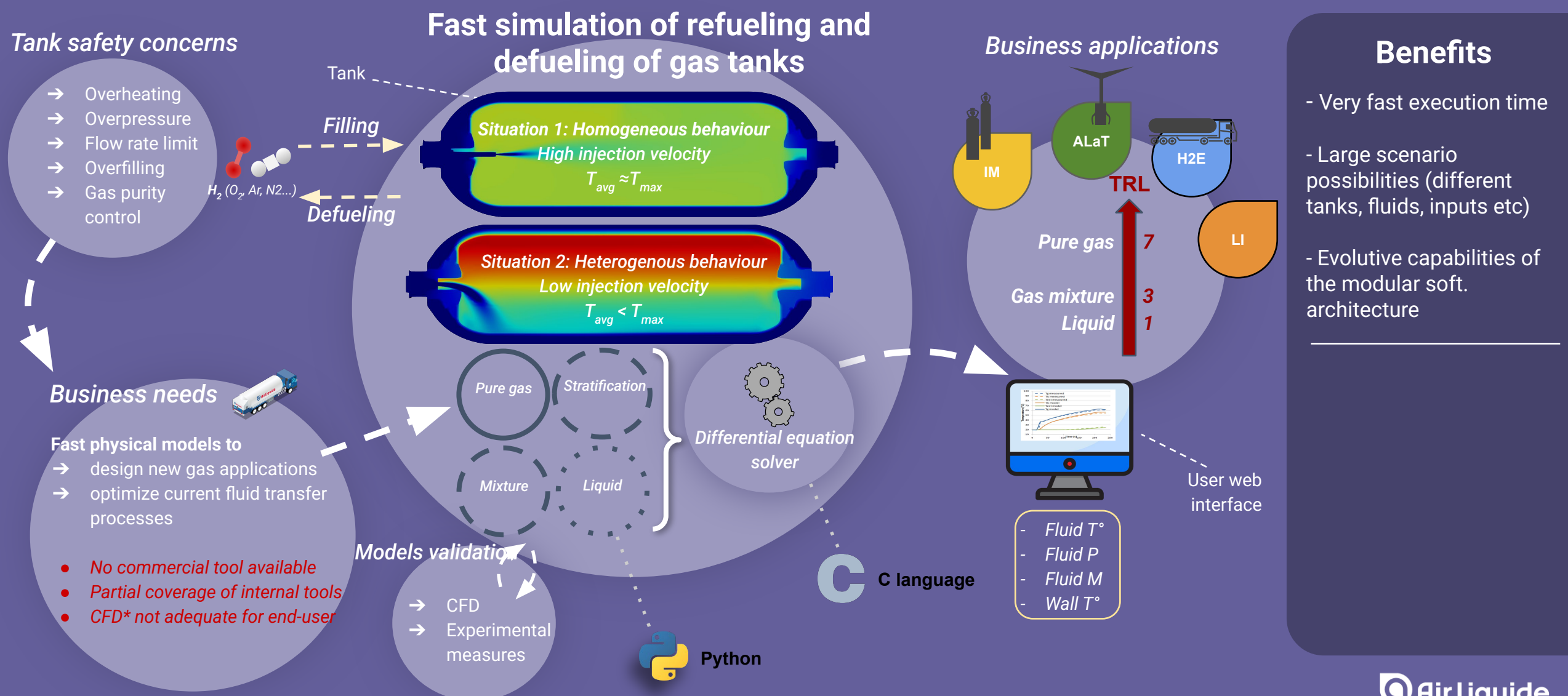
- Optimizing the filling time which depends on tank initial conditions and ambient temperature
- Reducing the size of precooling system and power (CAPEX and OPEX) as higher temperature can be supported by wall material for type V tanks compared to type IV tanks

Filling and unfilling tests

- Validation of engineering modeling tool (**OneSOFIL**) to be used for filling and unfilling optimisation
- Tests conducted at Testnet mid May 2026 with 150L tank
- 4 tests fulfilled:
 - Horizontal position
 - 0.35 g/s constant flow rate
 - Vertical position (gas entering from tank top)
 - 0.35 g/s constant flow rate (representative for current GH2 trailer filling)
 - 0.7 g/s constant flow rate (representative for future GH2 trailer filling)
 - Fast filling in 4 min (to reach the highest gas temperature achieved with Testnet compressor and to check for gas tightness)

OneSOFIL tool overview

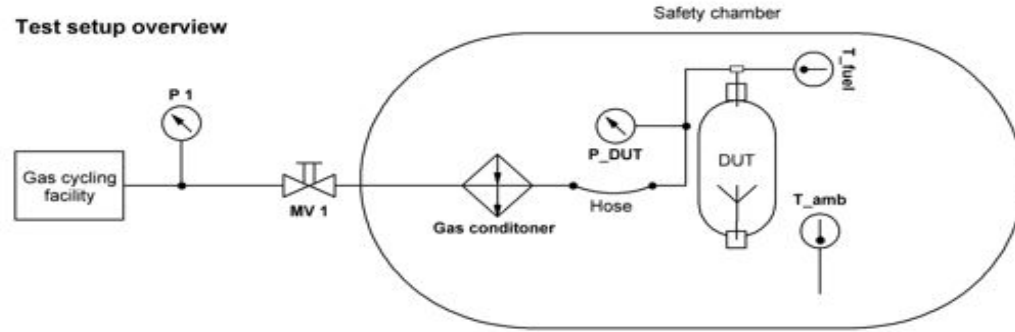
Engineering internal tool that allows modeling all gas fueling/defueling for any type of tanks, incl. gas mixture and liquid phase



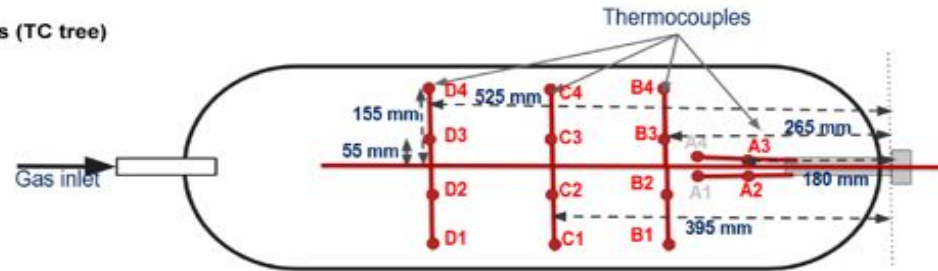
*CFD: Computational Fluid Dynamics, requires weeks to months of calculation

Filling and unfilling tests: experimental setup

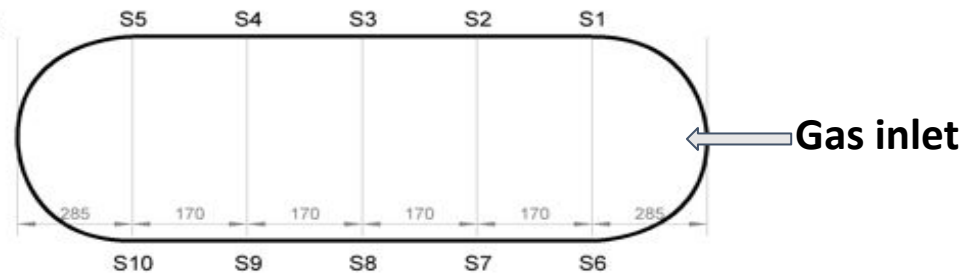
Test setup overview



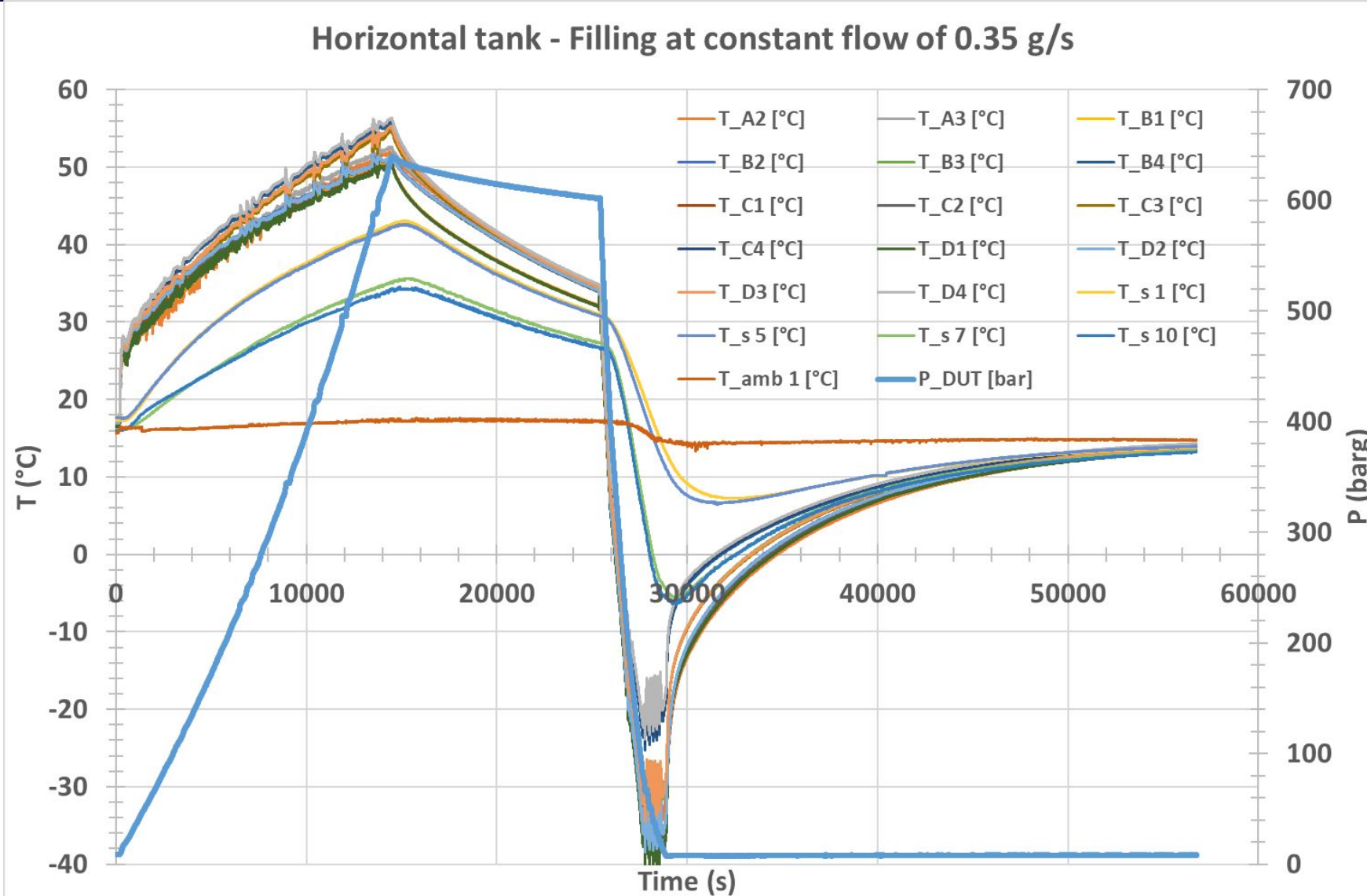
Internal TCs (TC tree)



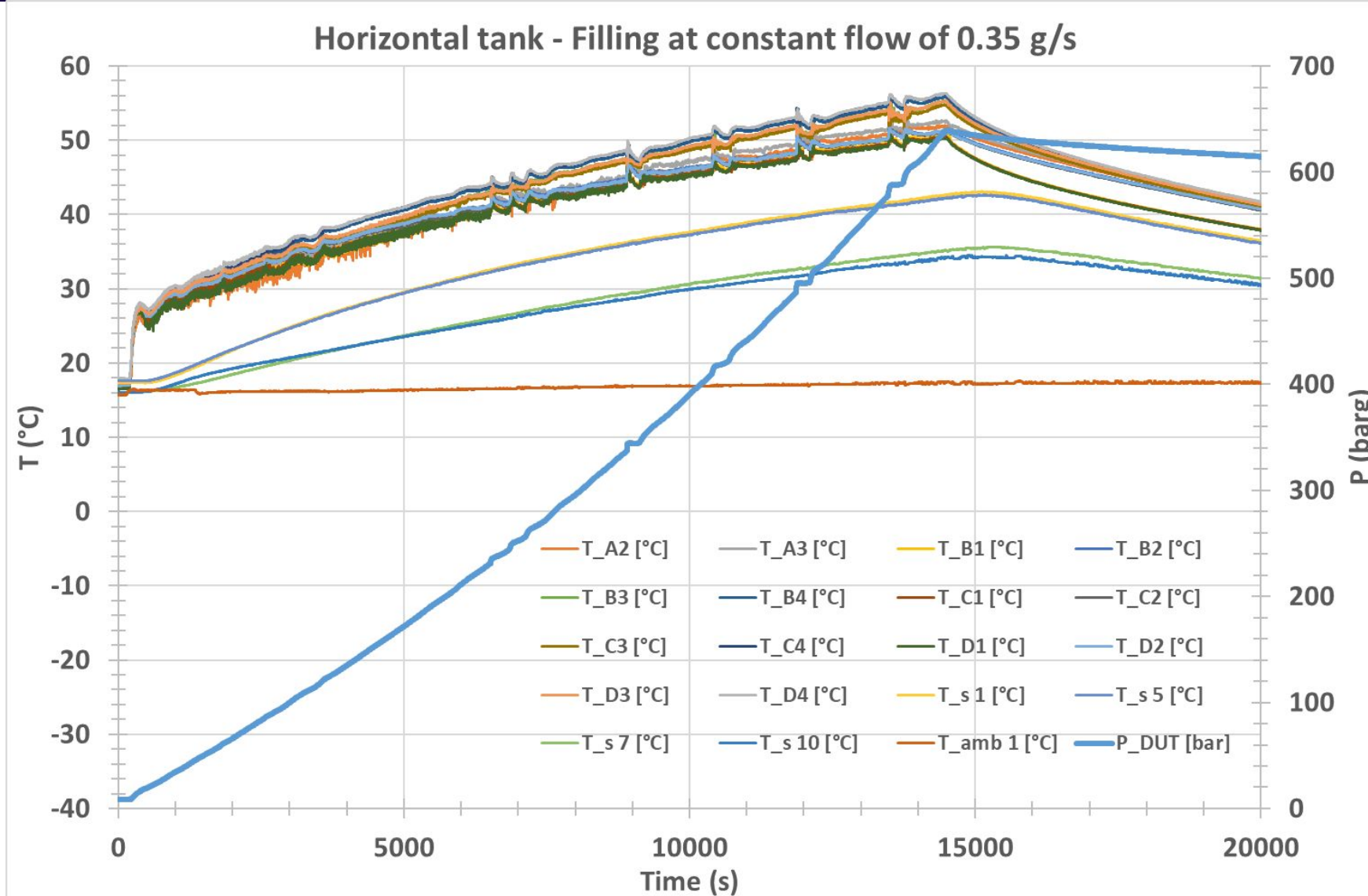
External TCs (tank surface)



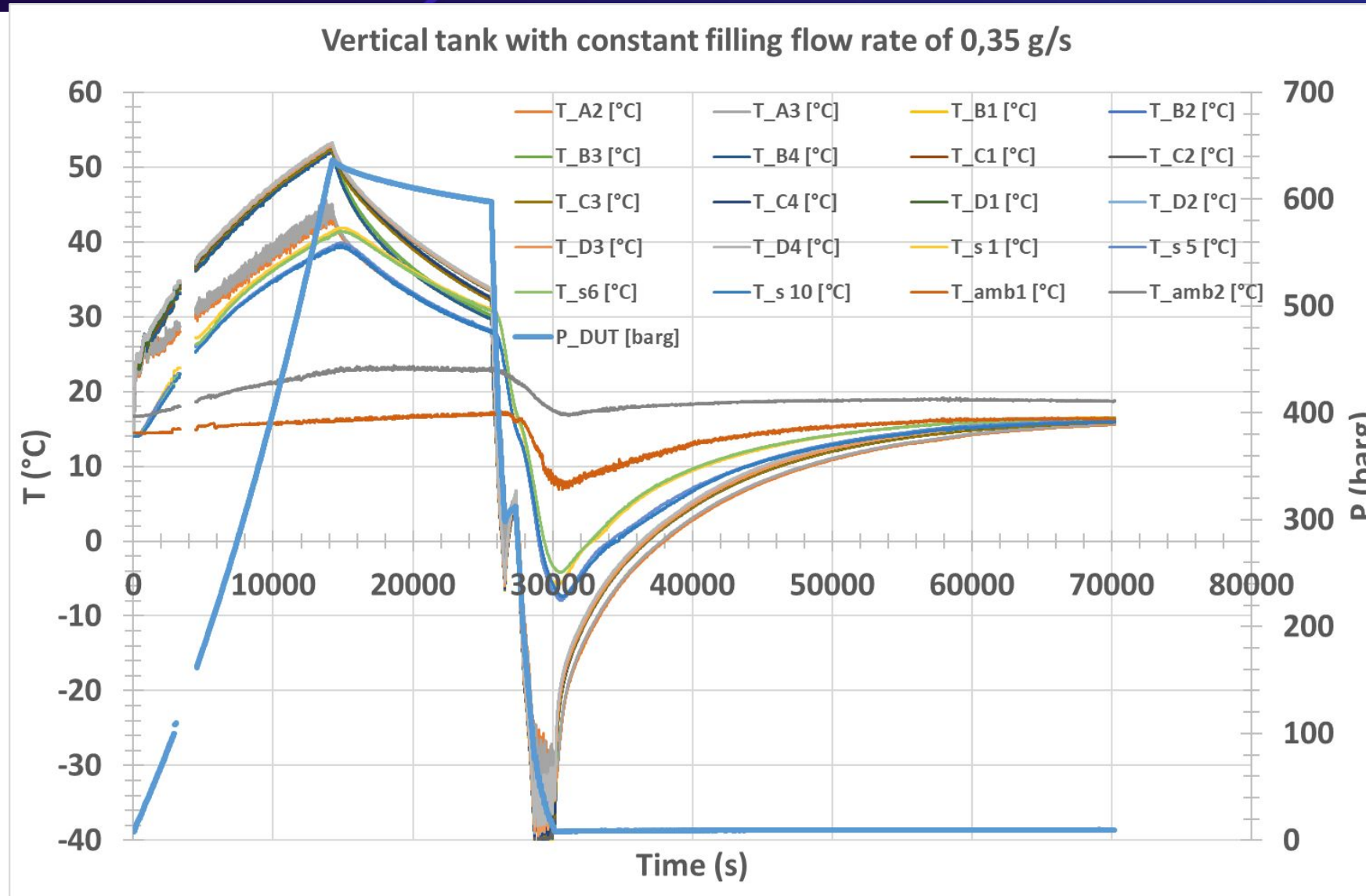
Filling and unfilling tests: tank in horizontal position



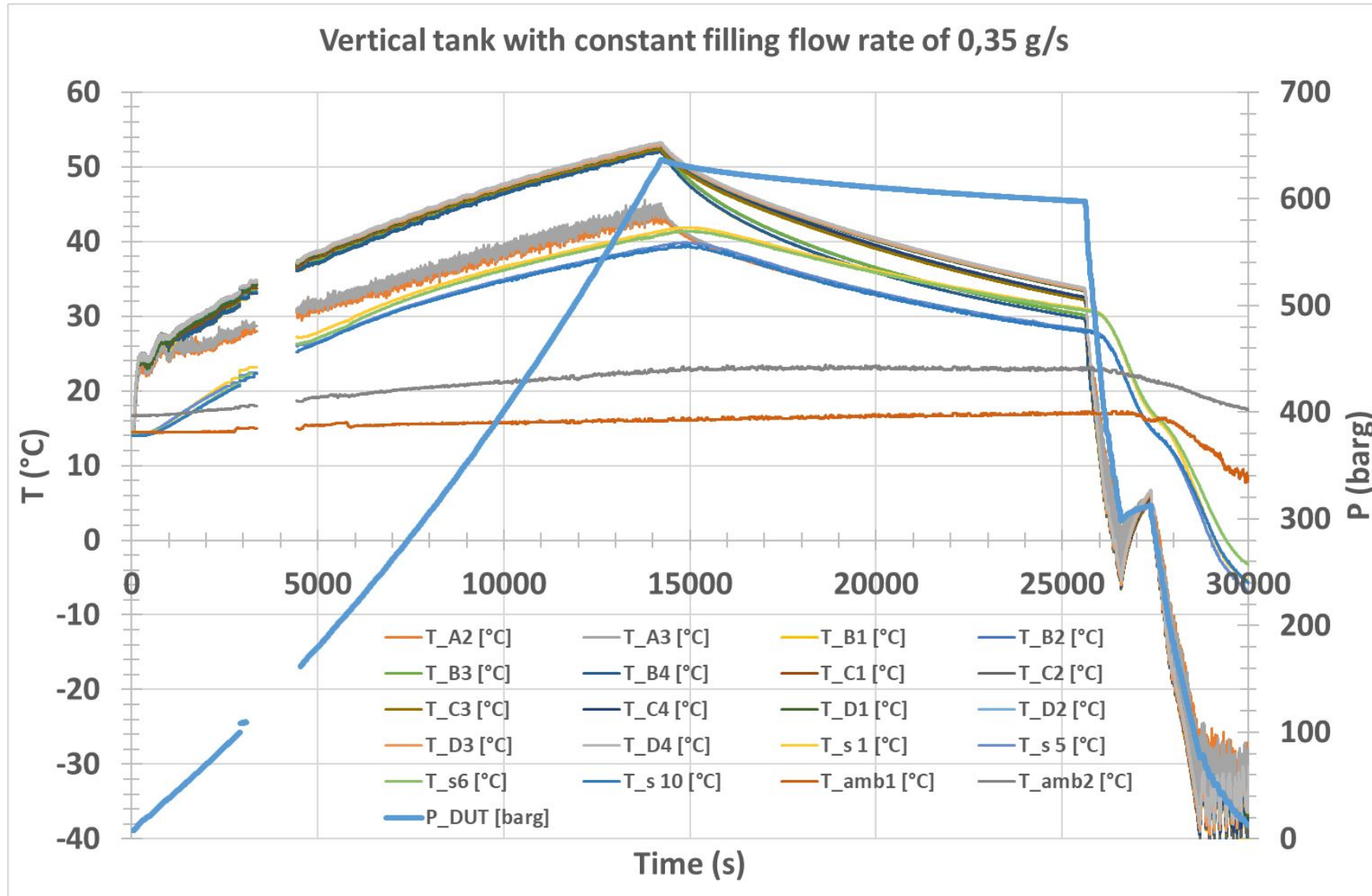
Filling and unfilling tests: zoom on the filling period



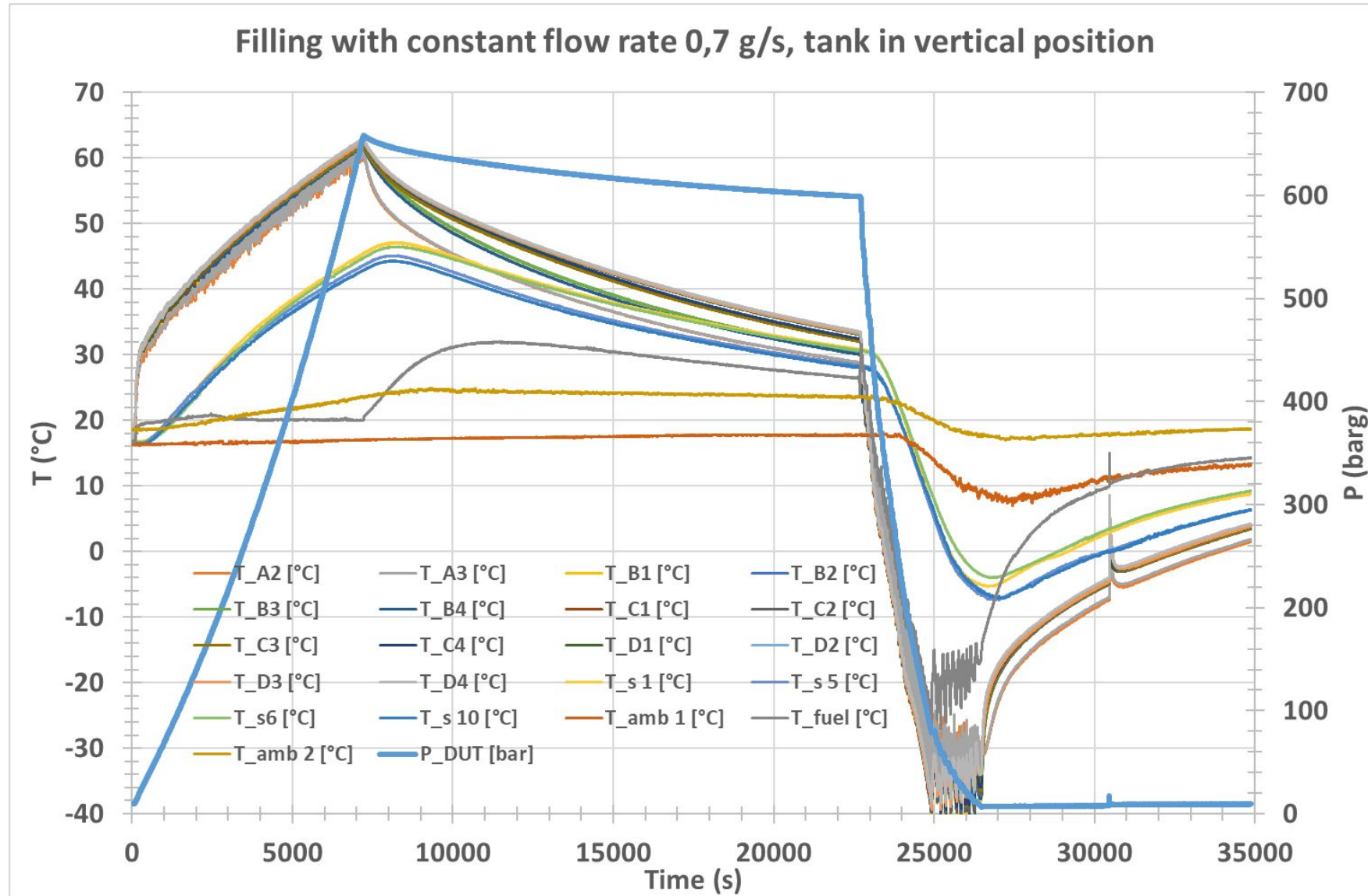
Filling and unfilling tests: tank in vertical position, normal flow rate



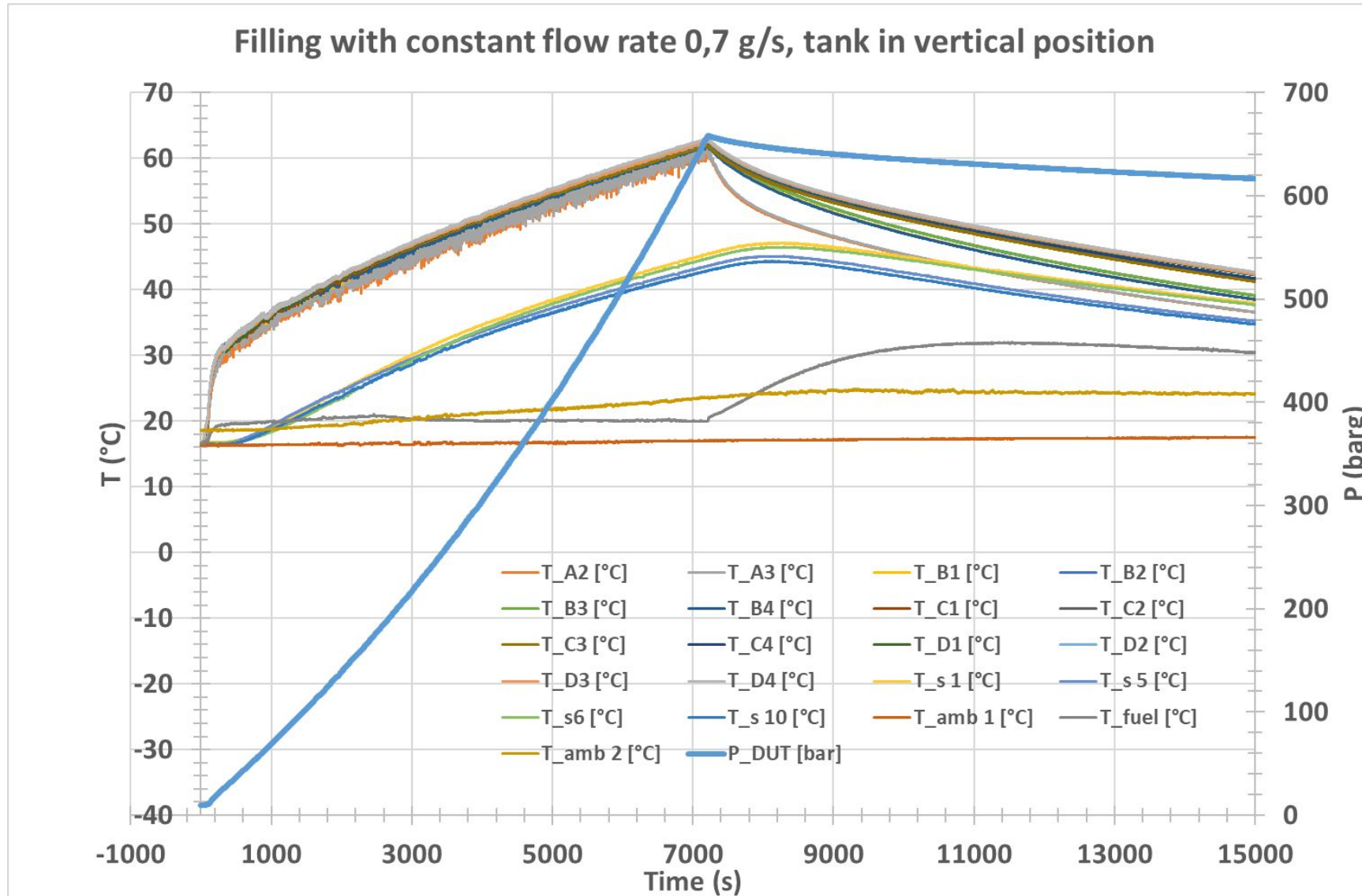
Filling and unfilling tests: zoom on filling time with normal flow rate



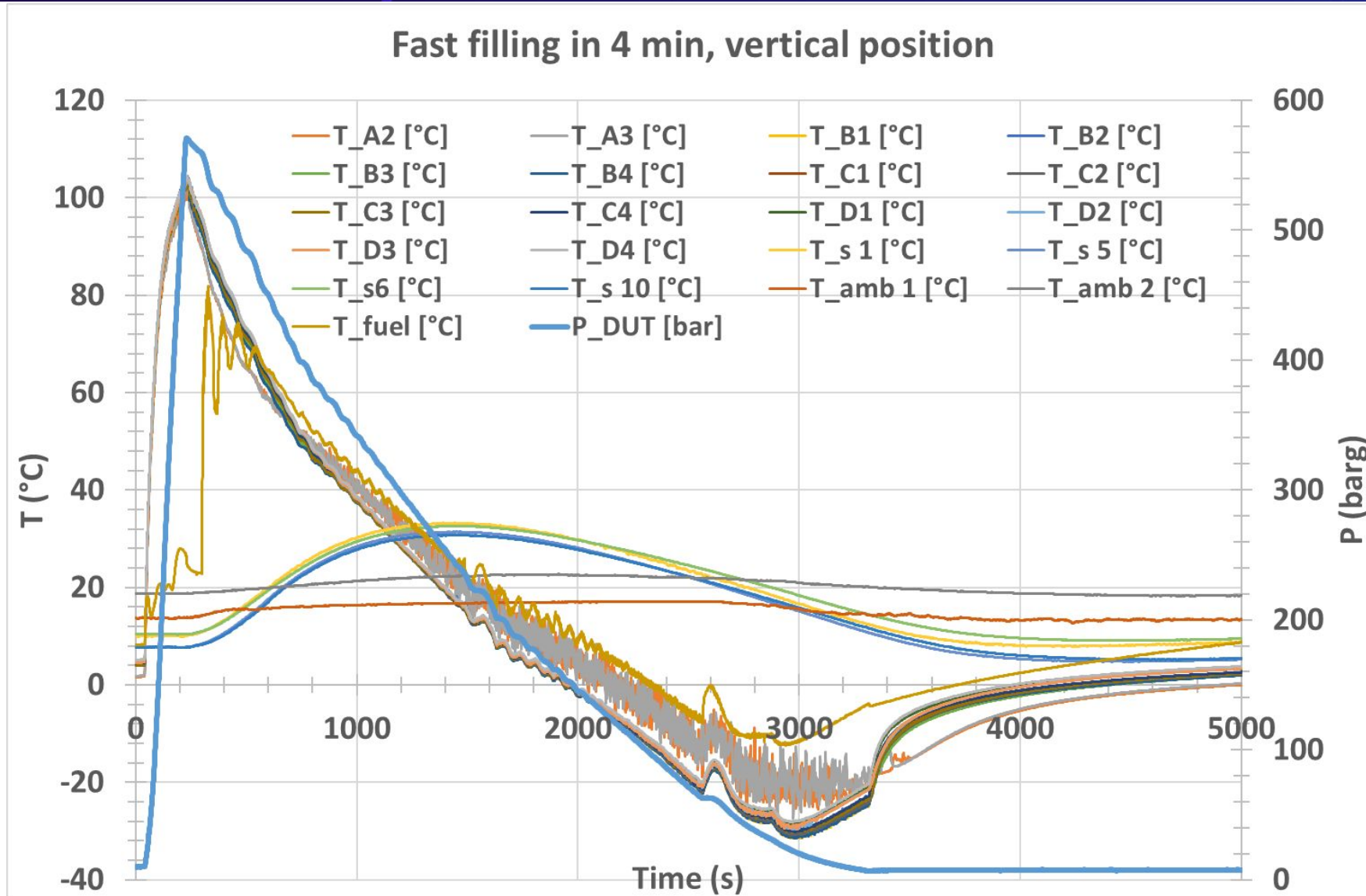
Filling and unfilling tests: vertical position with double of flow rate



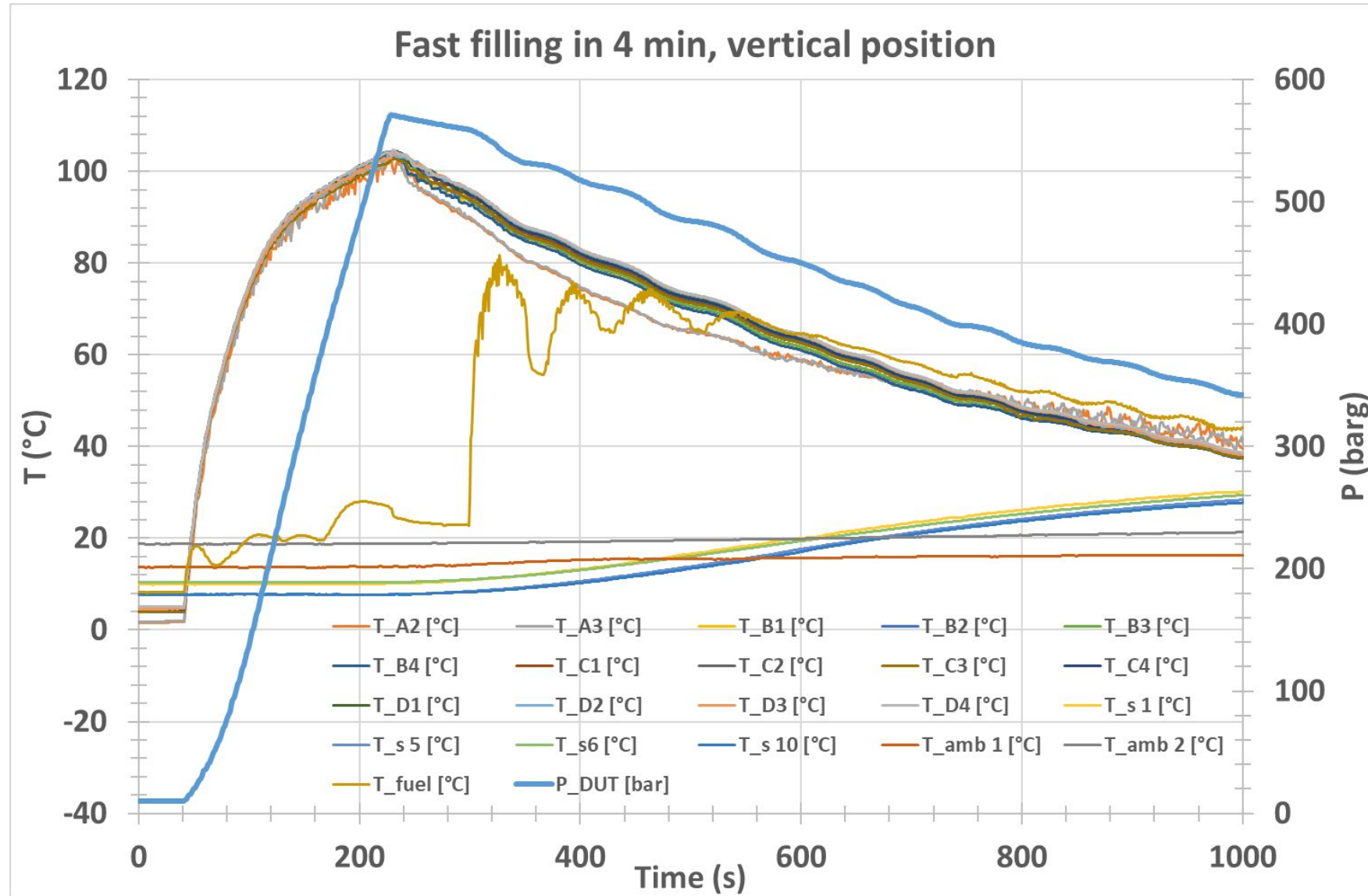
Filling and unfilling tests: zoom on filling time



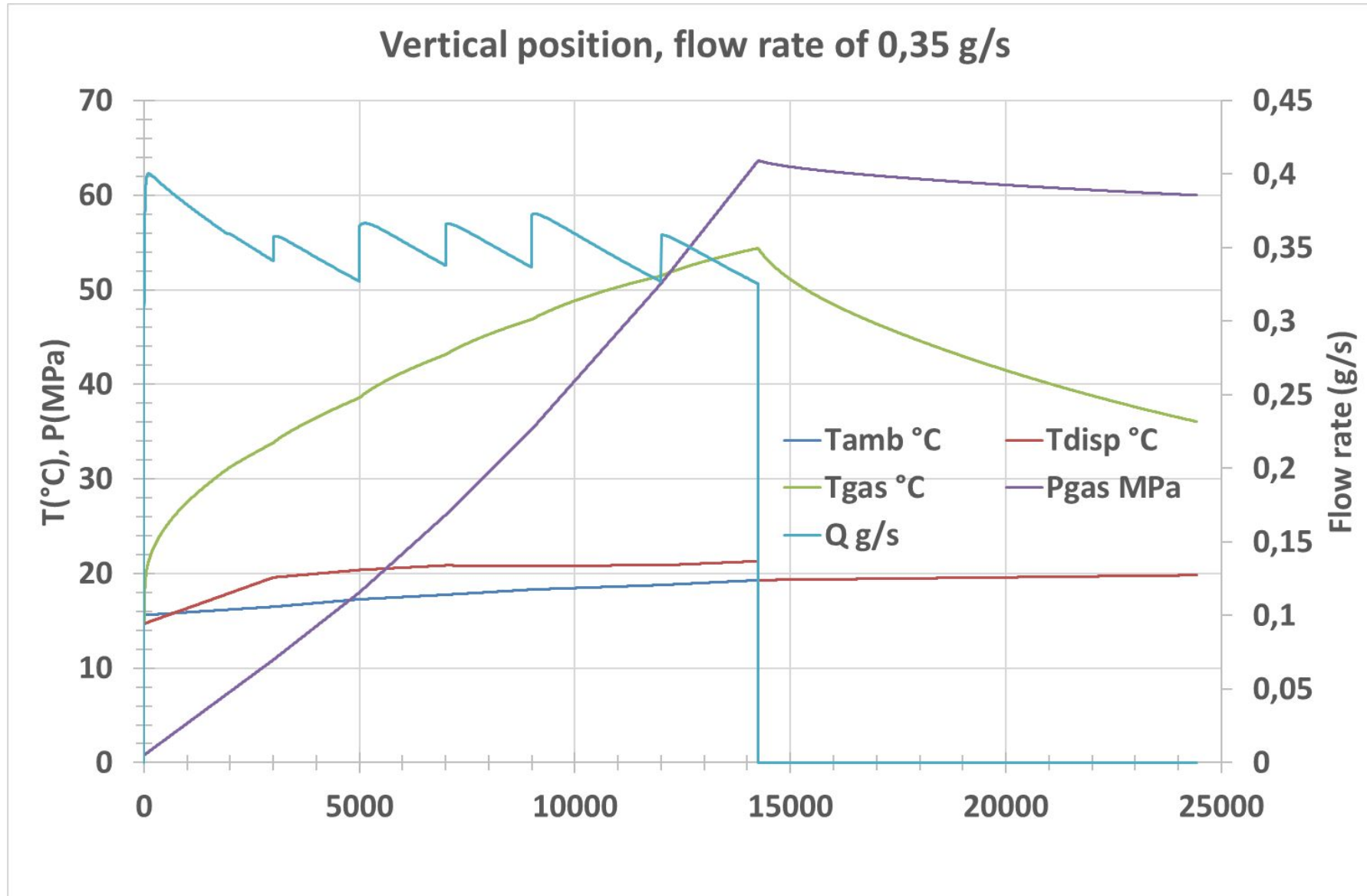
Filling and unfilling tests: very fast flow rate vertical position



Filling and unfilling tests: zoom on filling time with very fast filling



Filling and unfilling tests: first results of OneSOFIL for tank vertical position and normal flow rate



Conclusion & perspectives for the filling and unfilling tests

- Validation of OneSOFIL tool in progress
- One CFD (Computational Fluid Dynamics) calculation will be launched in the case of tank vertical position and normal flow rate to assess the thermal stratification inside the tank
- Optimisation of the filling and unfilling of type V GH2 trailers

TCO of a dedicated supply chain

CAPEX

- Initial Investment = EPC (Engineering, Procurement & Construction)
- Return on Investment



+

OPEX

- Energy/water consumption
- Other operational costs (operators...)
- Maintenance
- General & Administrative expenditures



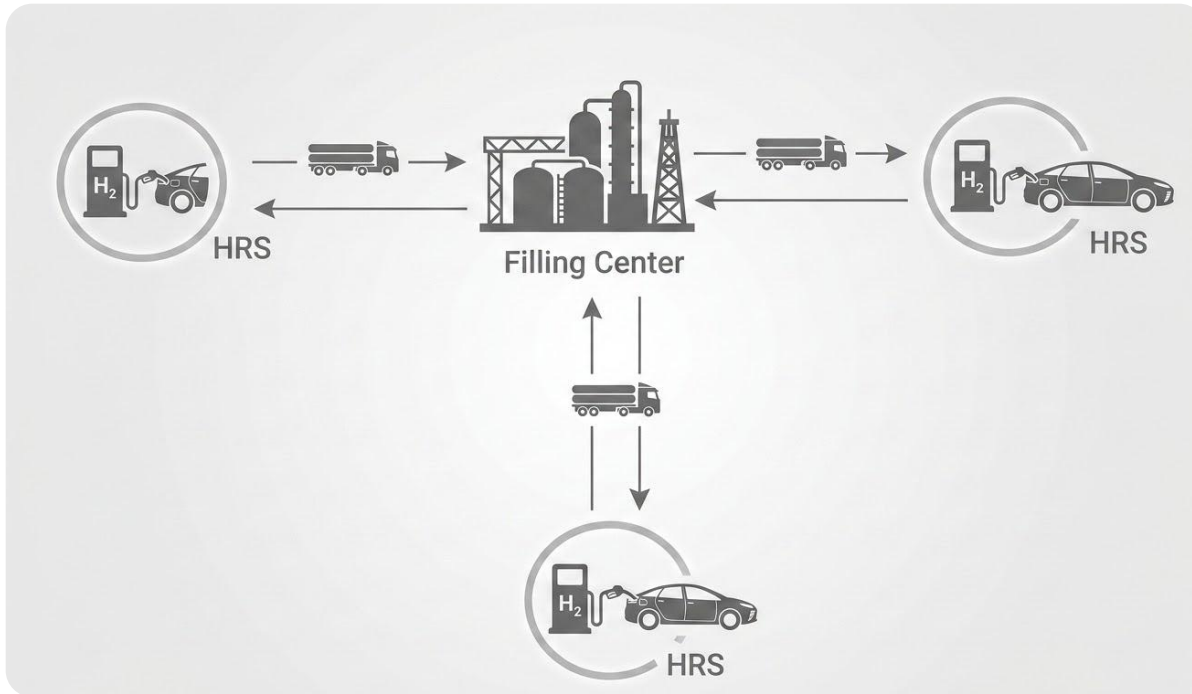
$$\text{TCO} = \text{OPEX} + \text{CAPEX} \text{ [€/kg H}_2\text{]}$$

*TCO is calculated as a specific unit cost: € per kg of H2 delivered.
This allows to objectively compare two different technologies (Type IV vs Type V).*



- Not a cash position indicator
- All depends on assumptions
- Definitions may vary

GH2 Supply Chain Assumptions



Distribution Network

Stations are equally distant from Filling Center

Network Losses

Assumes a standard gas loss during distribution

HRS Station Requirements

Daily demand: fixed | Autonomy: fixed

Filling Center

Capacity: ~X tons per day (tpd)

SWAP Distribution


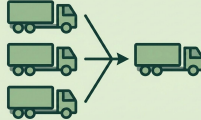
- Single customer delivery
- Trip duration: Travel + Waiting + Filling + Delivery

Trailers

Includes maintenance downtime, filling/waiting times, and handling for trailer switches

Same CAPEX for 1 trailer Type IV and Type V (not known today)

Evolution of GH2 transportation

Variables	Type I: metal	Type IV: composite + liner	Type V: linerless composite
Cylinder			
Trailer Nominal Pressure	200 bar	300 bar 635 bar	300 bar 700 bar
Water desorption after drying	no	yes	no
Payload	350 kg (200 bar)	840 kg (300 bar) 1270 kg (635 bar)	847 kg (300 bar) 1485 kg (700 bar)
Effect on logistics			<p><i>Fewer trips</i> <i>Less maintenance</i> <i>Less energy</i> <i>Reduced fleet</i></p> 

TCO Driver Analysis

Water Management

System Efficiency Drivers:

Type IV:

Liner desorbs water

Type V:

No water release after drying

→ More Type IV trailers needed in summer

Increased Net Payload

+1%

at 300 bar

+17%

at High Pressure

→ ***Significant reduction in required fleet sizing***

Reduced annual trips and total distance

Lighter composite cylinder



Lower diesel and maintenance costs

TCO comparison : Type IV vs Type V

TCO improvement: Type IV vs Type V (with data breakdown)



17% Improvement

Overall TCO reduction at **300 bar** compared to Type IV technology.

24% Improvement

Reduction at **High Pressure (700 bar)**, significantly cutting supply chain costs.

→ Adopting Type V cylinders cuts logistics costs in high-pressure GH2 supply chains by ~25% while improving delivery reliability.

Conclusion: Type IV TCO compared to Type V



TCO Reduction

Transition to linerless Type V reduces TCO by up to 24% at high pressure.

Industrial Performance

- Lighter cylinders : Reduction of OPEX (lower diesel and maintenance cost)
- Water management improvement

Fleet sizing

Higher payload at high pressure for Type V compared to Type IV

PA11 raw material adapted to Covess process for type V manufacturing

Conclusion

Raw material UDX Tape PA11

Properties & Performance

- 57 % vol carbon fiber content → **high tensile strength** (> 2 500 MPa)
- No slitting during manufacturing → no fiber cut → **maximum performance**
- Very low moisture uptake → **constant performance** in real conditions
- **100 % biobased** Rilsan® PA11 resin
- Low viscosity Rilsan® PA11 resin → **high processability** in in-situ consolidation

Tape Spool Characteristics

- Carbon spool length = initial carbon roving (3.5 km)
 - Fewer stops during tank manufacturing
 - **Higher productivity** & less defects
- No slitting, no splicing → **no dust or defects** on spools
- No specific storage or pre-drying conditions → **higher efficiency**

Type V cylinder design now fit for purpose - GH2 supply chain applications

Conclusion

Type V cylinder design

- Monolithic structure - Liner is part of the composite structure - One step manufacturing process
- No liner blistering or collapse - Possible to do vacuum
- Thin liner: Increased storage volume for same outer diameter & low water storage
- Low void content - K_{Ic} of UDX PA11 composite is about twice higher than CF/Epoxy
- Stress quite evenly spread throughout the composite structure (cf Type V burst photo)
- So far, ~ 5 % weight saving on Type V cylinder compared to Type IV, can be optimised, GI ~ 9 %
- Possible to change the boss thread if damaged or to store another gas
- Few assembly arrangements, few manufacturing steps and less operator dependant compared to Type IV

Type V cylinder design now fit for purpose - GH2 supply chain applications

Conclusion

Usages → objective: Type V behavior close to metallic tubes

- Faster & cheaper cylinder preparation (decontamination, drying < 5 μmol/mol, conditioning)
- Rapid defuelling
- PA11 large elongation at break, even when cylinder is dry, can cope with cylinder expansion when filling
- More resilient to mechanical impact (no dome protection for instance)
- Better behavior to fatigue
- Higher GH2 quantities transported in a trailer : at 700 bar WP → 1,5 Ton
- Can predict the temperature at filling & unfilling with a AL in house model with such a Type V design

Type V cylinder intrinsic features meet safety requirements

Conclusion

Safety Performance

- Withstands engulfing fire: 33+ min @ 550 bar. No issue with boss - composite arrangement
- Intrinsic material properties can withstand low temperature (- 60°C) and higher temperature than + 65°C as PA11 is a semicrystalline polymer
- Better thermomechanical properties of C/PA11 (vs thermoset)
 - *Higher pyrolysis onset temperature : delayed degradation*
 - *Lower effective diffusivity : protection against temperature rise*
 - *Higher mechanical resistance and deformability in a fire*

Bonfire Simulation Insights

- Possible to predict leak and burst independently
- Leak is more likely and occurs earlier than burst
- Efficient tool to simulate different conditions (heat flux, inner pressure, material, ...)
- Conservative prediction of bonfire test (no damage in less than 30 min)

Trailer with type V cylinders designed for large GH2 quantities

Conclusion

Trailer Design & Capacity

- **High Storage Capacity:** Design of Type V trailer can store 1,5 Tons of GH2
- **Enhanced Safety:** Features to facilitate periodic inspection, reduce the probability of damage and increase fire safety
- **Circular Economy:** Recyclable cylinders

Environmental Performance (LCA)

LCA for Type V trailer generally delivers the **best environmental performance**, particularly at medium and long transport distances.

Key Success Drivers:

- Higher transport capacity
- Biosourced PA11
- Dry cylinder

TCO: OPEX Savings

Conclusion

Type V Trailer OPEX Efficiency

Significant OPEX savings are achieved with Type V trailers through:

- Lighter cylinders
- Maintenance
- Hydrogen specification whatever the working pressure & temperature - 5 $\mu\text{mol/mol}$
- Trailer design adapted to simplify periodic inspection

Perspectives : GH₂ supply chain savings potentials

Raw material UDX PA11 Tape

UDX[®] PA11 tapes industrialisation for GH₂ tank manufacturing

- Reasonable production capacity today at Arkema to start a business in GH₂
- Extension possible internally and/or externally (license on UDX[®] PA11 tapes manufacturing)

Type V cylinder

- Increase the gravimetric Index from 9 % to 12 %
- Increase working pressure for mobility market i.e. 700 bar
- For stationary applications 1 000 bar
- Increase weight saving up to ~20 % → Reduce winding time & labor & cost
- Manufacture large cylinder from 50 l to 3 000 l
- Demonstrate Type V cylinder can withstand high temperatures 120°C - 130°C : no GH₂ pre-cooling needed at HRS and only decontamination is needed & no need to guarantee H₂O content below 5 µmol/mol at any pressure

Perspectives : GH2 supply chain savings potentials

Usages

- Reduce the number of GH2 trailer rotations for a supply chain
- No need for cylinder drying (still need to be decontaminated)
- Fill faster a trailer
- No need HRS pre-cooling → high temperature Type V tubes

Safety

- With high temperature Type V tubes, water will have desorbed from the liner. Fire increases p&T, then liner depolymerisation starts → could do away with TPRD, save weight & cost
- Verification of leak / burst criteria: bonfire tests on smaller tanks in different conditions
- Optimisation of fire resistance: Boss, shape, conductivity, ...
- Non axisymmetric bonfire simulation, set of several tanks

Perspectives : GH2 supply chain savings potentials

Trailer Design

As less Type V tubes as possible → For instance long 16 tubes

- Reduce piping & valves
- Simplify the periodic inspection
- *High temperature cylinder - Fast filling*

TCO

Saving on OPEX with Type V trailers thanks to:

- Lighter cylinders
- Hydrogen specification whatever the working pressure & temperature - 5 $\mu\text{mol/mol}$
- Trailer design adapted to simplify periodic inspection
- Faster trailer filling

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HIGH PAYLOAD HYDROGEN TRAILERS WITH NEW COMPOSITE CYLINDERS

