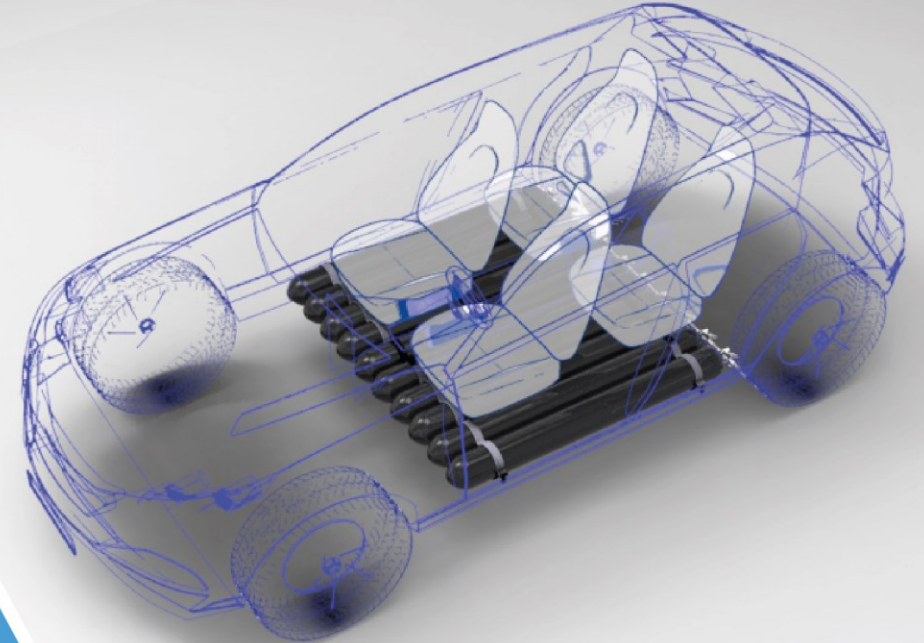


# Welcome

STAKEHOLDER's Workshop Brussel  
September 26<sup>th</sup> and 27<sup>th</sup>, 2024



[www.sh2aped.eu](http://www.sh2aped.eu)

# Agenda of Stakeholder's workshop – Day 1

| Day 1, 26 September 2024                                               |                                                                                           |                                |
|------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|--------------------------------|
| Introduction and concept of conformable tanks for onboard storage      |                                                                                           | Speaker                        |
| 09:45 – 10:00                                                          | Arrival and registration                                                                  |                                |
| 10:00 – 10:10                                                          | Welcome                                                                                   | B. Criel, POAIR; V. Molkov, UU |
| 10:10 – 10:35                                                          | SH2APED project overview and objectives                                                   | B. Criel, POAIR                |
| A standard conformable tank storage system with TPRD                   |                                                                                           |                                |
| 10:35 – 10:55                                                          | Design and manufacturing of liner, boss, composite                                        | B. Criel, POAIR                |
| 10:55 – 11:15                                                          | Coffee break                                                                              |                                |
| 11:15 – 11:35                                                          | Design and manufacturing of manifold, valve system and TPRD                               | E. Dal Gal, OMB                |
| 11:35 – 11:55                                                          | TPRD design and expected performance                                                      | E. Dal Gal, OMB                |
| An innovative self-venting (TPRD-less) conformable tank storage system |                                                                                           |                                |
| 11:55 – 12:20                                                          | Breakthrough safety technology of explosion free in fire self-venting (TPRD-less) tanks   | S. Kashkarov, Ulster           |
| 12:20 – 12:45                                                          | Design of self-venting (TPRD-less) tank: liner (HDPE vs PA), composites                   | S. Kashkarov, Ulster           |
| 12:45 – 13:15                                                          | Manufacturing of self-venting (TPRD-less) system                                          | B. Criel, POAIR                |
| 13:15 – 14:25                                                          | Lunch                                                                                     |                                |
| Hydrogen Safety Engineering                                            |                                                                                           |                                |
| 14:25 – 14:40                                                          | Fire resistance of standard and self-venting tanks in a smouldering and hydrogen jet fire | S. Kashkarov, Ulster           |
| 14:40 – 14:55                                                          | Performance of vehicle conformable hydrogen storage system in an incident fire            | S. Kashkarov, Ulster           |
| 14:55 – 15:25                                                          | TPRD as a safety device: underground parking and performance during fuelling failure      | V. Shentsov, H. Xie, Ulster    |
| 15:25 – 15:50                                                          | Performance of conformable tanks during fuelling                                          | H. Xie, S. Kashkarov, Ulster   |
| 15:50 – 16:00                                                          | Defueling of conformable tanks                                                            | V. Shentsov, Ulster            |
| 16:00 – 16:20                                                          | Coffee break                                                                              |                                |
| 16:20 – 17:00                                                          | Round-table discussion and wrap-up session                                                | All                            |



# Agenda of Stakeholder's workshop – Day 1

## Day 2, 27 September 2024

### Testing of storage systems with and without TPRD

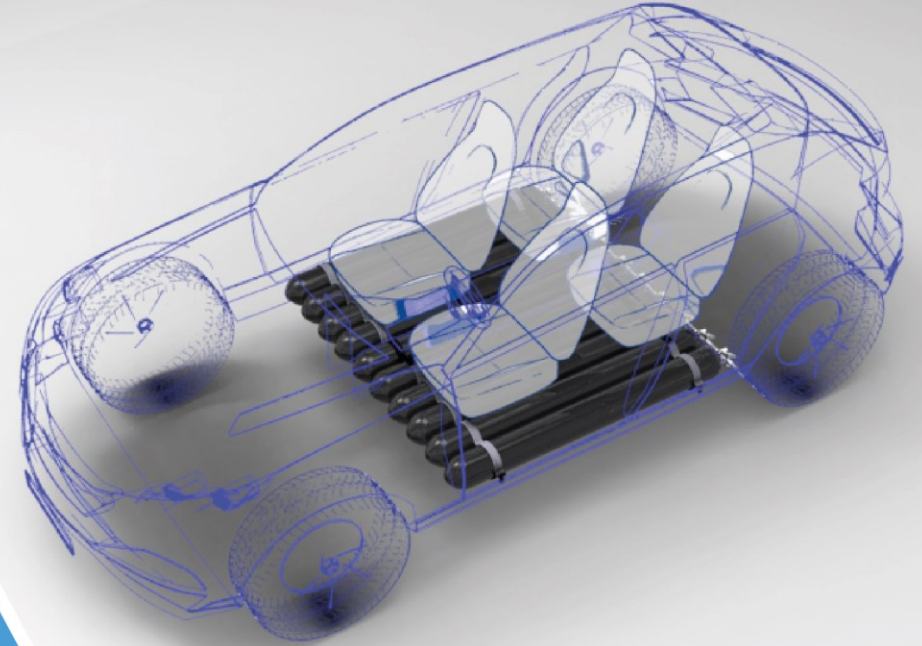
|               |                                                                                         |                 |
|---------------|-----------------------------------------------------------------------------------------|-----------------|
| 09:30 – 09:50 | Overview of experimental testing at BAM: hydraulic pressure, drop and fire tests        | N. Lengas, BAM  |
| 09:50 – 10:10 | Distributed fibre optic strain sensing for structural health monitoring of COPV         | A. Wosniok, BAM |
| 10:10 – 10:30 | Investigations on fire resistance of COPV with respect to validation of fire test setup | C. Sklorz, BAM  |
| 10:30 – 10:15 | Results of TPRD testing                                                                 | E. Dal Gal, OMB |
| 10:15 – 10:35 | Coffee break                                                                            | All             |

### Economic and industrial perspectives

|               |                                                                                       |                                   |
|---------------|---------------------------------------------------------------------------------------|-----------------------------------|
| 10:35 – 12:00 | Cost-effective analysis, including standard and self-venting (TPRD-less) systems      | B. Criel, POAIR                   |
| 12:00 – 12:15 | Recommendations for update of Regulations, Codes, and Standards (RCS)                 | S. Kashkarov, V. Shentsov, Ulster |
| 12:15 – 12:35 | Industrial perspective for future technology exploitation by SH2APED project partners | B. Criel, POAIR                   |
| 12:35 – 13:00 | Final discussion and wrap-up session                                                  | All                               |

# Project Overview and Objectives

STAKEHOLDER's Workshop Brussel  
September 26<sup>th</sup> and 27<sup>th</sup>, 2024



# Agenda of Project Overview

- Introduction
- Project Objectives
- Challenges
- Key Product Indicators
- Process and tasks
- Impact

# Project introduction

## Physics laws driving the pressure storages



## Battery weight leading to a Standard “Battery Electric Vehicles” architecture



- Standardization of vehicle architecture

→ Need of an hydrogen storage system compliant with the “battery pack” shape.

THE EUROPEAN SH<sub>2</sub>APED PROJECT has been build to this end .

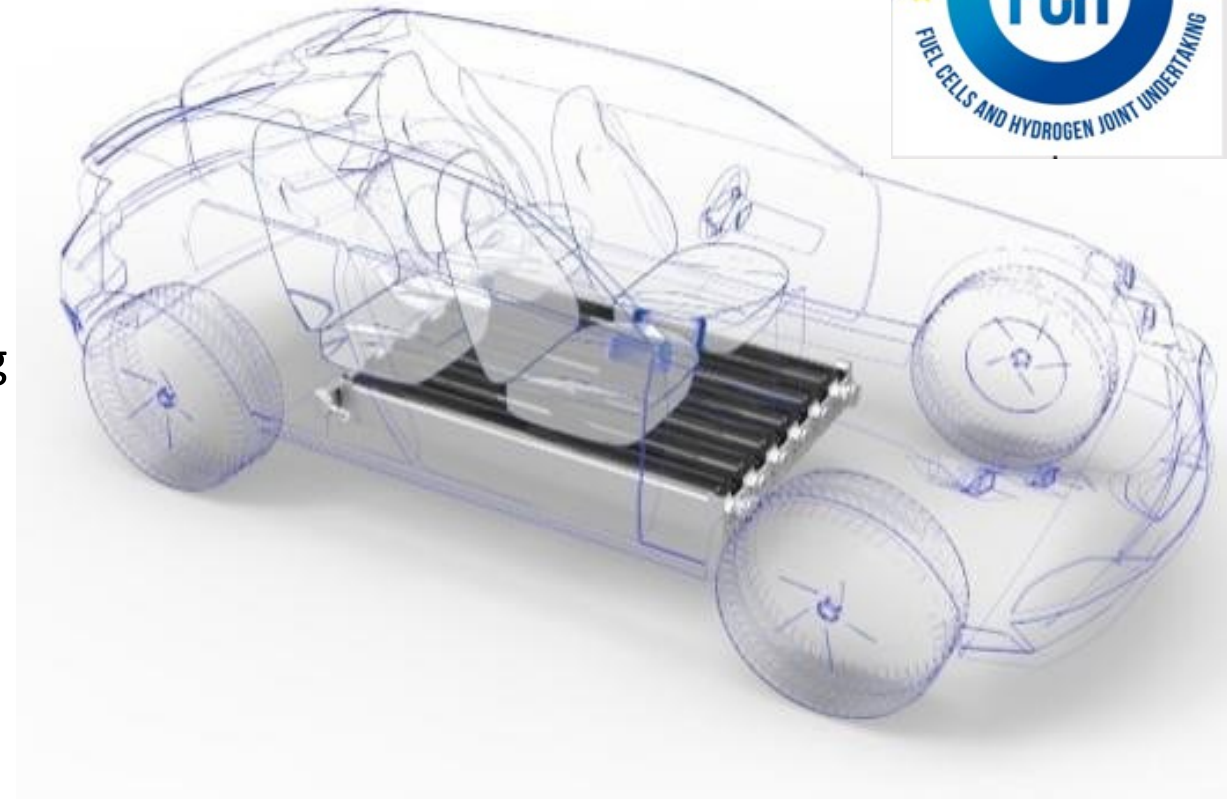
STORAGE OF HYDROGEN: ALTERNATIVE PRESSURE ENCLOSURE DEVELOPMENT





# Overall Project Objectives

- Objective 1: innovative hydrogen 70 MPa storage(full-size demonstrator),targeting 5,9kg H<sub>2</sub>, in an initial size 1800x1300x140 , including 12 tubular vessels.
- Objective 2: Technical, safety and performance validation at vessel, modular system and full-size demonstrator tank system level.
- Objective 3: Economic assessment for industrial mass manufacturing targeting a cost of less than 400€ per kg of hydrogen
- Objective 4: Contribution to safety and type-approval harmonized standards for conformable hydrogen vessels.

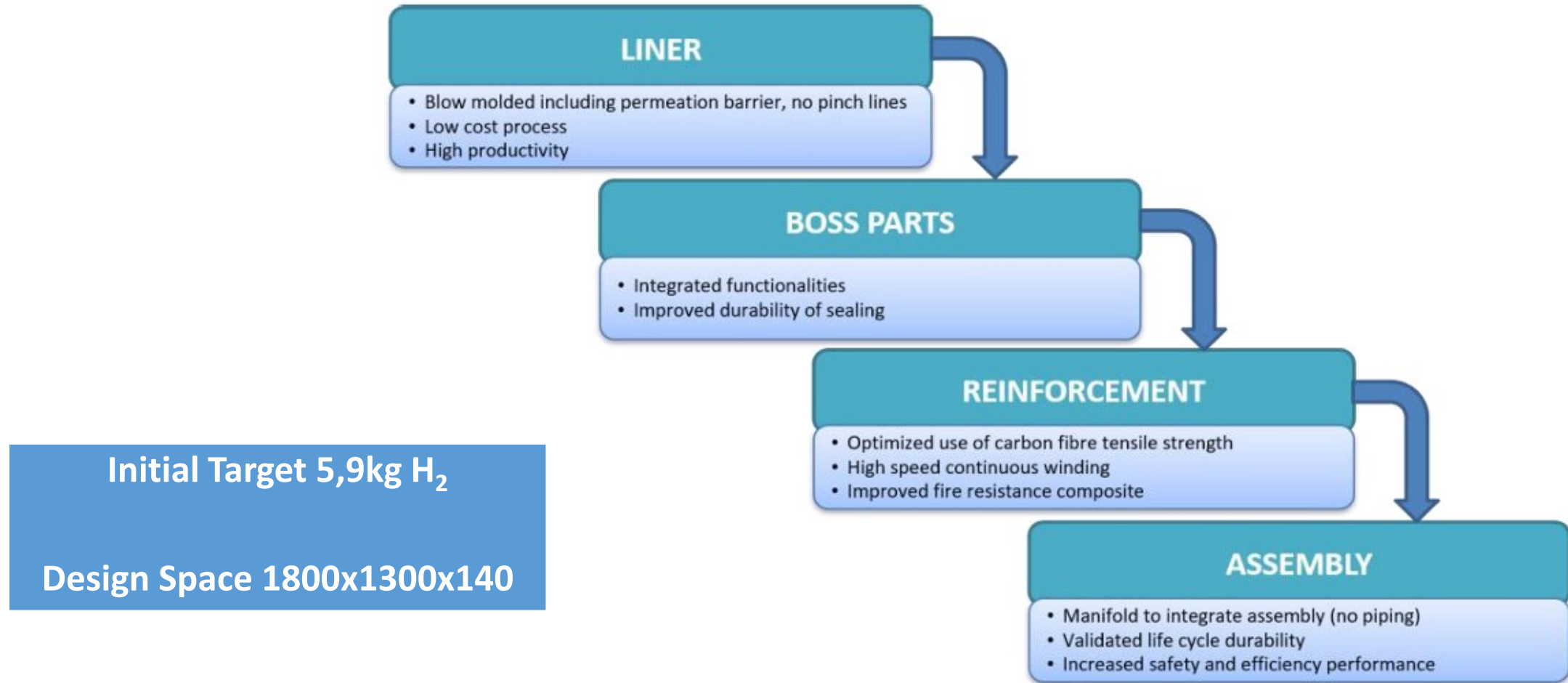


- **SH<sub>2</sub>APED is a FCHJU / H2020 funded project : Total grant: 1 993 550 EUR**

# Project Partners



# Objective 1 – Design innovative HSS



# Objective 2 – Safety and Performance

- Design innovative  $\mu$ LNB (TPRD-less) tank prototypes at NWP (nominal working pressure) 70 MPa that doesn't explode in a fire
- Develop engineering solutions that allow faster fueling of  $\mu$ LNB vessel with a PA (Polyamide) liner
- Advance in the understanding of the manufacturing technology of a tank and its assembly
- Create and validate models allowing better understanding and predictive simulation of temperature dynamics inside novel pressure vessels during hydrogen refueling / defueling / blowdown

# Objective 3 – Economical assessment

- Cost optimized : -20% respect to the state-of-the-art at the start of the project
- Efficient, conformable and highly integrated storage system, minimizing BoM, OPEX and CAPEX
- Which can potentially produce in series of over 100,000 units per year
- Meeting the technical and economical expectations of the automotive industry

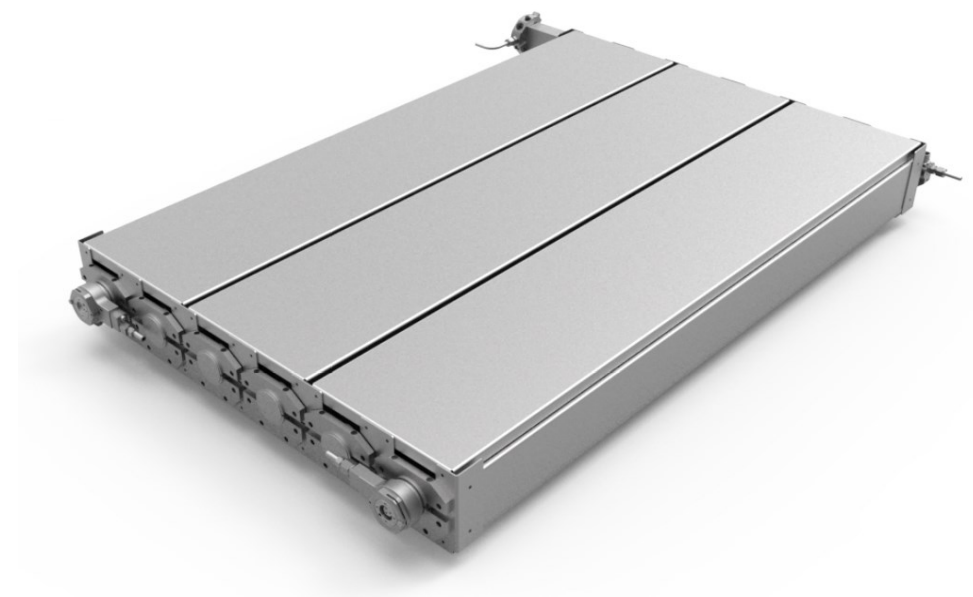


# Objective 4 – Contribution to Standards

- Active participation and contribution of partners in activities of different Regulations.
- Support and facilitate completion of the GTR13 Phase 2
- Improved harmonization of requirements in regulations not only in the traditional markets of the European Union, Japan and US, but also in emerging economies such as China, Korea, India, and Brazil.
- Produce whitepapers for standardization guidance
- Establish detailed test protocols to ensure global uniformity of qualification test results for storage systems

# Challenges

| SAFETY     | Fire Behavior<br>Hydrogen leakage<br>Hydrogen permeation level |
|------------|----------------------------------------------------------------|
| TECHNOLOGY | Long and thin vessels<br>Manifold<br>Design & manufacturing    |
| WEIGHT     | Vessel and System weight ratio                                 |
| COST       | Multiplication of components                                   |
| REGULATION | System validation GT13 V2 and R134 update                      |



# List of Technical KPI

| OBJECTIVES                                                                             | UNIT                                            | KPI                                                    |                                                   |
|----------------------------------------------------------------------------------------|-------------------------------------------------|--------------------------------------------------------|---------------------------------------------------|
|                                                                                        |                                                 | SoA Type IV vessel                                     | SH2APED vessel                                    |
| H2 storage volume for estimated design space (1800x1300x140 mm) (ref. Hiphone project) | %                                               | 41                                                     | > 45                                              |
| Reduction of carbon fibre use                                                          | kg carbon fibre / kg stored H2                  | 10.8                                                   | < 8                                               |
| Reduction of winding time (ref. Hiphone project)                                       | min / kg stored H2                              | 36                                                     | 18                                                |
| Permeation barrier (R134)                                                              | cm <sup>3</sup> /h/l at 55 °C                   | 46                                                     | < 46                                              |
| Development of explosion-free in a fire TPRD-less $\mu$ LNB tank                       | NA                                              | Protection by TPRD                                     | No blast wave, fireball, projectiles, long flames |
| Increased mechanical robustness (at system level) (R134 and EC79/2009)                 | NA                                              | To be compliant to current regulations                 | Compliant to regulations                          |
| Improved durability of sealing                                                         | Number of refuelling cycles                     | To be compliant to current regulations                 | Compliant to regulations                          |
| Assembly without piping                                                                | Number of connection elements                   | Possible leakages points at connections and interfaces | 1/3 less compare to a standard Type IV tank       |
| Low cost process for liner                                                             | CAPEX based on 100.000 liner/year manufacturing | 3M€ (10 rotomoulding machines + 10 moulds)             | 1M€ (1 blowmoulding machine including mould)      |

# List of Technical KPI

| OBJECTIVES                           | UNIT                            | KPI                                                                                                                                                               |                                                                                                                                                                         |
|--------------------------------------|---------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                      |                                 | SoA Type IV vessel                                                                                                                                                | SH2APED vessel                                                                                                                                                          |
| Volumetric efficiency                | kg H <sub>2</sub> / l           | 0.03                                                                                                                                                              | > 0.033                                                                                                                                                                 |
| Gravimetric efficiency               | %                               | 5.3                                                                                                                                                               | > 5.7                                                                                                                                                                   |
| Cost for tank system                 | € / kg of stored H <sub>2</sub> | 500                                                                                                                                                               | < 400                                                                                                                                                                   |
| Fire safety (R134)                   | NA                              | R134: No rupture at engulfing fire. Release not through TPRD that results in a flame greater than 0.5 m beyond the perimeter of the applied flame shall not occur | Compliant with R134, provides no rupture at both localised and engulfing portions of the fire test. Release through the wall could have harmless invisible micro-flames |
| Burst pressure (R134)                | MPa                             | 157.5                                                                                                                                                             | > 157.5                                                                                                                                                                 |
| Hydraulic pressure cycle test (R134) | NA                              | No leakage before 11,000 cycles and no burst before 22,000 cycles at 87.5 MPa                                                                                     | Compliant to R134                                                                                                                                                       |

# List of Technical KPI

| OBJECTIVES                                                                                                | UNIT       | KPI                                                       |                                                                             |
|-----------------------------------------------------------------------------------------------------------|------------|-----------------------------------------------------------|-----------------------------------------------------------------------------|
|                                                                                                           |            | SoA Type IV vessel                                        | SH2APED vessel                                                              |
| TPRD-less tank that don't explode in any fire                                                             | NA         | Validated for tank system volume of 7.5 l                 | To be achieved for tank system volumes of 147 l (5.9 kg of H <sub>2</sub> ) |
| Faster fuelling of tank with PA                                                                           | Flow (g/s) | Up to 120 g/s (SAE J2601)                                 | > 120 g/s                                                                   |
| Predictive numerical model                                                                                | NA         | Physical model of hydrogen storage tank thermal behaviour | Model development and validation for the chosen system concept              |
| Understanding of temperature changes of hydrogen and vessel for new geometries during fuelling/defuelling | NA         | Temperature hotspots expected in elongated vessel         | Engineering solutions to eliminate hotspots                                 |
| Certification procedures                                                                                  | NA         | Current R134 and EC79/2009                                | Update on the current regulations                                           |

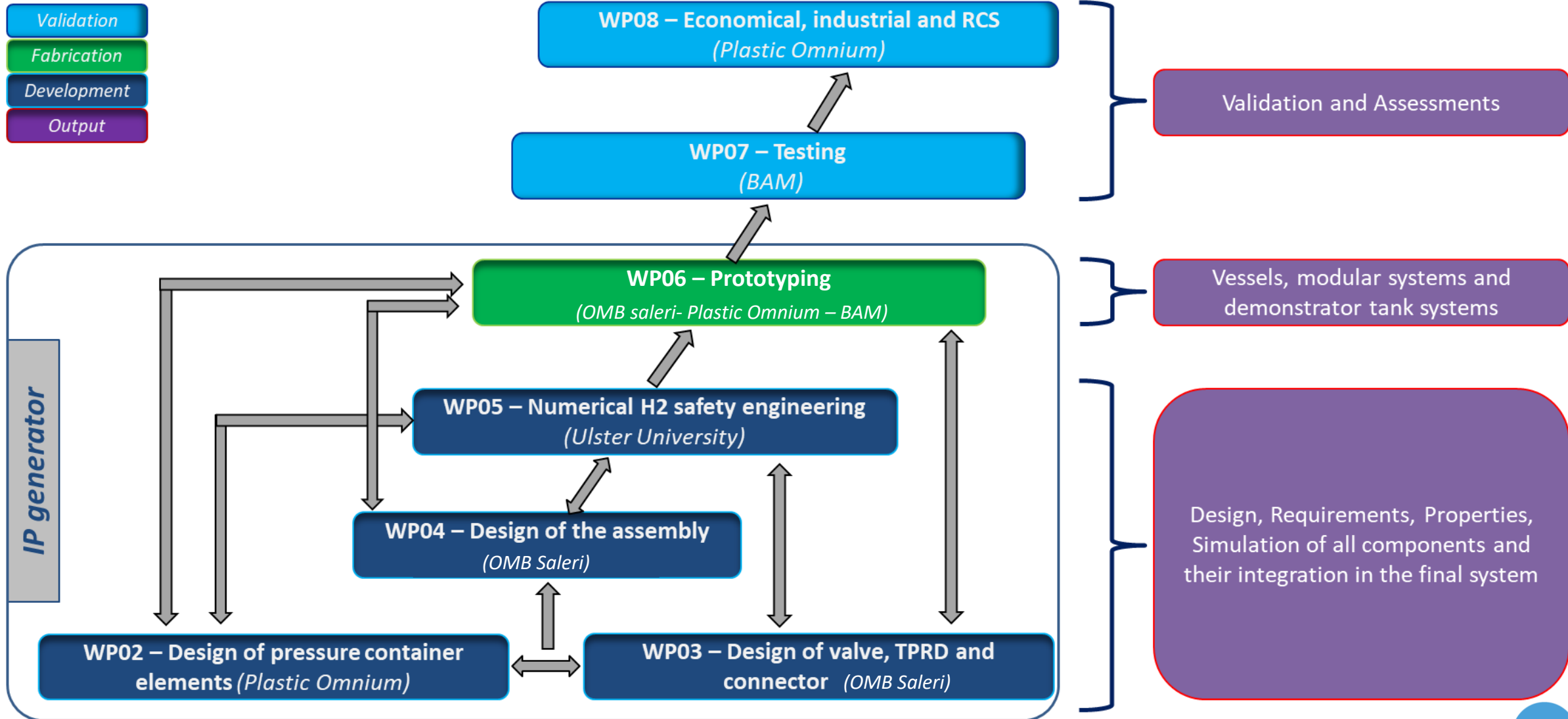
# Impact 1 → BC, 3 slides

|                                                                               | Specific impact of the FCH-01-1-2020 call                                                                                                                                                                                                                                                                 |
|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Impact 1:</b> Performance and safety of the hydrogen 70 MPa tank system    | <p>“Prototypes designed for storing hydrogen gas at a nominal working pressure of 70 MPa”</p> <p>“Better understanding for temperature changes inside the pressure vessels with new geometries due to hydrogen fuelling and defuelling”</p> <p>“Understanding of manufacturing hurdles and solutions”</p> |
| <b>Impact 2:</b> Integration of the hydrogen 70 MPa tank in electric vehicles | <p>“Developing an understanding for main requirements in future design space”</p> <p>“Demonstration that future fuel cell electric vehicles can share vehicle architectures with battery electric vehicles”</p>                                                                                           |
| <b>Impact 3:</b> Strengthen European hydrogen value chain for mobility        | <p>“Necessary steps for certification and standardization of investigated pressure vessel geometries should be shown (especially critical tests like drop and impact test)”</p>                                                                                                                           |



# Process and tasks attribution

Validation of the vehicle implementation with Advisory Board



## (b) List of work packages

| Work Package No | Work Package Title                                                                         | Lead Participant No | Lead Participant Short Name | Person-Months | Start Month | End Month |
|-----------------|--------------------------------------------------------------------------------------------|---------------------|-----------------------------|---------------|-------------|-----------|
| WP1             | Project management                                                                         | 1                   | PO                          | 8             | 1           | 36        |
| WP2             | Design of pressure containment elements                                                    | 1                   | PO                          | 38            | 4           | 24        |
| WP3             | Design of valve, TPRD and connectors                                                       | 2                   | MIS                         | 37,5          | 3           | 23        |
| WP4             | Design of the assembly                                                                     | 2                   | MIS                         | 35            | 1           | 36        |
| WP5             | Hydrogen safety engineering: modelling reaction to fire and thermal behavior of prototypes | 4                   | UU                          | 32            | 1           | 36        |
| WP6             | Different components and systems prototyping                                               | 1                   | PO                          | 31            | 7           | 36        |
| WP7             | Testing                                                                                    | 3                   | BAM                         | 33            | 12          | 36        |
| WP8             | Economical, industrial and RCS consideration                                               | 1                   | PO                          | 14            | 1           | 36        |
| WP9             | Dissemination and Exploitation activities                                                  | 1                   | PO                          | 4,5           | 1           | 36        |
|                 |                                                                                            |                     |                             | 233           |             |           |

# Timeline of the project

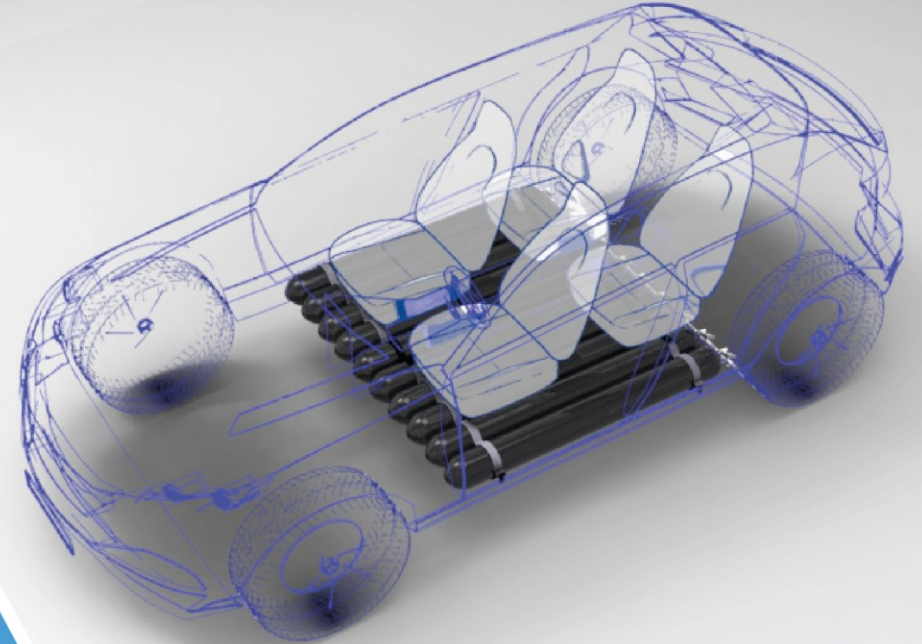
- Initial timeline:
  - Start : Jan 2021
  - End : Dec 2023
  
- Amendment for a 9-month extension has been agreed
  - End date September 30<sup>th</sup> 2024.



This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.

# Design and manufacturing of liner, boss, composite

STAKEHOLDER's Workshop Brussel  
September 26<sup>th</sup> and 27<sup>th</sup>, 2024



# Vessel design - phases

Liner / boss design

Liner Manufacturing

Reinforcement DEV

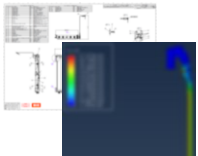
Proto Sample build

PO internal vessel  
validation

**3D design  
2D drawing**

**Simulation**  
- Blow molding  
- Mechanical  
(Burst, Cycling)

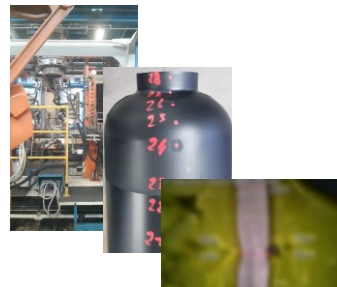
**Winding Pattern  
Optimization in  
Composicad™**



**Liner blow molding  
(PA6)**

Quality checks

**Liner Machining**



**Iterative winding trial**

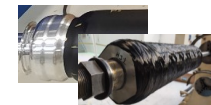
**Basic testing**  
(burst & cycling)

**Optimization  
Of Composite**



**Boss-liner assembly**

**Vessel winding &  
vessel proof testing**



**Burst**

**Ambient Temp.  
Pressure Cycling**





# Vessel Design – Composicad™

Import DXF and STL files



.mdr file

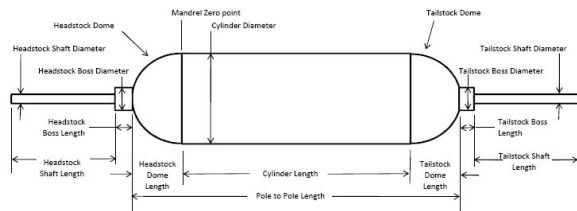
Examples:

File: Composicad Contour  
MM  
NumberRadial = 100  
-87.88 25.4 50  
0 127 50 HeadTurn  
25.4 127 50 TailTurn  
113.28 25.4

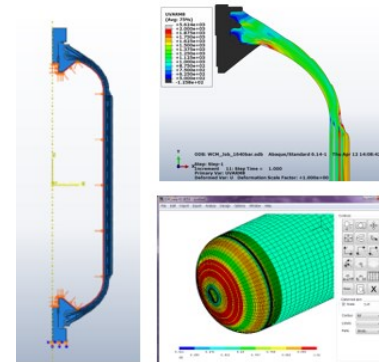
This line is a linear interpolated segment with 50 segments  
A linear interpolated segment and the start of the Tailstock turning zone



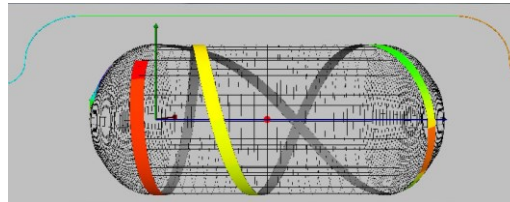
Note the use of the HeadTurn and TailTurn keywords to indicate the headstock and tailstock turning zones.



Export FEA Data



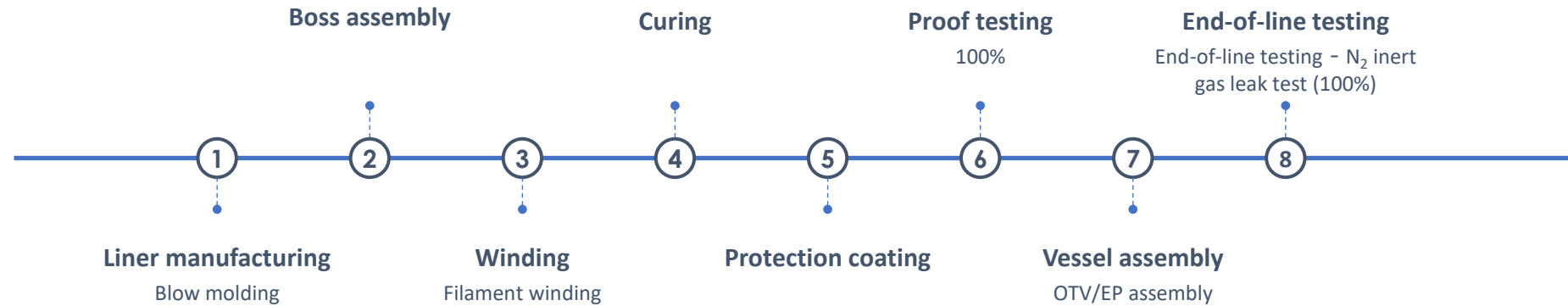
Path Data Output



Machine Data Input/ output  
for all winding machines



# Overview vessel manufacturing process



Blow molding



Winding



Curing



Vessel assembly & EoL testing

# Hydrogen tubular vessel design

## Tubular vessels characteristics

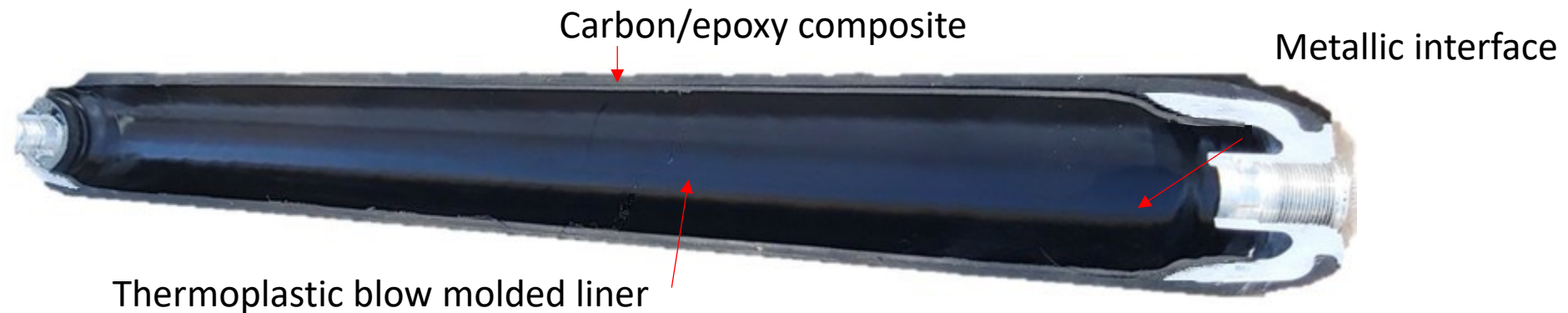
Size : 1280 \* 140 mm  
Liner : Blow molding technology  
Composite : Carbon Epoxy  
Interface : compliant with standard 70MPa OTV  
2 Versions : with TPRD and LeakNoBurst (μLNB)

## Challenges

Liner permeation due to the high ratio surface/volume  
Stress transfer from composite to metallic interface with very thin composite.

## Vessel targeted performances

Working Pressure : 70MPa  
Referential : R134



# Liner design – material choice

|                                                                          | PA6 grade A | PA6 grade B | HDPE grade A |
|--------------------------------------------------------------------------|-------------|-------------|--------------|
| Density [kg/m <sup>3</sup> ]                                             | 1070        | 1060        | 939,5        |
| Melting T [°C]                                                           | 219         | 280         | 111          |
| Permeation 15°C<br>[cm <sup>3</sup> .mm / m <sup>2</sup> .day.bar]       | 40          | 70          | 170          |
| Permeation 55°C<br>[cm <sup>3</sup> .mm / m <sup>2</sup> .day.bar]       | 120         | 270         | 650          |
| Standard vessel (L/D=2,4)<br>permeation level R134<br>[NmL/h]            | 741 (OK)    | 1657 (OK)   | 3619 (NOK)   |
| SH <sub>2</sub> APED vessel(L/D=9,4)<br>permeation level R134<br>[NmL/h] | 451 (OK)    | 973 (NOK)   | 2151 (NOK)   |

A HDPE liner would enhance the melting during a fire exposure  
However, only the PA6 liner material allows to pass the permeability requirement

# Liner Manufacturing – Blow-molding

Blow molding is a core competency from PLASTIC OMNIUM  
Market leader for plastic fuel tank (blow-molded)  
20 millions of plastic fuel tanks produced in 2019 in 40 plants

Blow molding equipment available in PLASTIC OMNIUM development center  
to support blow molded liner proto development.



## **PLASTIC OMNIUM's Experience with Polyamide Blow-molding:**

- Good overall thickness distribution
- Good pinch quality
- Able to mold PA parts up to 2m of length

BM machine



## Target Design Pressure

Design → 1750bar \_\_\_\_\_  
SF 2.25 → 1575bar \_\_\_\_\_  
  
MAWP = 875bar \_\_\_\_\_  
NWP = 700bar \_\_\_\_\_  
  
0bar \_\_\_\_\_

## Laminate buildup

- Mainly based on the 54,7° angle
- Adding some additional axial reinforcement
- Target to burst in the cylindrical section of the pressure vessel
- High Strength CF (4 x 24K)

## Laminate Simulation

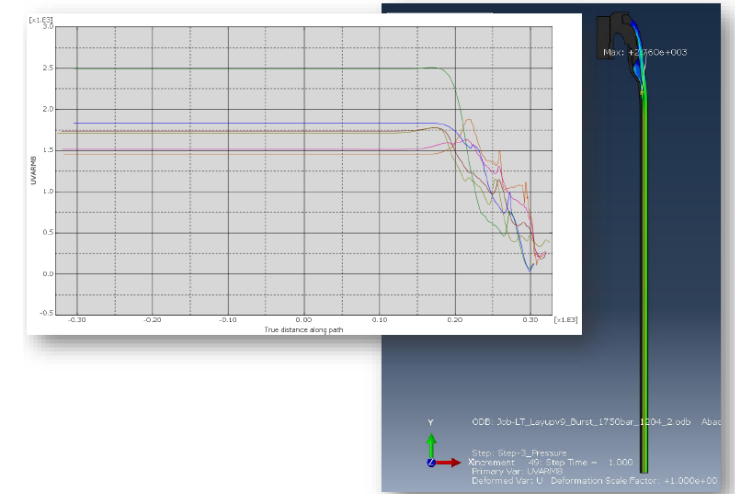
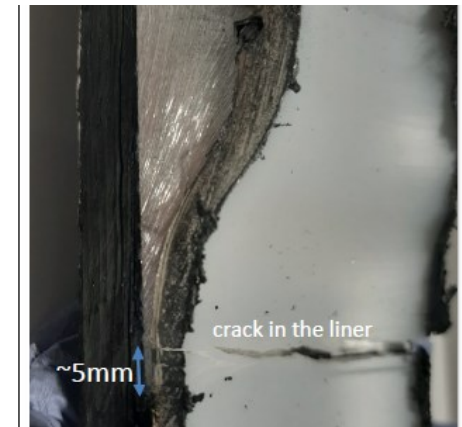
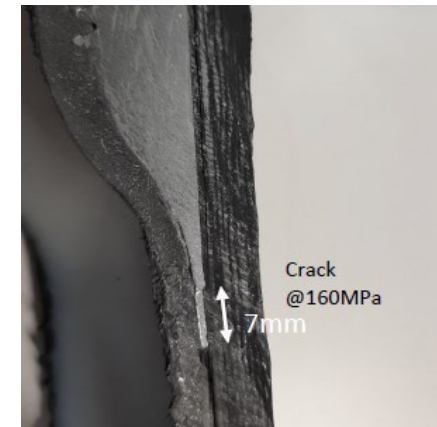
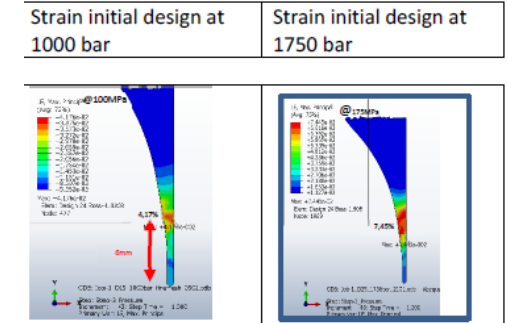
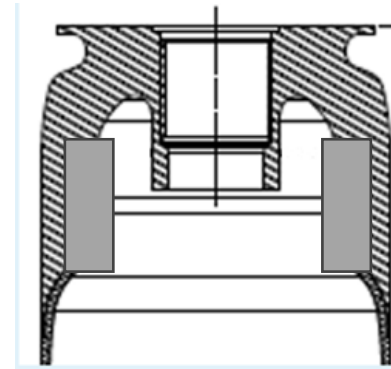


Figure 6: Stresses in fibre direction



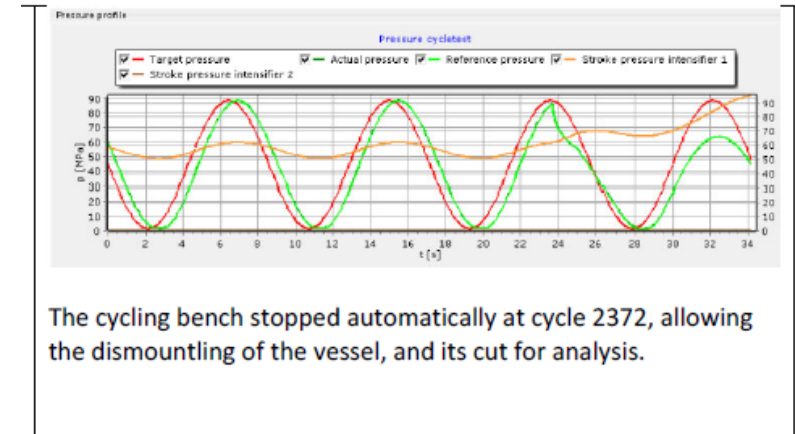
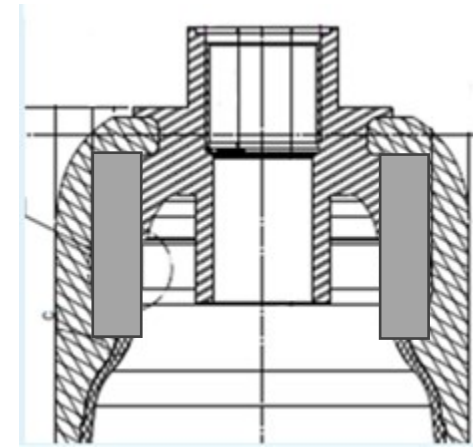
# Boss – liner interface design loop 1

- Targeted burst pressure generating important strain in tip of the boss
- Leading to premature liner break in burst tests
  - No Pressure cycling performed
- Several small design iterations done, but unable to reduce level of strain, therefore major change of boss-liner interface were needed



# Boss – liner interface design loop 2

- Design OK for burst >1700bar
- Ambient temperature cycling 20bar-875 bar with target of 22k cycles has been started, but failed after 2371 cycles
- Several small design iterations done, but unable to reduce level of strain, therefore major change of boss-liner interface needed



# Boss – liner interface design loop 3

- Major change on boss-liner interface design
- Still OK for burst (>1700 bar)
- Finally passing 22k cycles of ambient temperature pressure cycling
- Design frozen based on this liner-boss design
- Internal Volume = 10.9L
- Vessel Weight = 10.3kg
- Gravimetric Efficiency (vessel) = 4,25%



Burst test result - Burst design target : 170MPa



Part 012 700 088 : Burst result 172,3 MPa

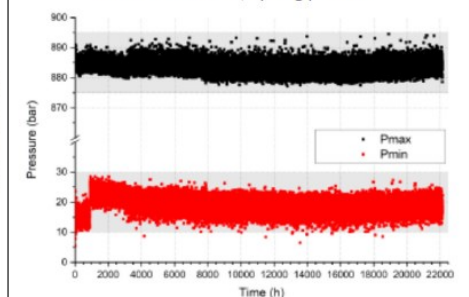
Ambiant cycling test result - target : 22000cycles

Ambiant cycling test result –  
# of cycles recording – max and min pressures

Part 012 700 100 after cycling test



Part 012 700 100 ; cycling pressure



# Overview test results final vessel at Plastic Omnium

## Plastic Omnium internal vessel validation results for standard vessel

### ✓ Burst test

| Vessel - final | Test  | Result (internal target: >1700bar) |
|----------------|-------|------------------------------------|
| Vessel         | Burst | Okay 1730 bar                      |
| Vessel         | Burst | Okay 1750 bar                      |
| Vessel         | Burst | Okay 1756 bar                      |

### ✓ Ambient cycling test

| Vessel – final | Test            | Result             |
|----------------|-----------------|--------------------|
| Vessel         | Ambient Cycling | Okay 22.000 cycles |
| Vessel         | Ambient Cycling | Okay 22.000 cycles |
| Vessel         | Ambient Cycling | Okay 22.000 cycles |

## Plastic Omnium vessel production after design freeze

| Type               | Picture                                                                              | # of parts produced | Purpose                                                                                              |
|--------------------|--------------------------------------------------------------------------------------|---------------------|------------------------------------------------------------------------------------------------------|
| Standard           |   | 54                  | Internal vessel validation; Vessel, modular system & full system assembly at OMB & validation at BAM |
| Fiber Optic Sensor |                                                                                      | 6                   | D6.3 (burst) & D7.1 (cycling) at BAM with fiber optic sensors                                        |
| μLNB               |  | 19                  | internal vessel validation; Vessel, modular system & full system assembly at OMB & validation at BAM |



# Overview of (sub) system definitions

## SYSTEM Assemblies



Figure 3: Pics of the full-size system

Drop Testing at System Level (R134 Phase 2)  
Fire Testing on System level (R134 Phase 2)

## Modular Assemblies



Ambient Temp Pressure Cycling ATC  
(standard vessel)  
Second for Fire Test ( $\mu$ LNB vessel)

Contact : [bjorn.criel@opmobility.com](mailto:bjorn.criel@opmobility.com)



This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.

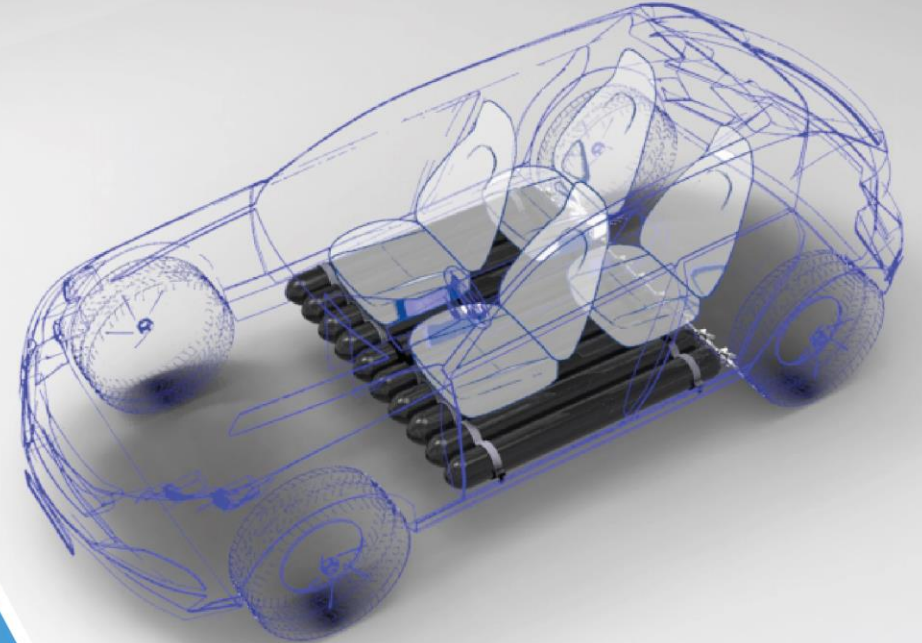


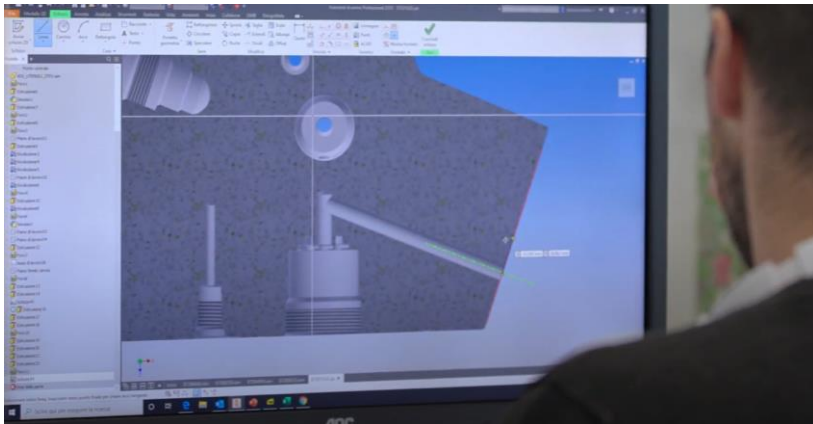
# Design and manufacturing of manifold, valve system and TPRD

Stakeholder's workshop, Brussels – 26/09/2024

OMB Saleri Spa SB

PM: Elisabetta Dal Gal





- Founded in 1980
- Since 2012 designing and manufacturing of H<sub>2</sub> components
- Facilities: R&D, Laboratory, Production, Quality and Cleanroom

<https://www.omb-saleri.it/>



# Our Tasks

- To provide the TPRD and End Plug valves
- To design and manufacture of the manifolds and test plan
- To design and manufacture of pipe systems
- To design of protective box
- To assembly and check the Tightness test

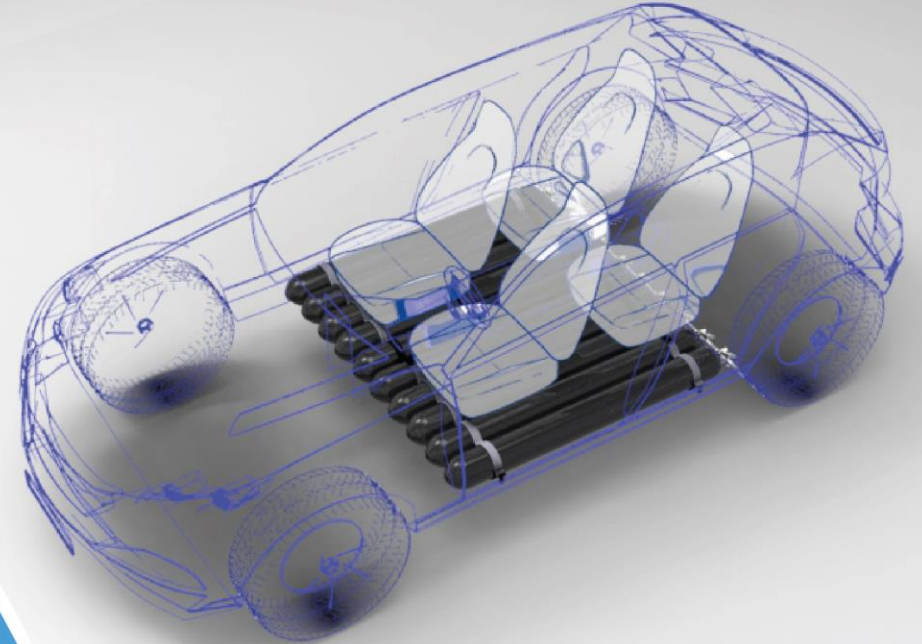




Storage of Hydrogen  
Alternative Pressure Enclosure Development



# The final system

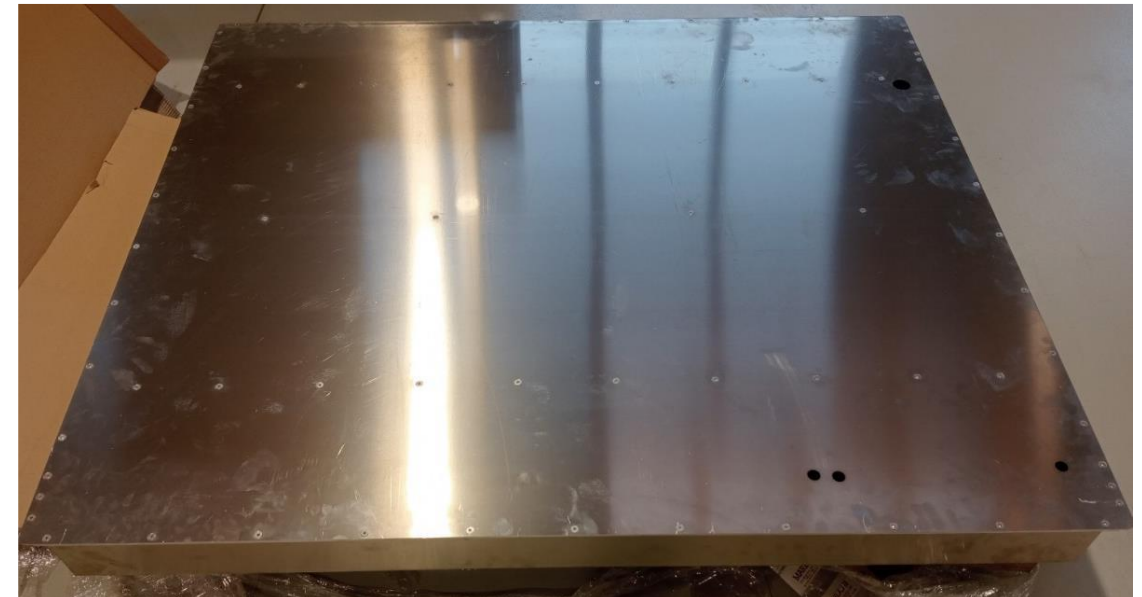


[www.sh2aped.eu](http://www.sh2aped.eu)



# Final system components

- The full-size system designed is a 9-tanks system
- The tanks used for these two are of IV type.
- 3 manifolds:
  - INLET for the filling
  - PASSIVE for guarantees the continuity of the H<sub>2</sub> flow
  - OUTLET for the defueling
- 1 ESV in the defueling (or outlet) manifold.
- 5 TPRDs: 2 on the top of the system and 3 on the bottom
- 2 main piping pathways:
  - the venting system (low pressure, to safely discharging the TPRDs)
  - the fuelling-defuelling system (high pressure)
- Protective box

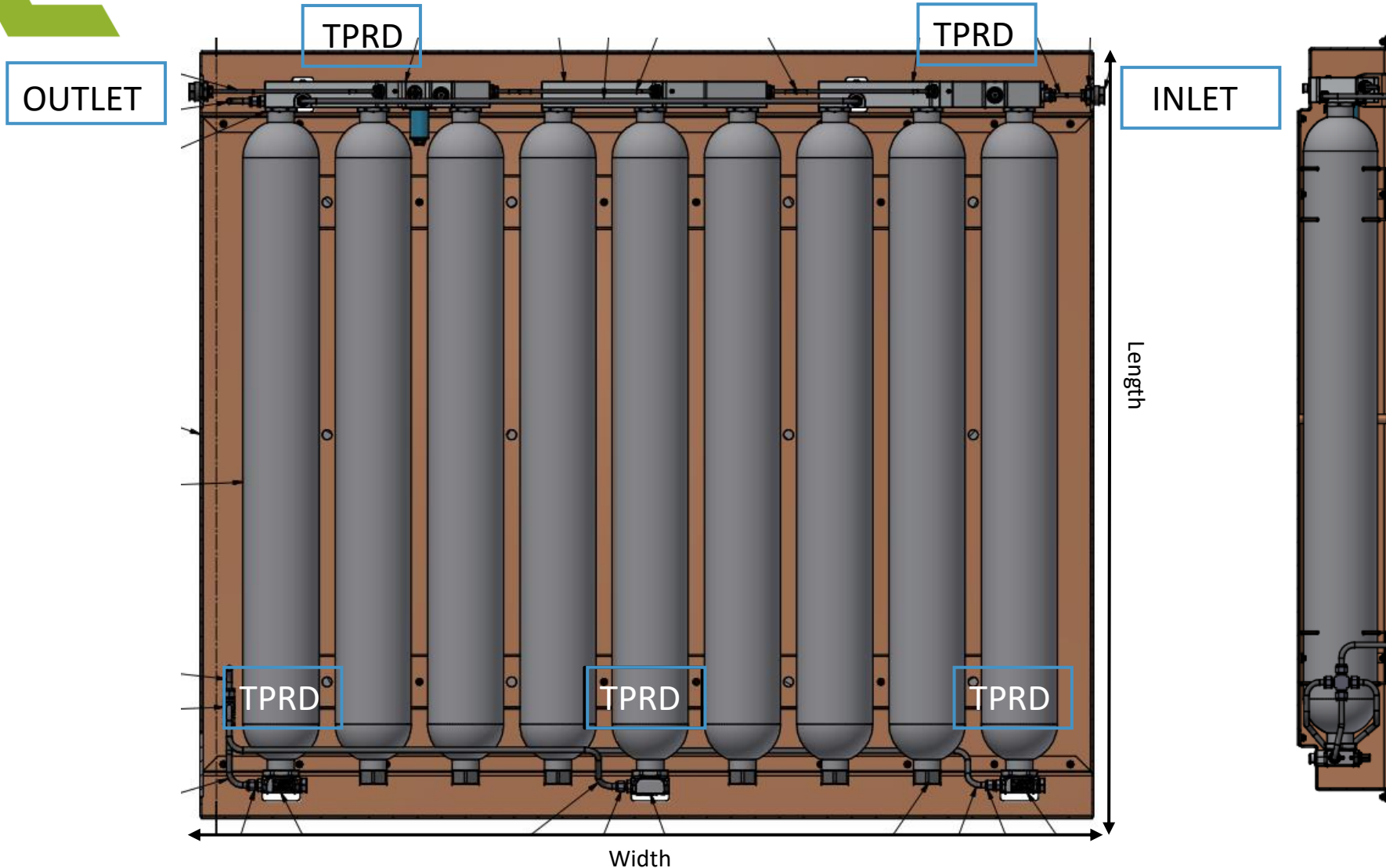


# Final system prototype





# Design of the Full-size system



## Prototype DIMENSIONS:

- Total weight of 174 kg
- L: 1560 mm
- W: 1690 mm
- H (height): 176 mm

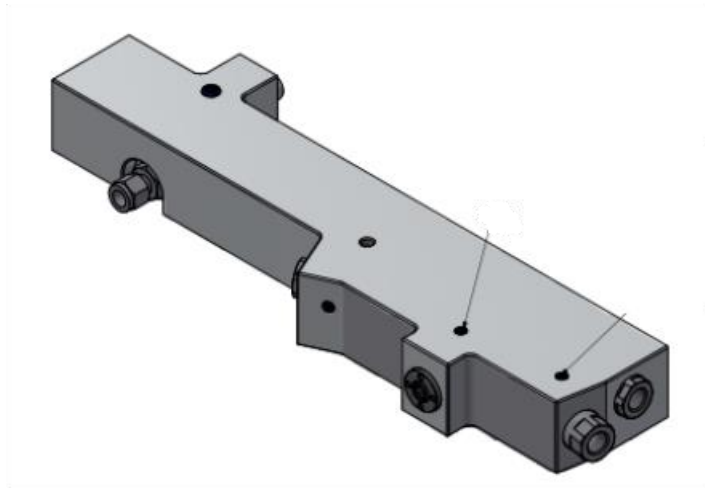
## Initial project Target:

- L: 1800 mm
- W: 1300 mm
- H: 140 mm

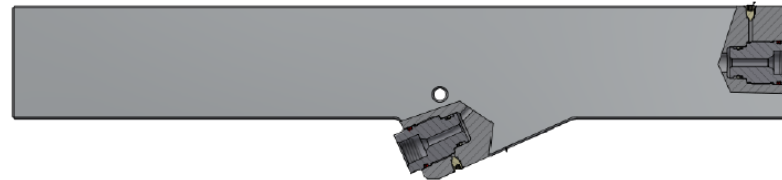
# Manifolds design

The solution:

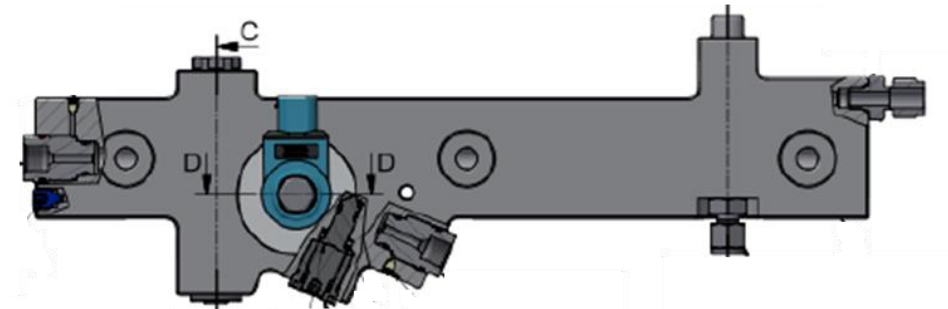
3 Manifolds instead of 9 on-tank valves  
Each manifold manages 3-tanks module



**INLET**

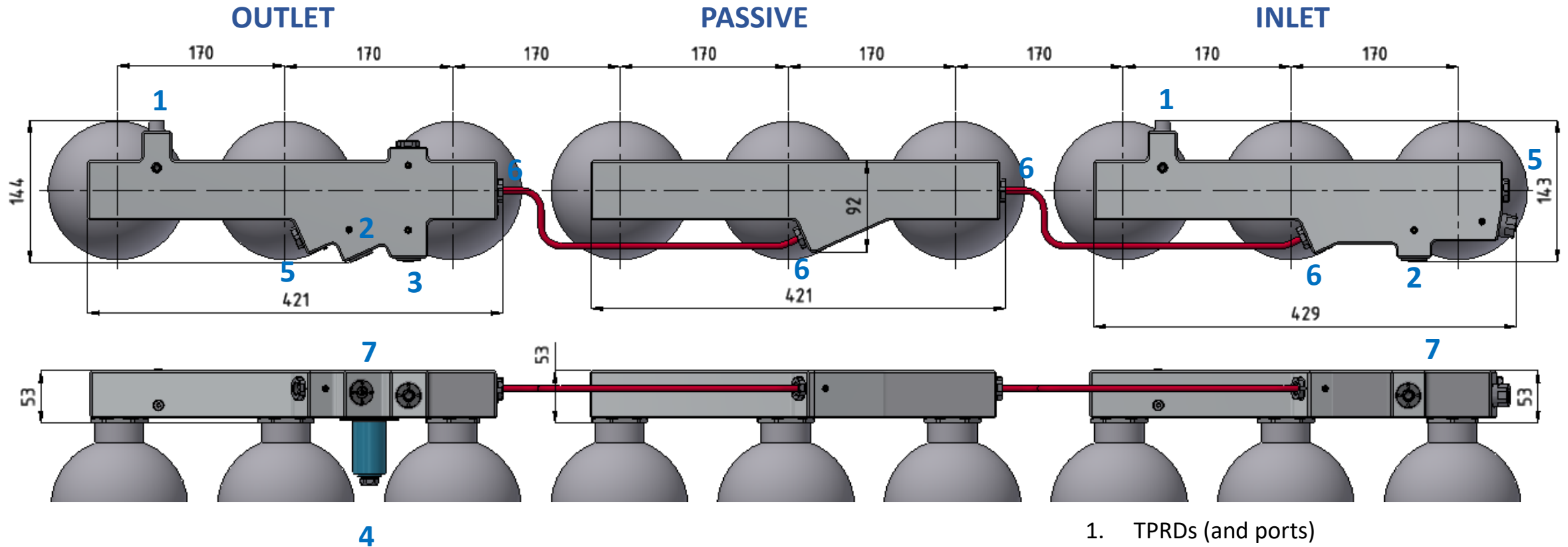


**PASSIVE**



**OUTLET**

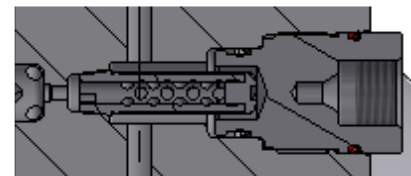
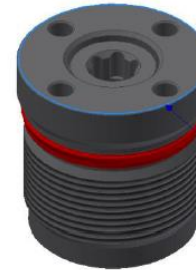
# Manifold final design



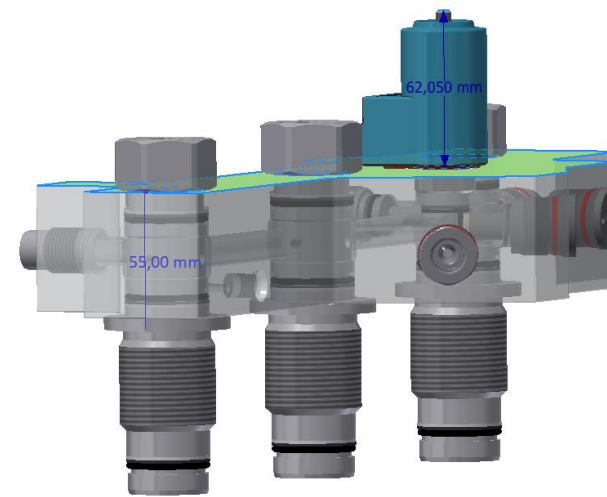
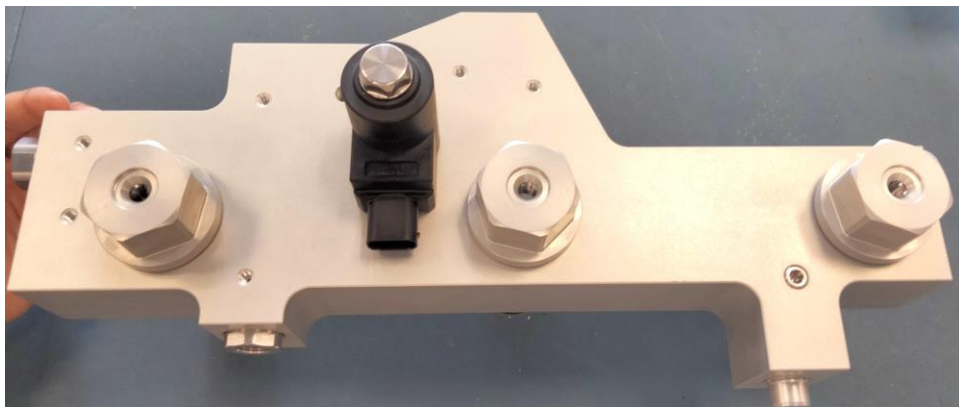
1. TPRDs (and ports)
2. Manual valve
3. Service Valve/ Bleed valve
4. SOV (Solenoid Valve)
5. Inlet/Outlet connections
6. Fittings
7. Filters

# Functionalities in the manifolds

- TPRDS (AND PORTS):  
activates in case of fire, driving the vessel emptying to avoid explosion
- MANUAL VALVE  
a safety component to close manually for maintenance or repair
- SERVICE VALVE/BLEED VALVE:  
a safety component to defuel in case of automatic defueling malfunctioning
- SOV (Solenoid Valve)/ESV:  
manages the H<sub>2</sub> flow from tanks to the system during automobile movement
- INLET/OUTLET CONNECTIONS AND FITTINGS:  
components that handle the H<sub>2</sub> flow
- FILTERS (x2): 10 µm filtration, in fueling and defueling sections



# Manifold design process – Modular system prototype

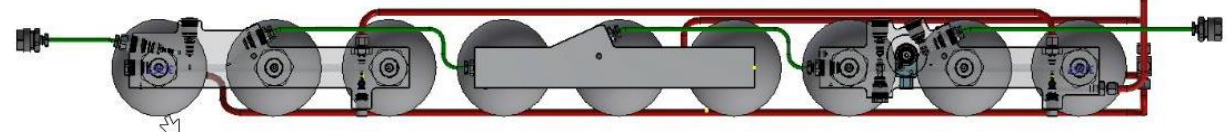
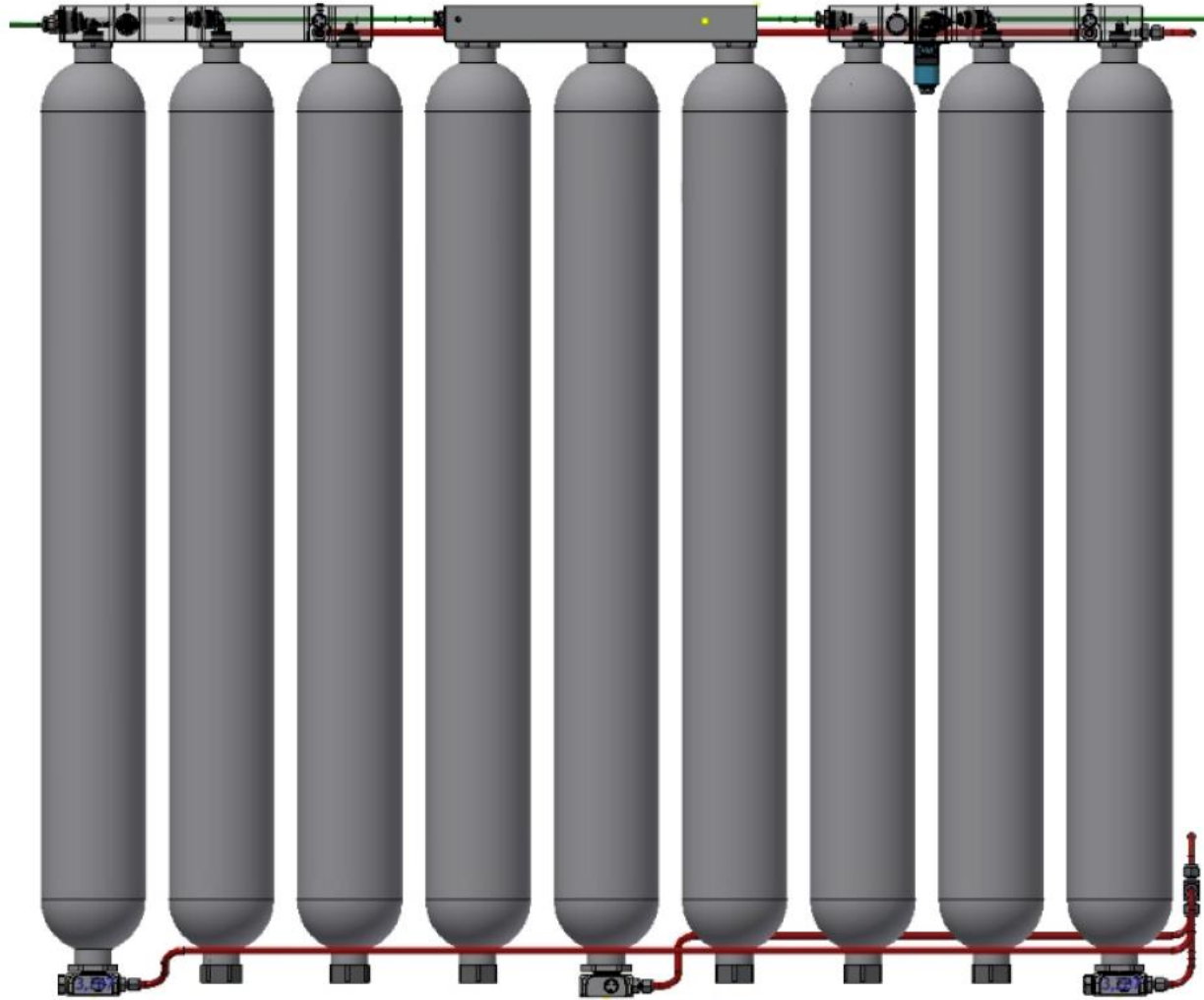


## IMPROVEMENTS IN FINAL DESIGN:

- Reduction in size
- Reduction in weight
- Reduction of tightness points
- Reduction in cost



# Piping system



- Green: fuelling and defuelling piping system -  
Working at high nominal pressure: 700 bar
- Red: venting system –  
Safely discharging the TPRDs, working at low pressure

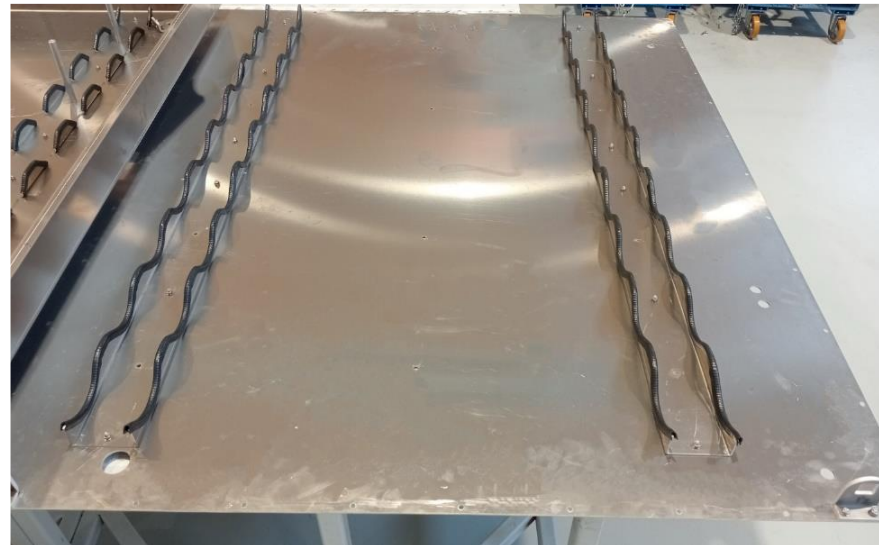
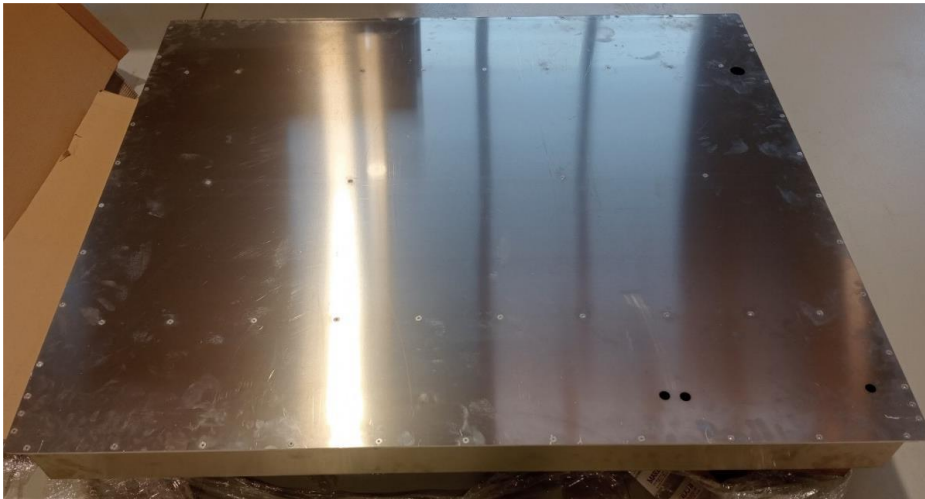


# Design of the protective frame

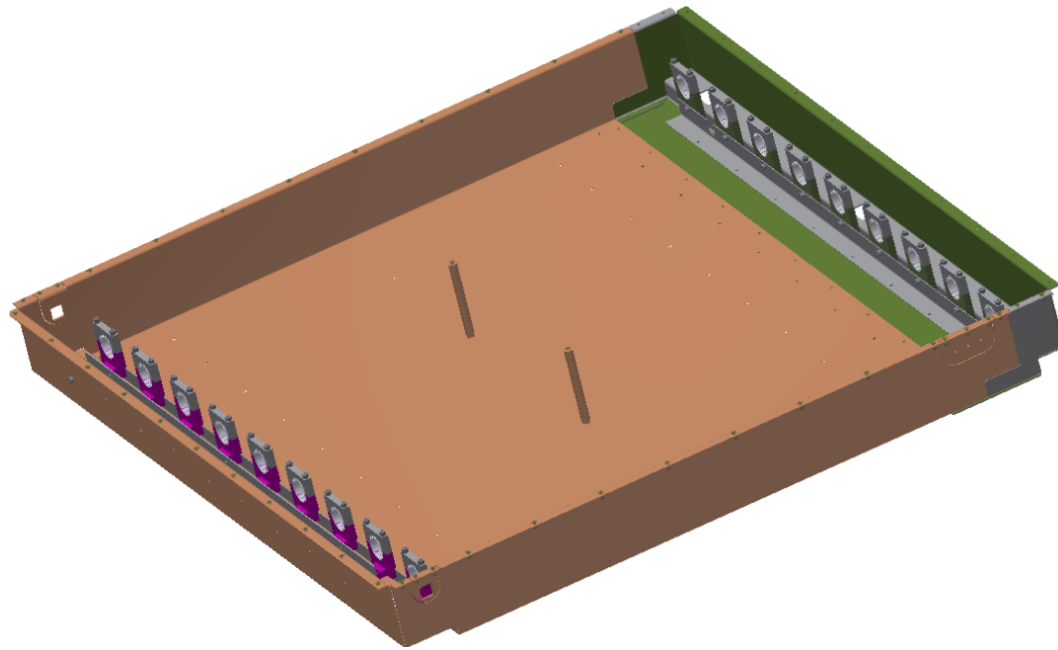


Prototype produced by cold working/bending of 3mm thick Al sheet:

- TPRDs are out of the box
- The box consists of a base and a lid closed by screws;
- Not contact between tanks and the box;
- Cradles for the tanks, to take them easily in place;
- Cradles covered in PVC to isolate and protect tanks;
- Box respects the elongation and expansion of the tanks



# Design of the protective frame



- A C-shaped metal component enables the fastening of each manifold to the box;
- Fastening the tanks on the manifold side, leaves tanks free to slide longitudinally during expansion.
- Metal plates to attach the tanks to the box and ease the assembly of the system;
- PTFE bushings ensure smooth sliding during elongation, protecting by possible scratches.



# Thank you for the attention



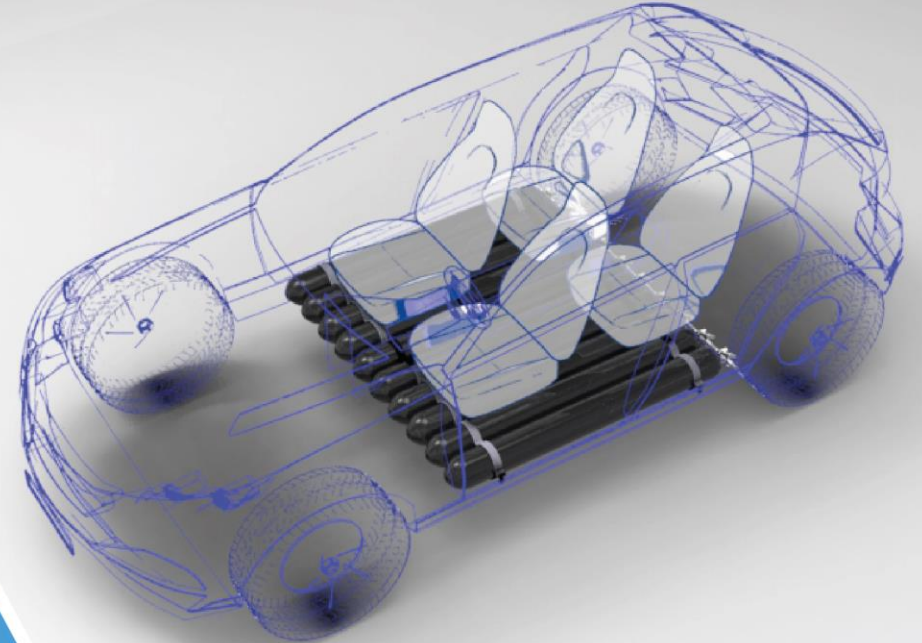
This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.

# TPRD design and expected performance

Stakeholder's workshop, Brussels – 26/09/2024

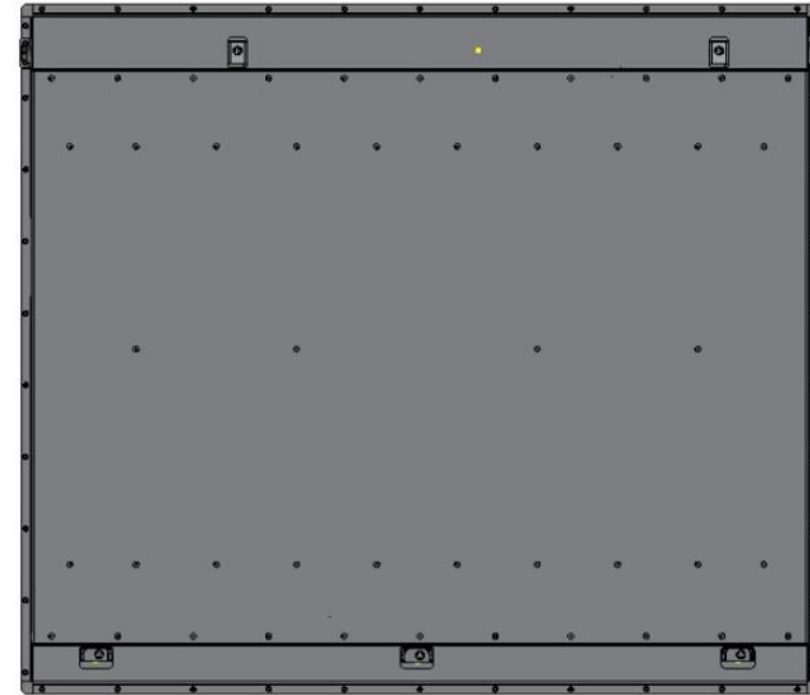
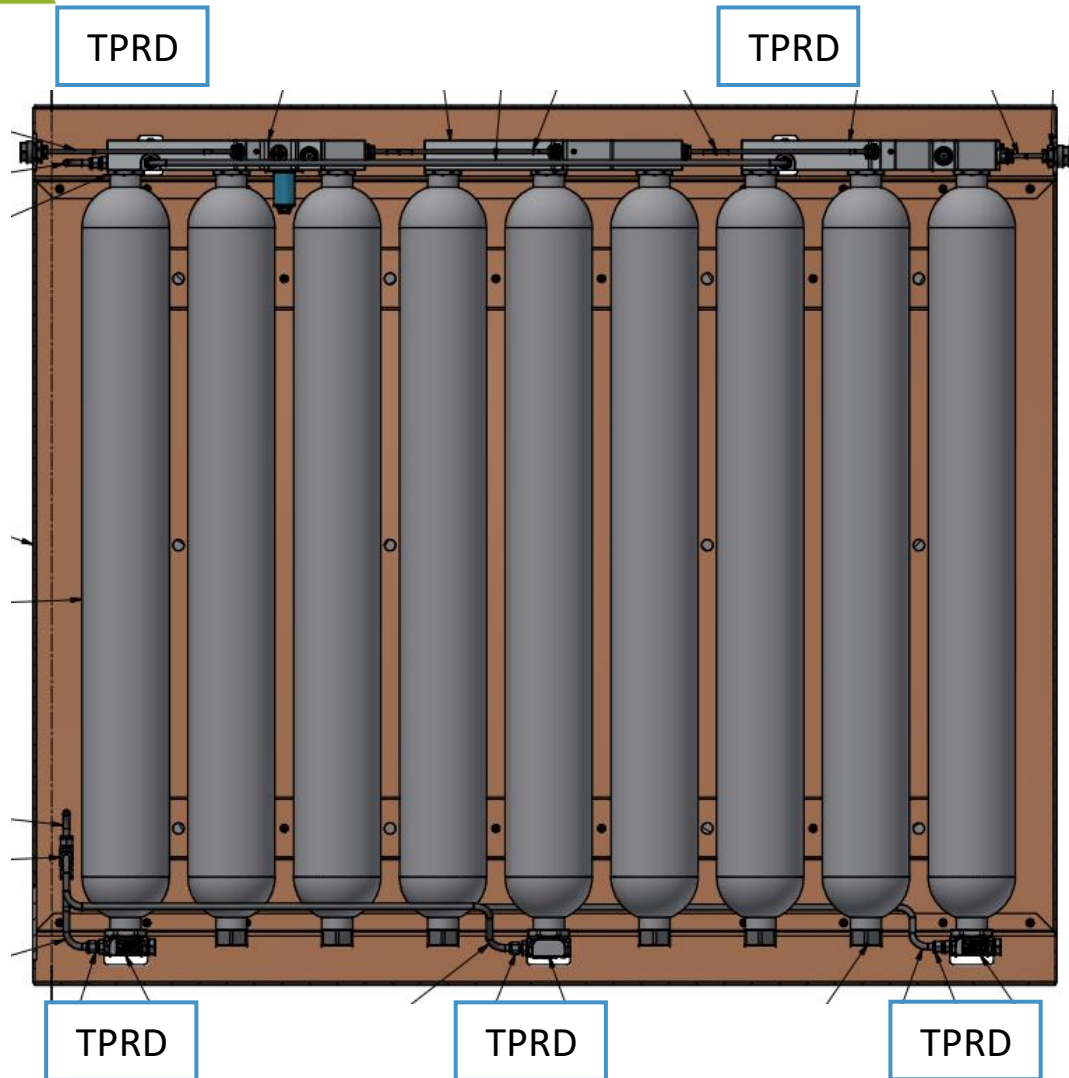
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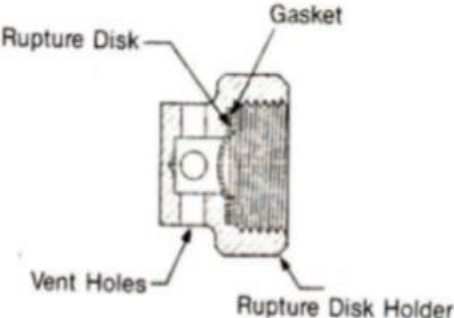
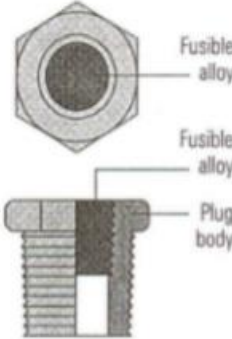
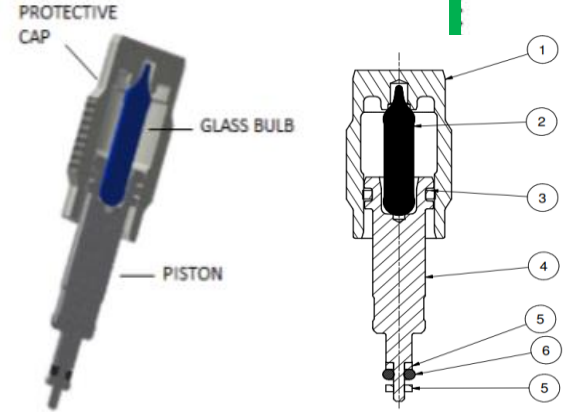
# Design of the system



End Plug  
without TPRD

End Plug  
with TPRD

## Thermal Pressure Relief Devices

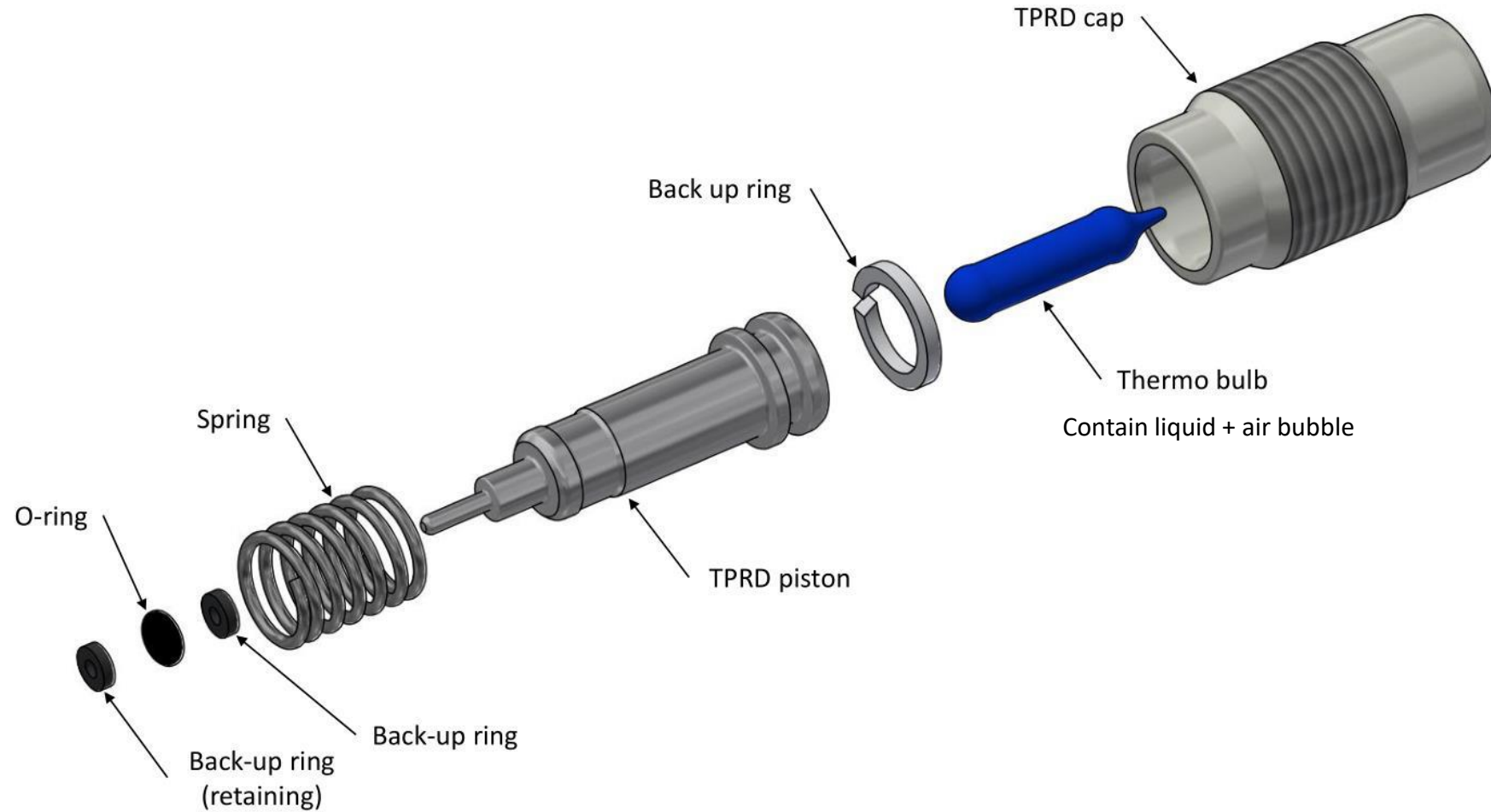
| TYPES             | RUPTURE DISK                                                                                                                                                                     | FUSIBLE METAL PRDs                                                                                                                          | GLASS BULB PRD                                                                                                                                                                                 |
|-------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| SCHEME            |  <p>Image credit: Handbook of Compressed Gases (1990).</p>                                      |  <p>Image credit: Malek (2006).</p>                      |                                                                                                             |
| WORKING PRINCIPLE | <ul style="list-style-type: none"><li>Activated by high pressure (burst of the rupture disk)</li><li>Potential drawbacks include shrapnel and sensitivity to corrosion</li></ul> | <ul style="list-style-type: none"><li>Thermal activated (melting of the fusible alloy)</li><li>Eutectic metal alloys are the fuse</li></ul> | <ul style="list-style-type: none"><li>Thermal activation: bulb contains liquid + air bubble. When the temperature increases the pressure inside the bulb grows till the glass burst.</li></ul> |

No due to the type of tanks

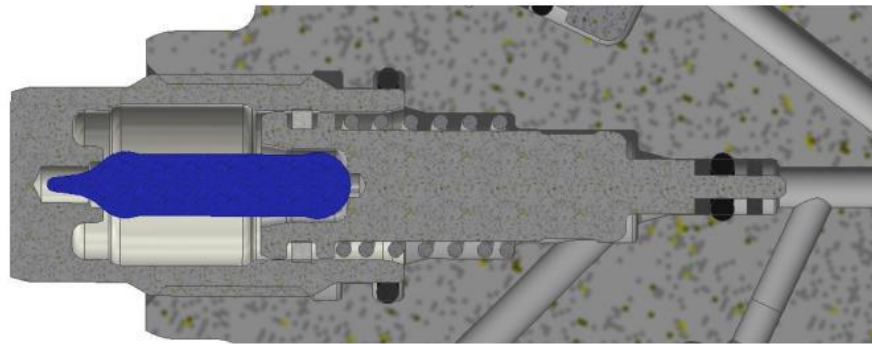
No due to the delay in activation

YES

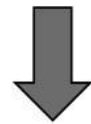
# Design of TPRDs



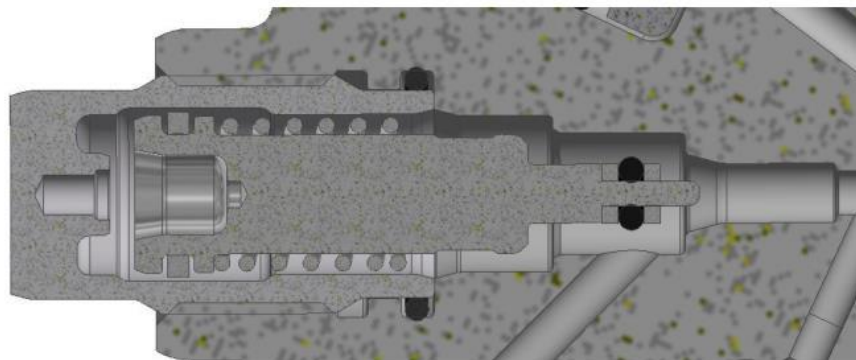
# Activation Strategy



CLOSED STATE



$T \geq 110 \pm 5 \text{ } ^\circ\text{C}$



ACTIVATED STATE

- 1) As the glass bulb heats up, the liquid inside expands, causing the air bubble to disappear.

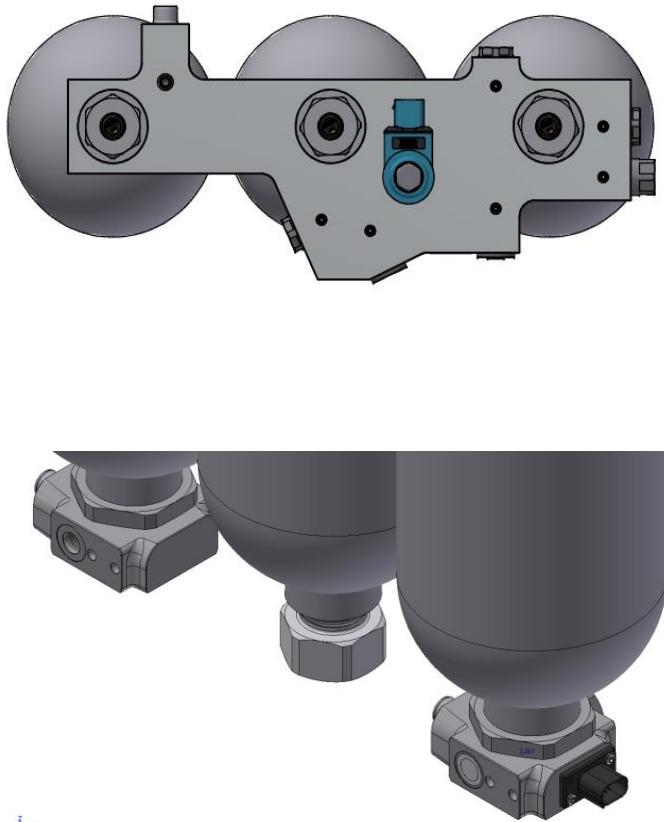
T increase → P increase → Bulb burst

- 2) The shattered glass triggers a spring-loaded piston, forcing open a gas release channel.

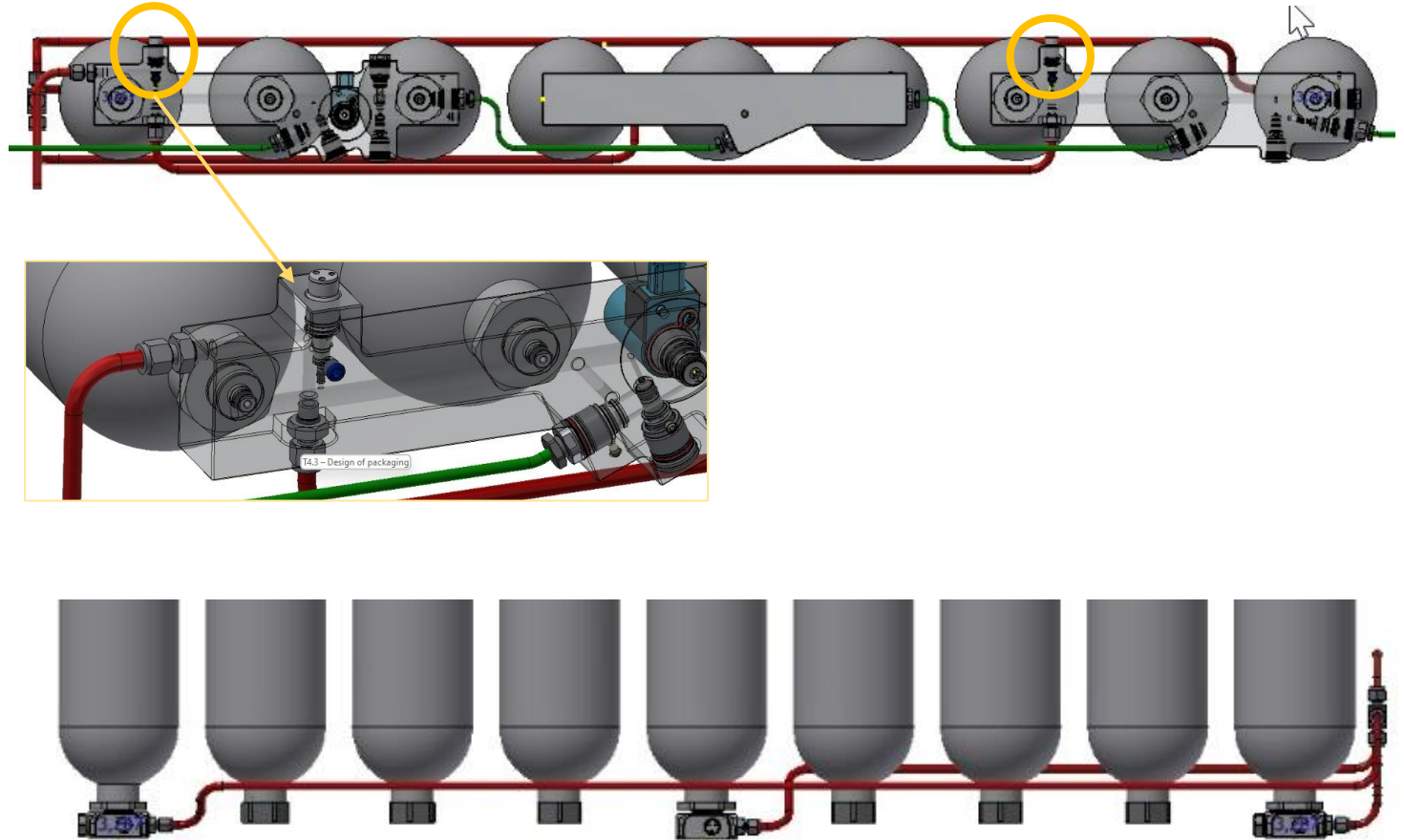
Piston pushed back → Gas release

# TPRDS and End Plugs (EP) localisation

MODULAR – SIZE SYSTEM



FINAL – SIZE SYSTEM



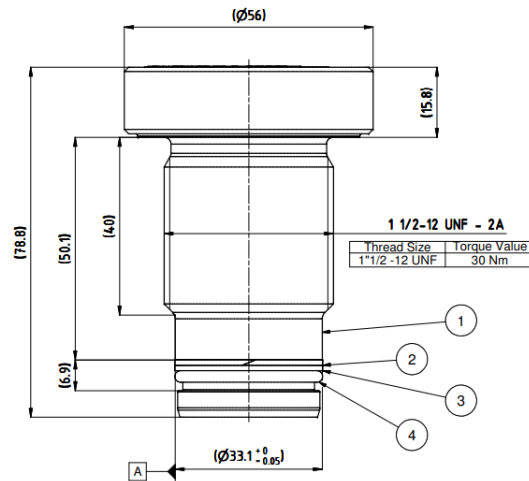


# End Plugs (EP) designs

## 1 - EP WITH TPRD

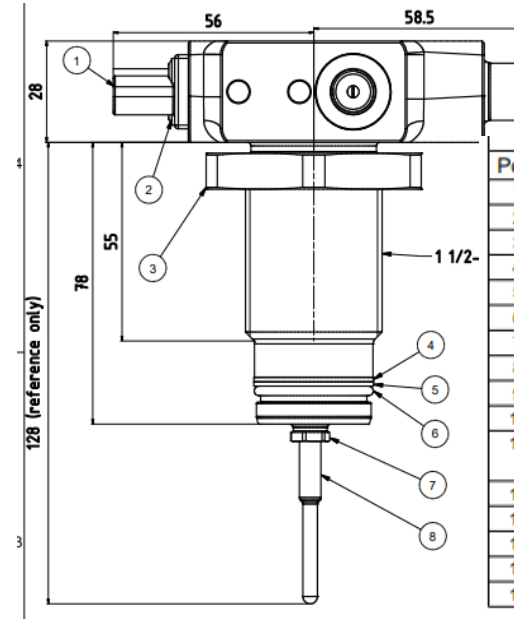


| POS. | DESCRIZIONE                             |
|------|-----------------------------------------|
| 1    | End Plug Body with TPRD- [1"1/2-12 UNF] |
| 2    | OR                                      |
| 3    | OTV TPRD Spring                         |
| 4    | TPRD PreAssembly                        |
| 5    | OR                                      |
| 6    | (BUR2) BOSS Back-up Ring w/ CUT (White) |
| 7    | (BUR1) BOSS Back-up Ring w/ CUT (Brown) |
| 8    | OR                                      |
| 9    | EP Adjustable Ring                      |
| 10   | Fixing NUT                              |
| 11   | Hexagon head Screw                      |
| 12   | LABEL                                   |



## 3 - END PLUG NO TPRD

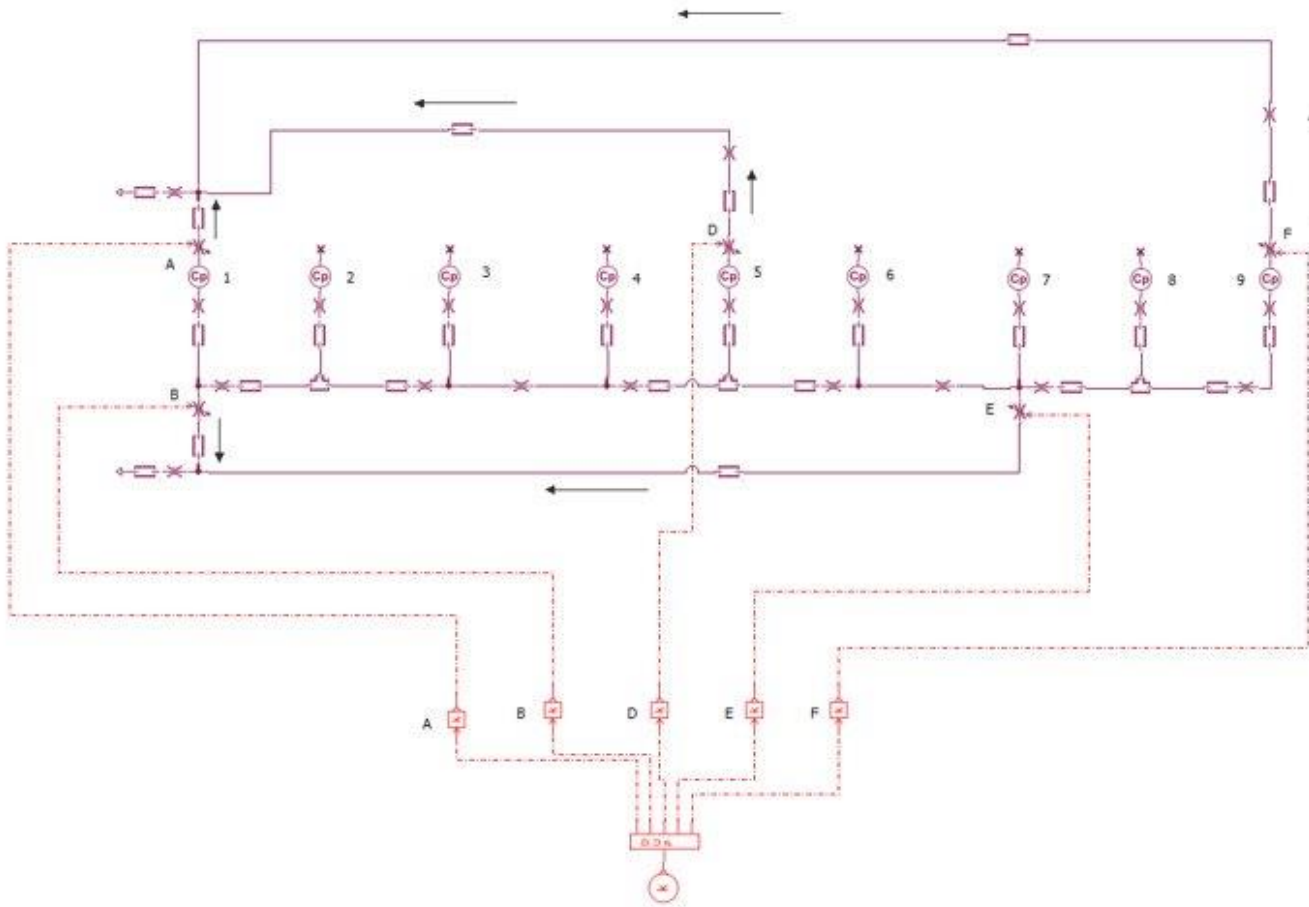
## 2 - EP WITH TPRD and T-SENSOR



| Pos. | Description                                                                   |
|------|-------------------------------------------------------------------------------|
| 1    | Tsensor connector                                                             |
| 2    | Screw M3x12 ISO 7380-2                                                        |
| 3    | 1 1/2 - 12 UNF NUT Anodized                                                   |
| 4    | (BUR2) BOSS Back-up Ring w/ CUT (White)                                       |
| 5    | (BUR1) BOSS Back-up Ring w/ CUT (Black)                                       |
| 6    | OR 28.00x2.62 (Tank Radial Sealing) NOK                                       |
| 7    | T-Sensor M11x1 NUT (1.4435) [Machining & Electropolishing]                    |
| 8    | Temperature Sensor EP full optional - BU&OR - Long                            |
| 9    | M14 x1 Plug                                                                   |
| 10   | Protection ring p-sensor [FCM]                                                |
| 11   | TPRD PreAssembly - BULB type - (Piston Seat Ø2 / Closed Cap / BU) NOK OR+ BUR |
| 12   | OTV TPRD Spring (Wire 1.2mm / 50N)                                            |
| 13   | OR 15.60x1.78                                                                 |
| 14   | FVMQ Ambient Gasket for HPR Second Stage Body Cup                             |
| 15   | EP full optional, 1-1/2-12 UNF                                                |
| 16   | Sphere 6mm                                                                    |

| POS. | DESCRIZIONE                                 |
|------|---------------------------------------------|
| 1    | ANODIZED Body - End Plug W/O TPRD - [1"1/2] |
| 2    | (BUR2) BOSS Back-up Ring w/ CUT (White)     |
| 3    | (BUR1) BOSS Back-up Ring w/ CUT (Brown)     |
| 4    | OR 28.00x2.62                               |
| 5    | Labels                                      |

H<sub>2</sub>



Simulation with Ansys software

- Medium: GH2
- Number of Tanks: 9
- Tank volume: 11,2 L
- Numbers of TPRDs: 5 (A, B, D, E, F)
- TPRDs A, D and F are on the bottom
- TPRDs B and E are in the manifolds

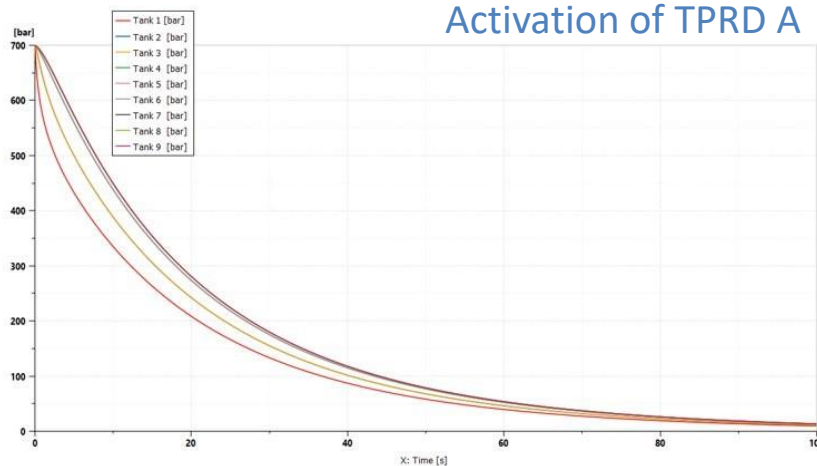
Operational method of discharging: One TPRD at the time

1° simulation: tanks at 700 barG

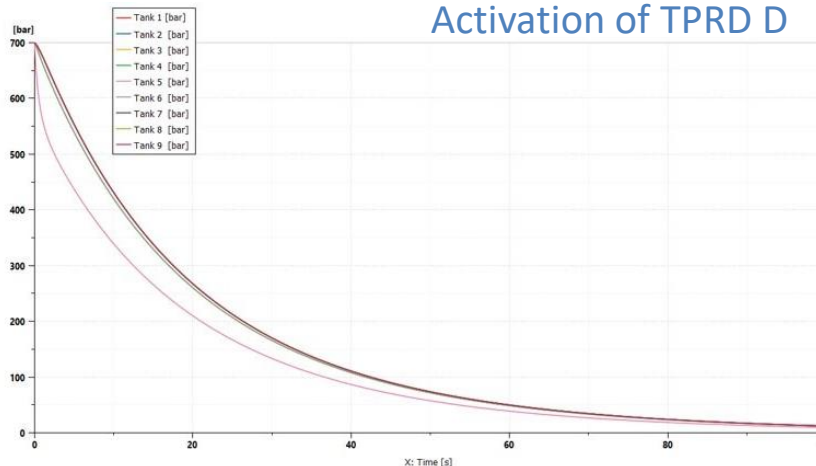
2° simulation: tanks at 20 barG

# Discharge at 700 barG

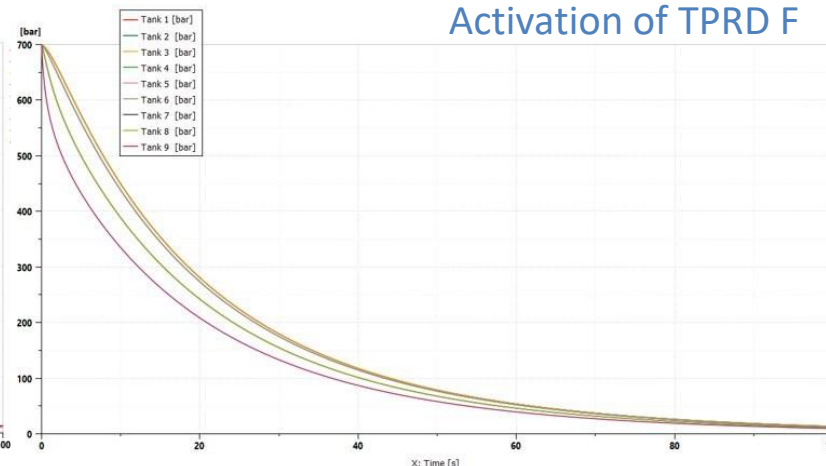
Activation of TPRD A



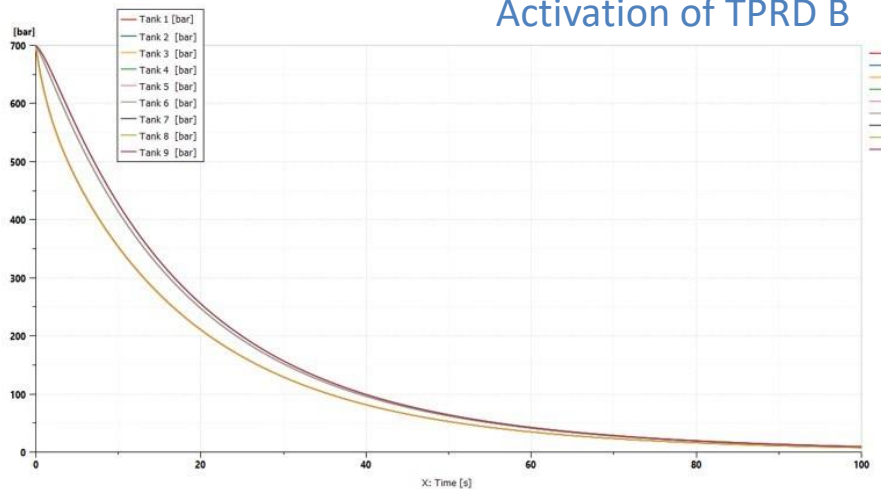
Activation of TPRD D



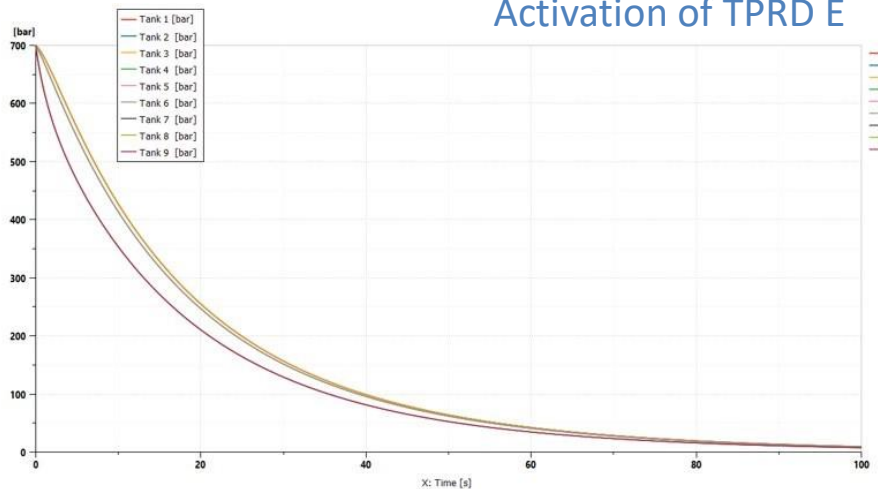
Activation of TPRD F



Activation of TPRD B



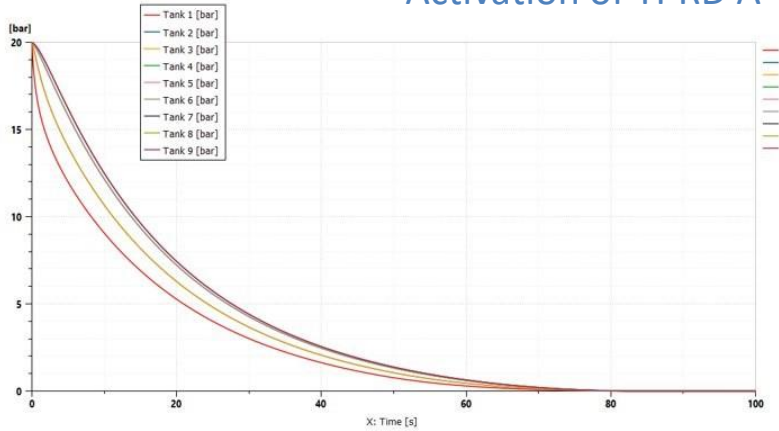
Activation of TPRD E



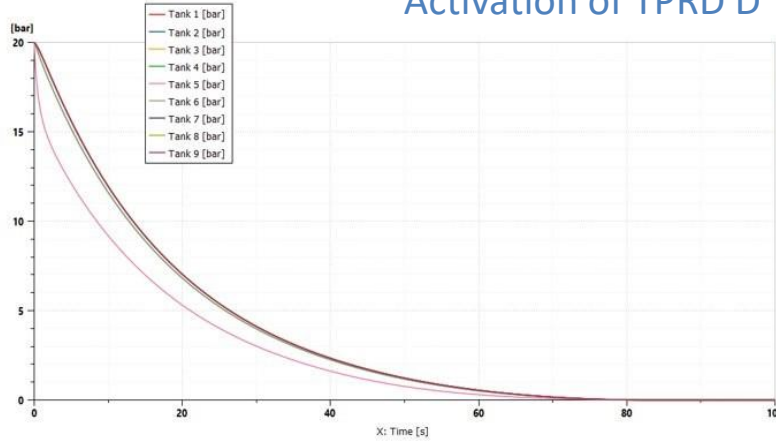
- No substantial differences are appreciated between the different tank discharging.
- The tanks are empty in less than 2 minutes.

# Discharge at 20 barG

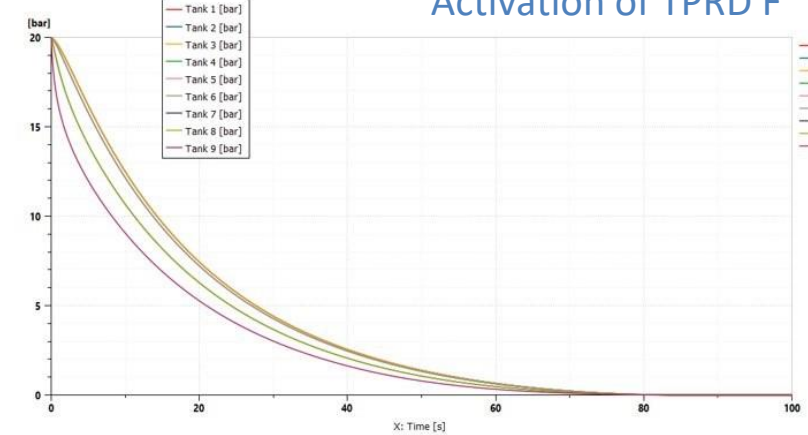
Activation of TPRD A



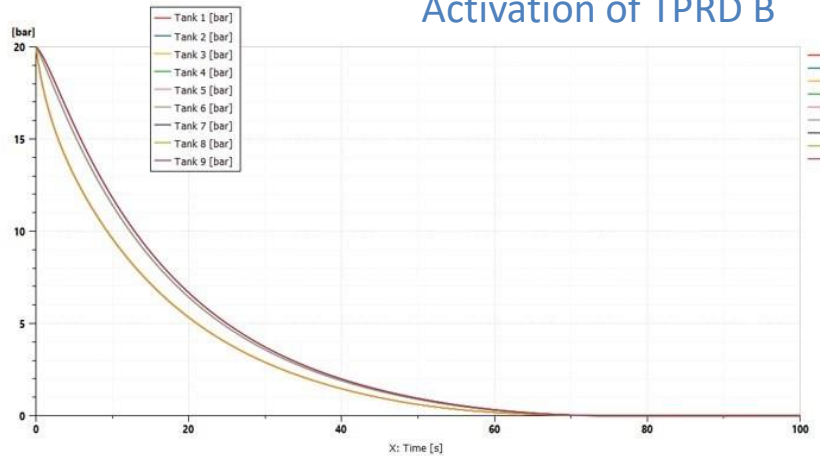
Activation of TPRD D



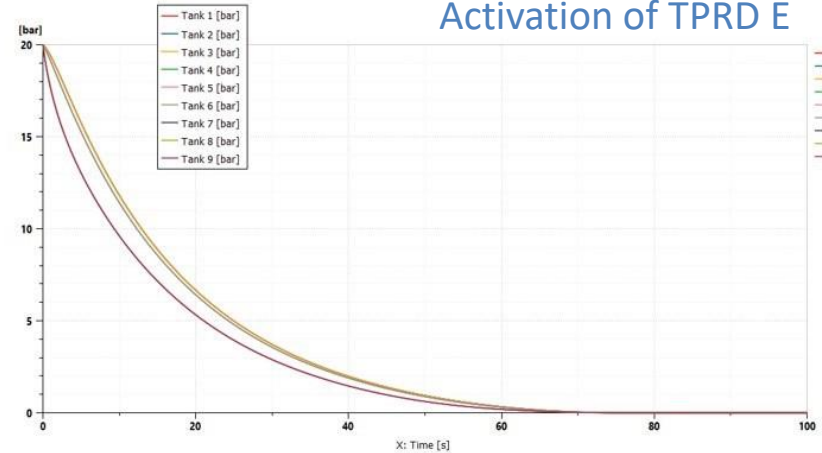
Activation of TPRD F



Activation of TPRD B



Activation of TPRD E



- No substantial differences are appreciated between the different tank discharging.
- The tanks are empty in less than 80 seconds

# Thank you for your attention

Elisabetta Dal Gal [OMB]

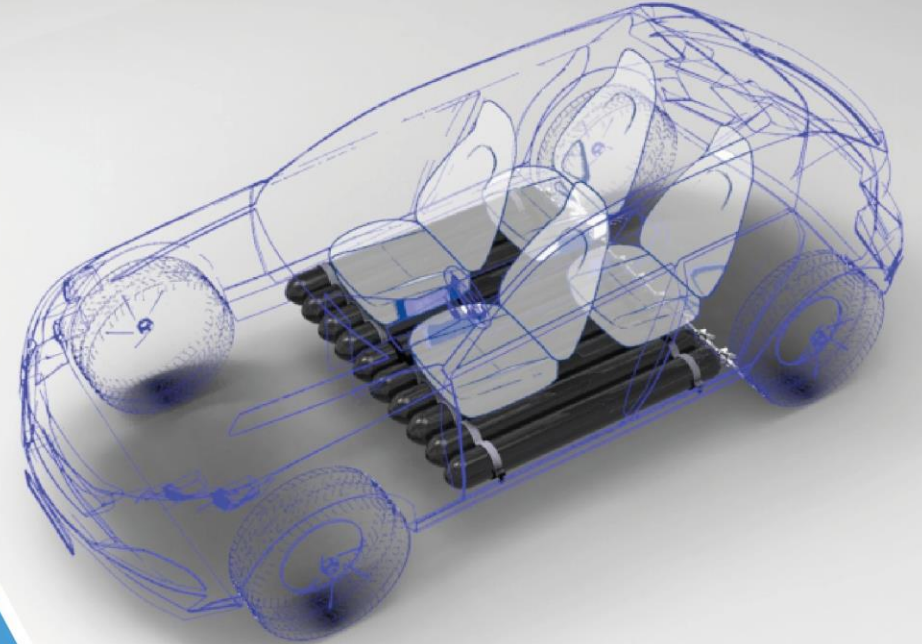


This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.



# Breakthrough safety technology of explosion free in fire self-venting (TPRD-less) tanks

Stakeholder's workshop of SH2APED project  
26-27 September 2024  
V. Molkov, D. Makarov, S. Kashkarov



- European (EPO) Patent Application No. 18706224.5.
- Title: **Composite vessel for hydrogen storage.**
- International (PCT) Application No: PCT/EP2018/053384.

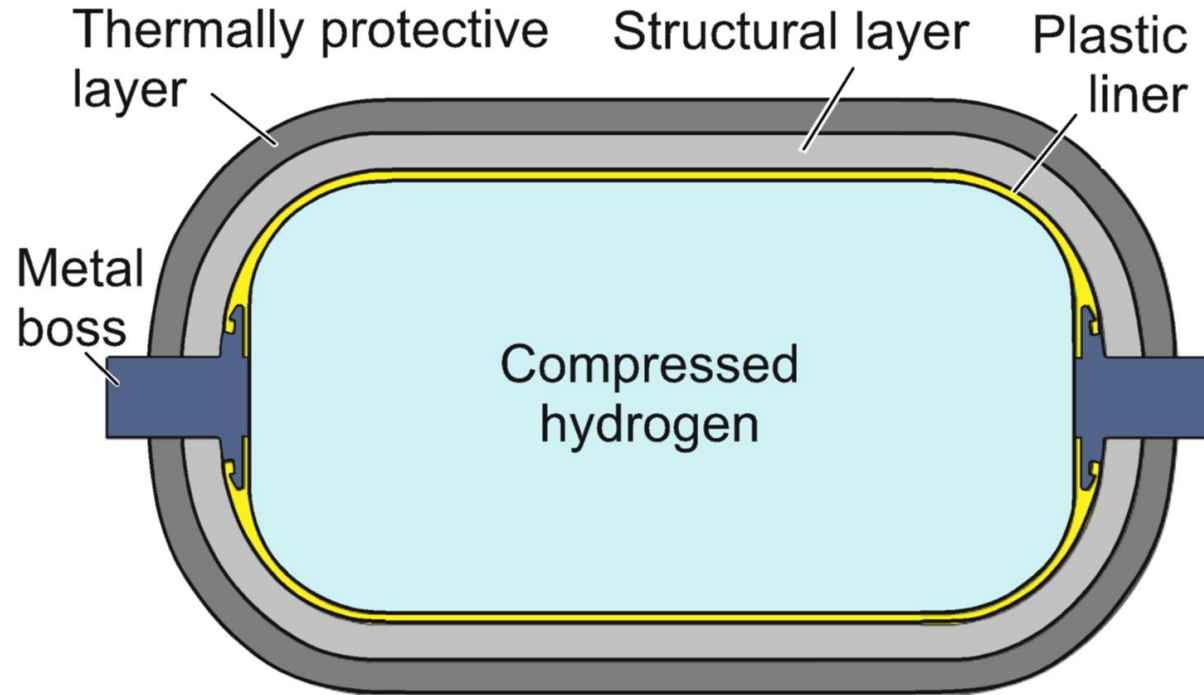


# Investments in the breakthrough technology



- EPSRC SUPERGEN Hydrogen and Fuel Cells Challenge: Safety Strategies for Onboard Hydrogen Storage Systems, EP/K021109/1, 2013-2017.
- Invest NI PoC 629 “Composite tank prototype for onboard compressed hydrogen storage based on novel leak-no-burst safety technology”.
- Invest NI PoC Plus “Optimisation of explosion free in a fire composite cylinder to industrial requirements”.
- Interreg Atlantic Area ERDF HYLANTIC “Atlantic network for renewable generation and supply of hydrogen to promote high energy efficiency EAPA\_204/2016”.
- H2020 FCH 2 JU HyTunnel-CS “Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces” project, 2019-2022.
- H2020. Call: H2020-JTI-FCH-2020-1. SH2APED: Storage of hydrogen: alternative pressure enclosure development. 2021-2023.
- Invest NI. Centre for Advanced Sustainable Energy (CASE) (start date 01.10.2021): Breakthrough safety technologies for hydrogen vessels from Northern Ireland, 4 partners.
- Innovate UK. Clean Maritime Demonstration Competition Round 2 (start date 01.01.2023): Hydrogen Fuel Cell Range Extender. 4 partners..
- EPSRC. UK National Clean Maritime Research Hub (MaRes) (EP/Y024605/1).

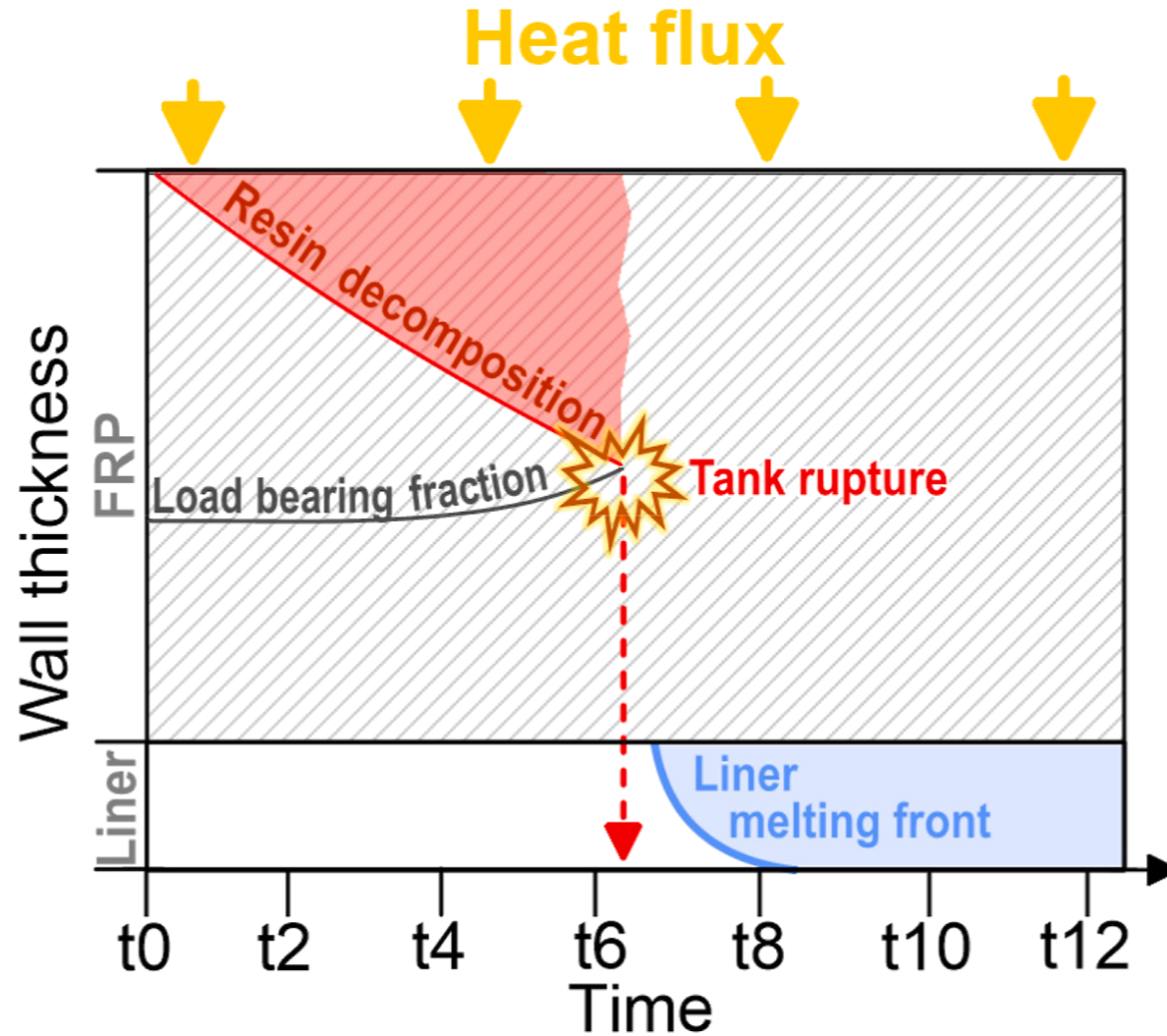
# $\mu$ LNB technology description



A vessel comprises a load bearing fibre-reinforced polymer (FRP) layer, inner liner against gas permeation and outer thermal protection layer (TPL) that can be load bearing.

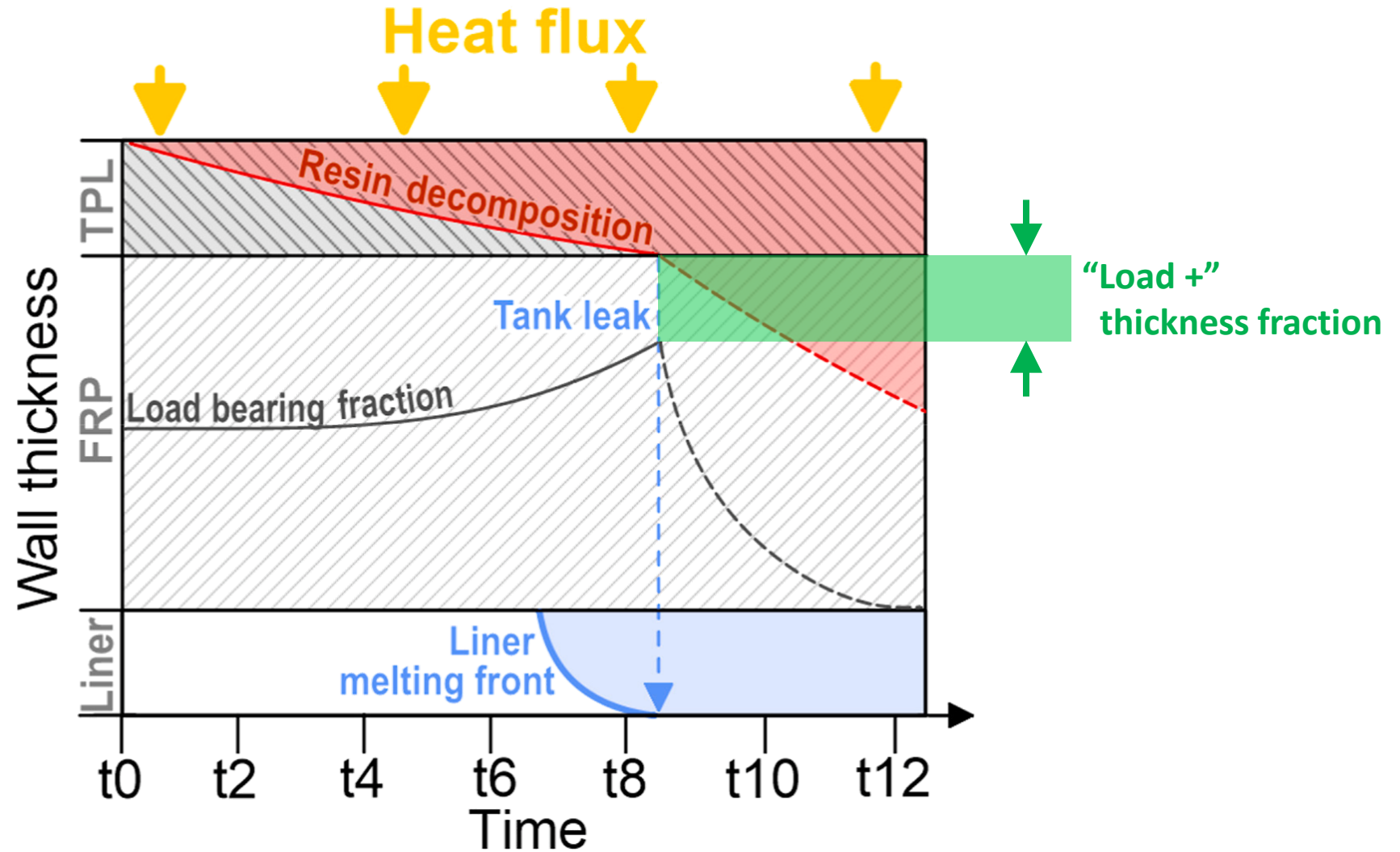
Liner melts and the gas leaks through the wall excluding tank rupture.

# Failure of a standard tank in a fire (faulty TPRD)

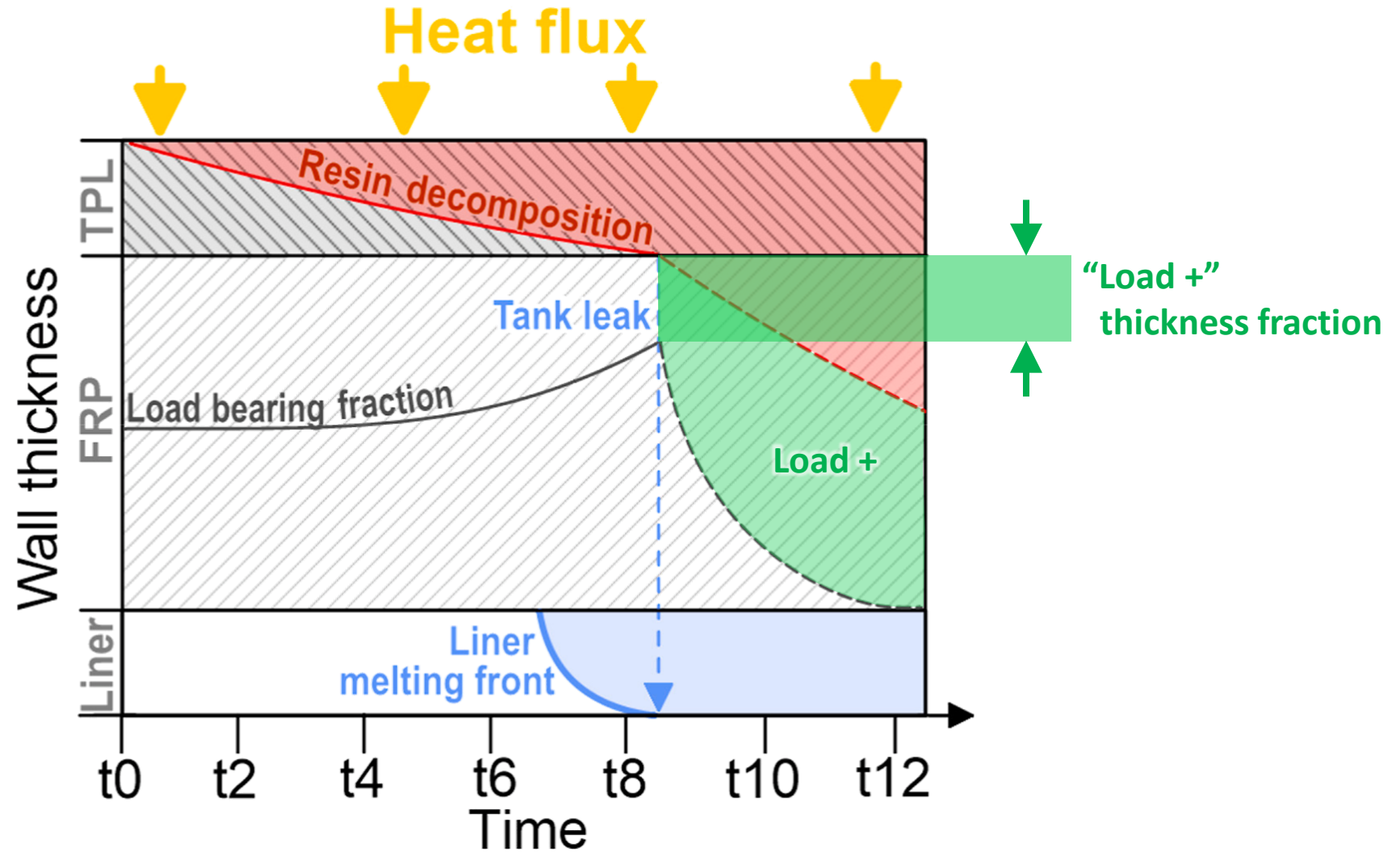




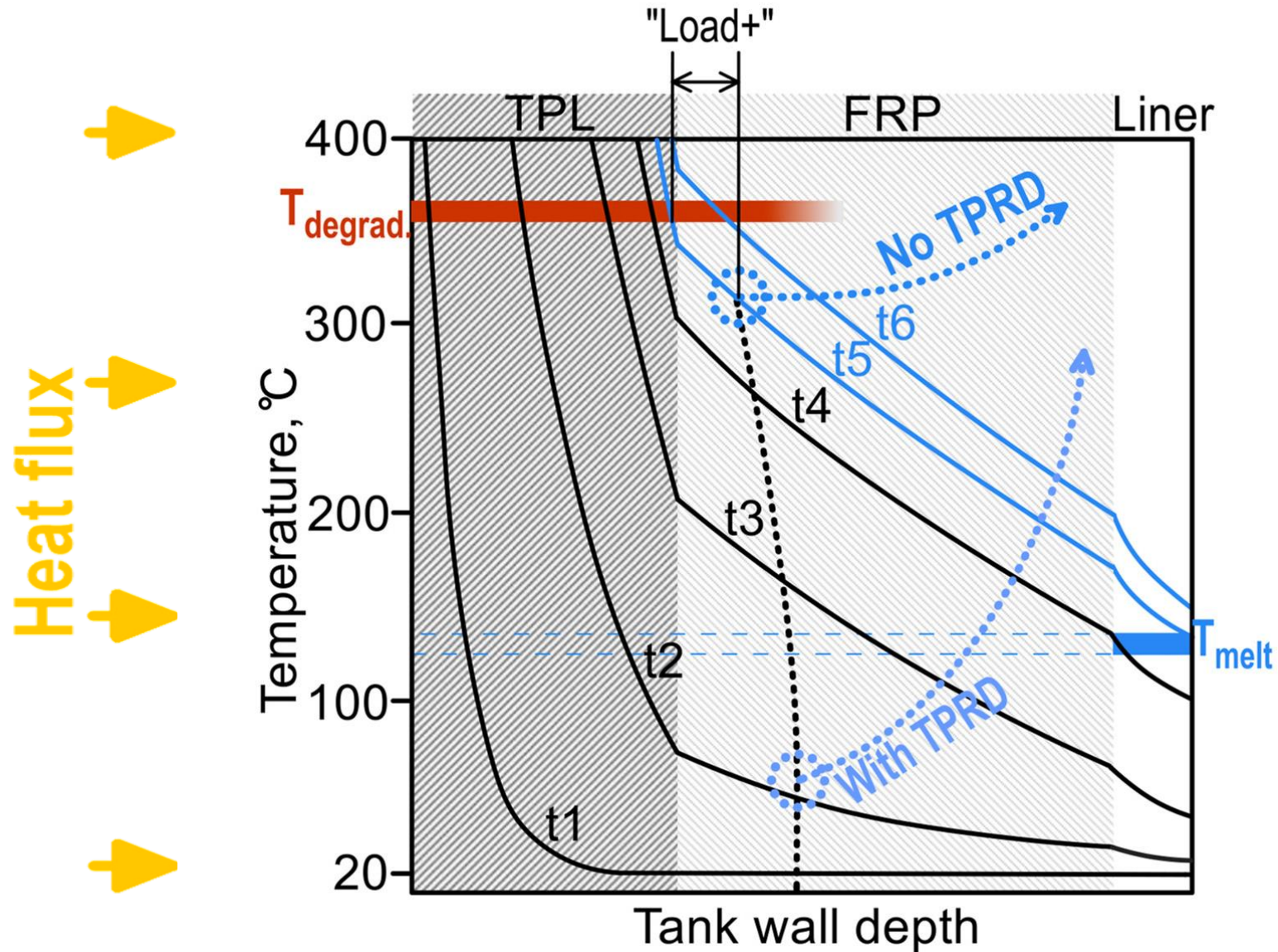
# Failure of a $\mu$ LNB (TPRD-less) tank in a fire



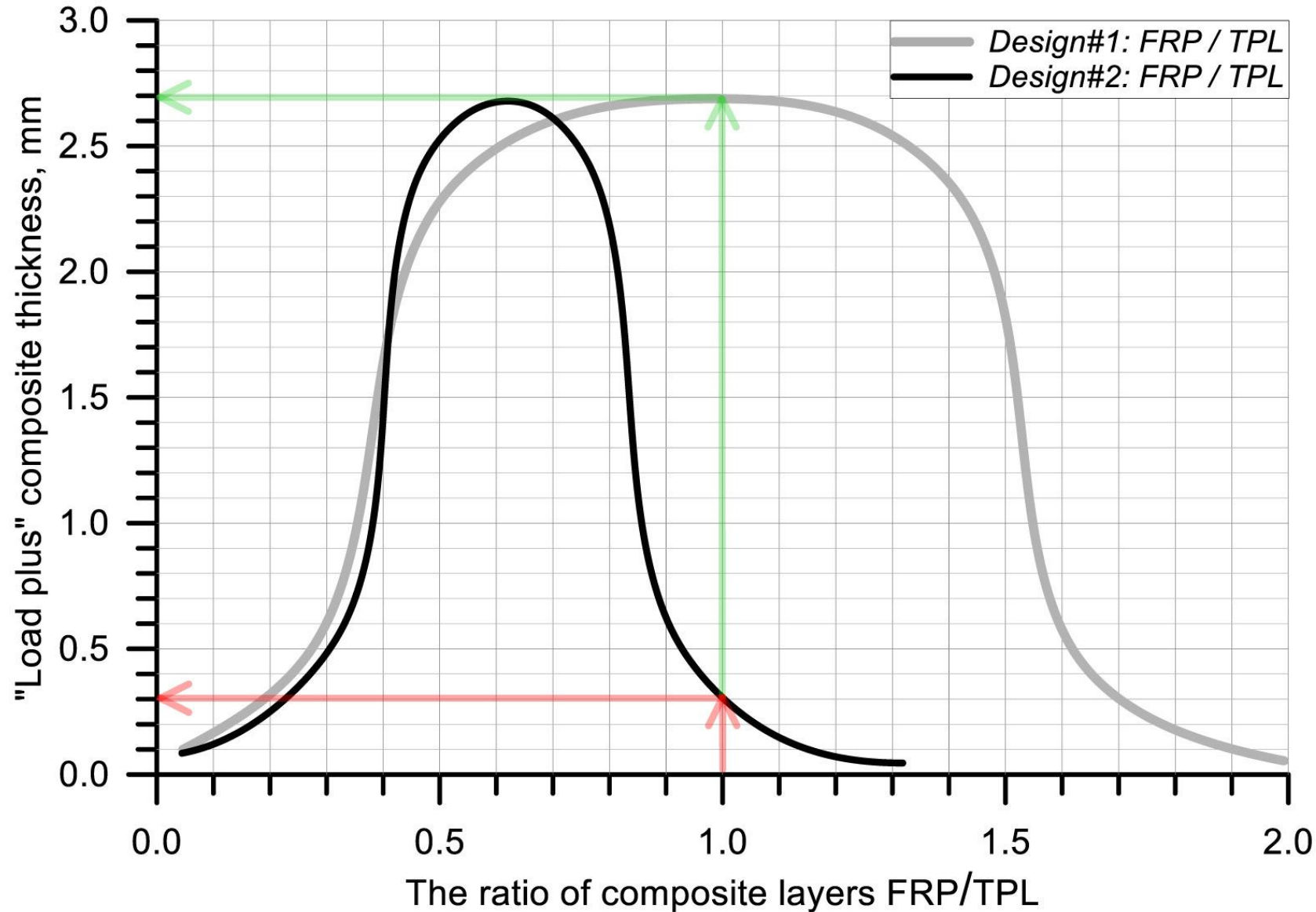
# Failure of a $\mu$ LNB (TPRD-less) tank in a fire



# $\mu$ LNB technology description



# Ratio of layers (FRP/TPL) vs Load+ fraction





# Experimental validation of the technology

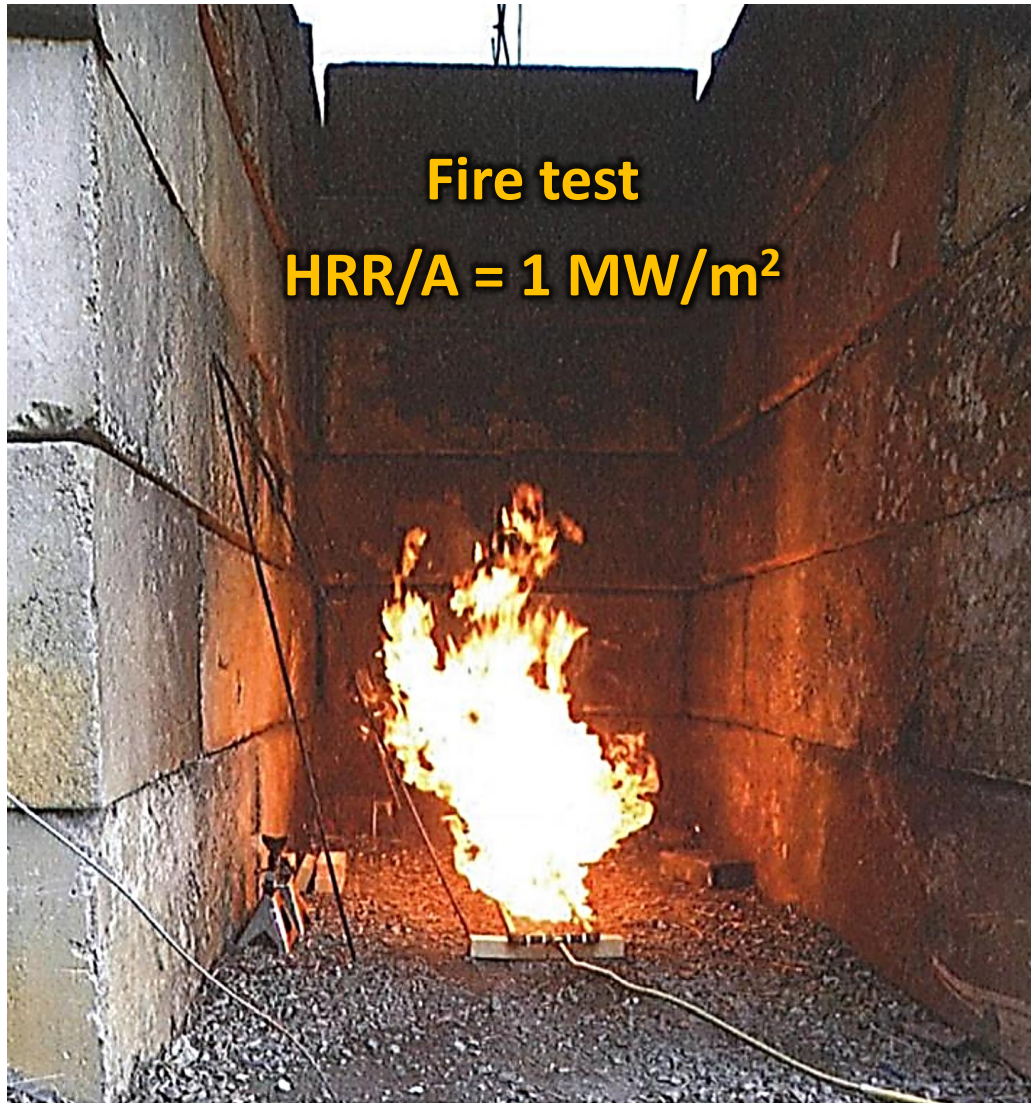


# Validation-series 1

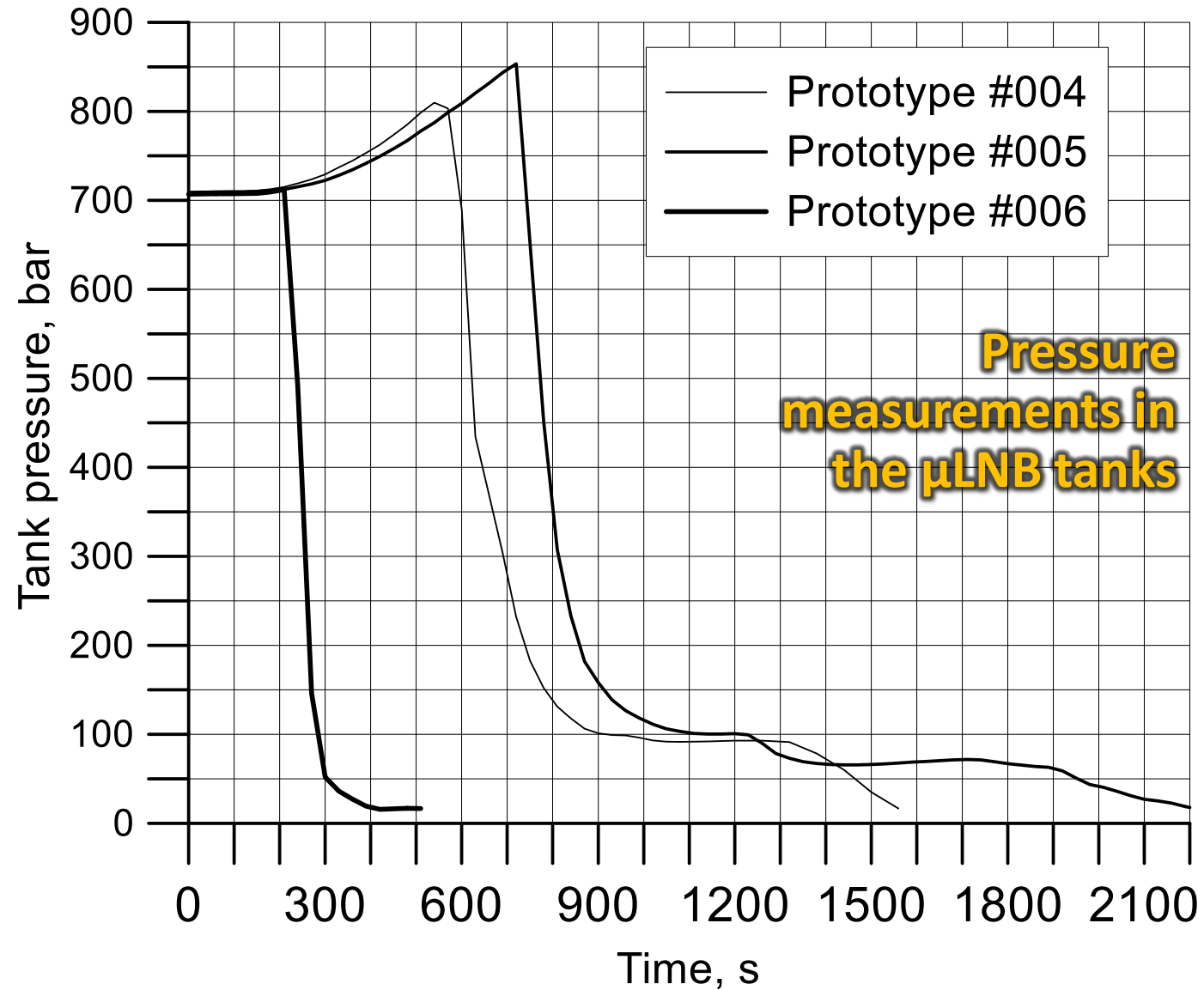




# Validation-series 1

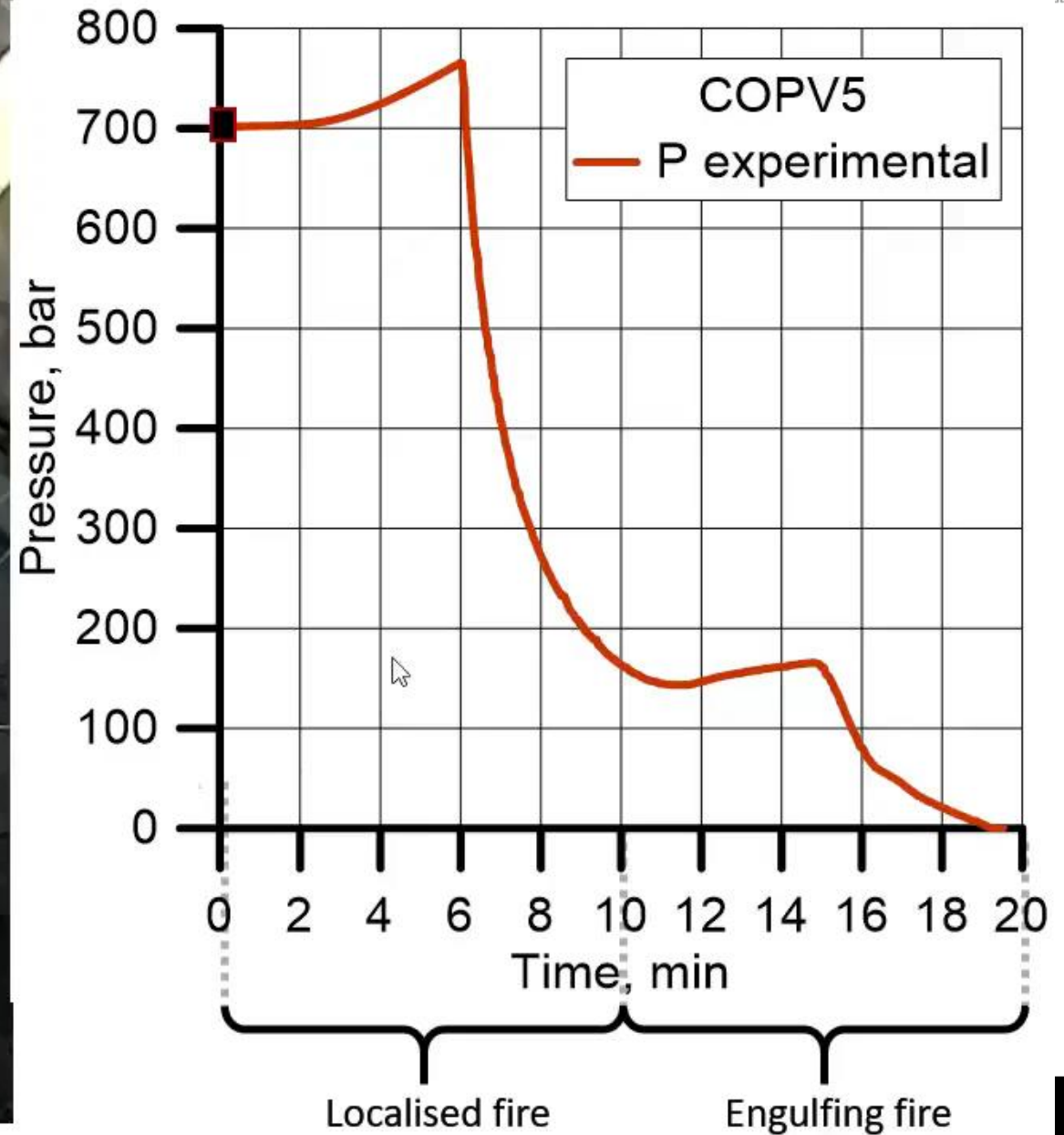


# Validation-series 1

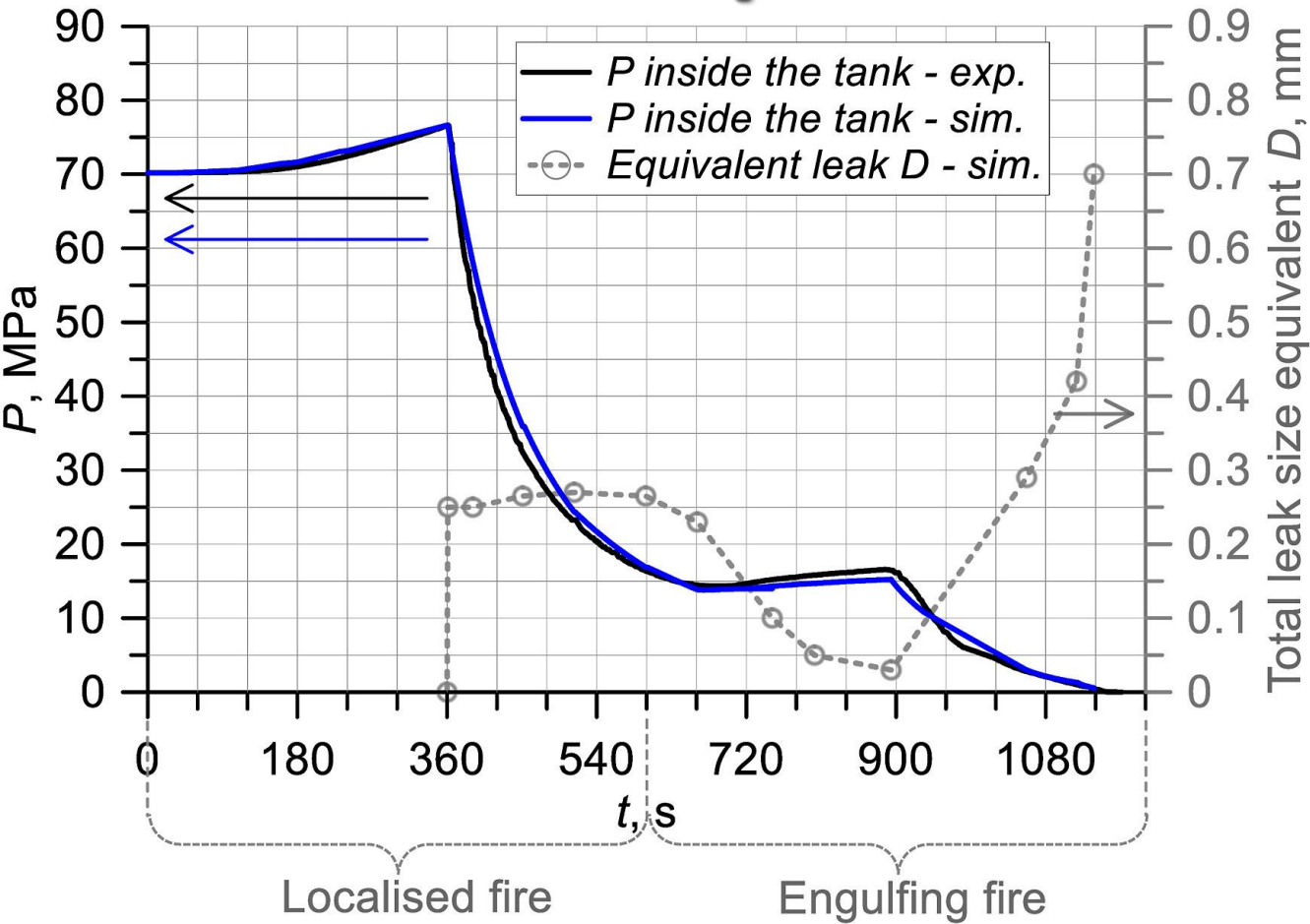




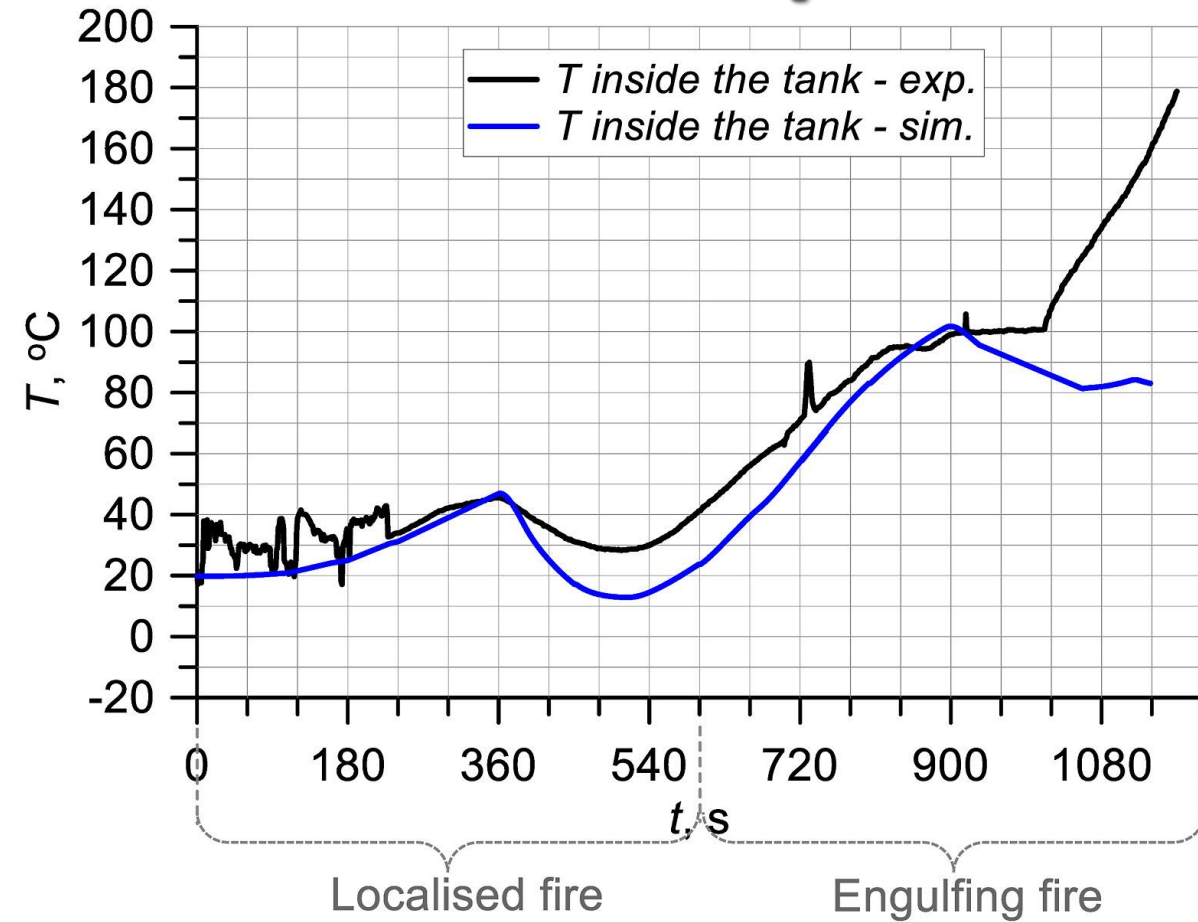
# Validation-series 2



## P measurements in $\mu$ LNB tank



## T measurements in $\mu$ LNB tank





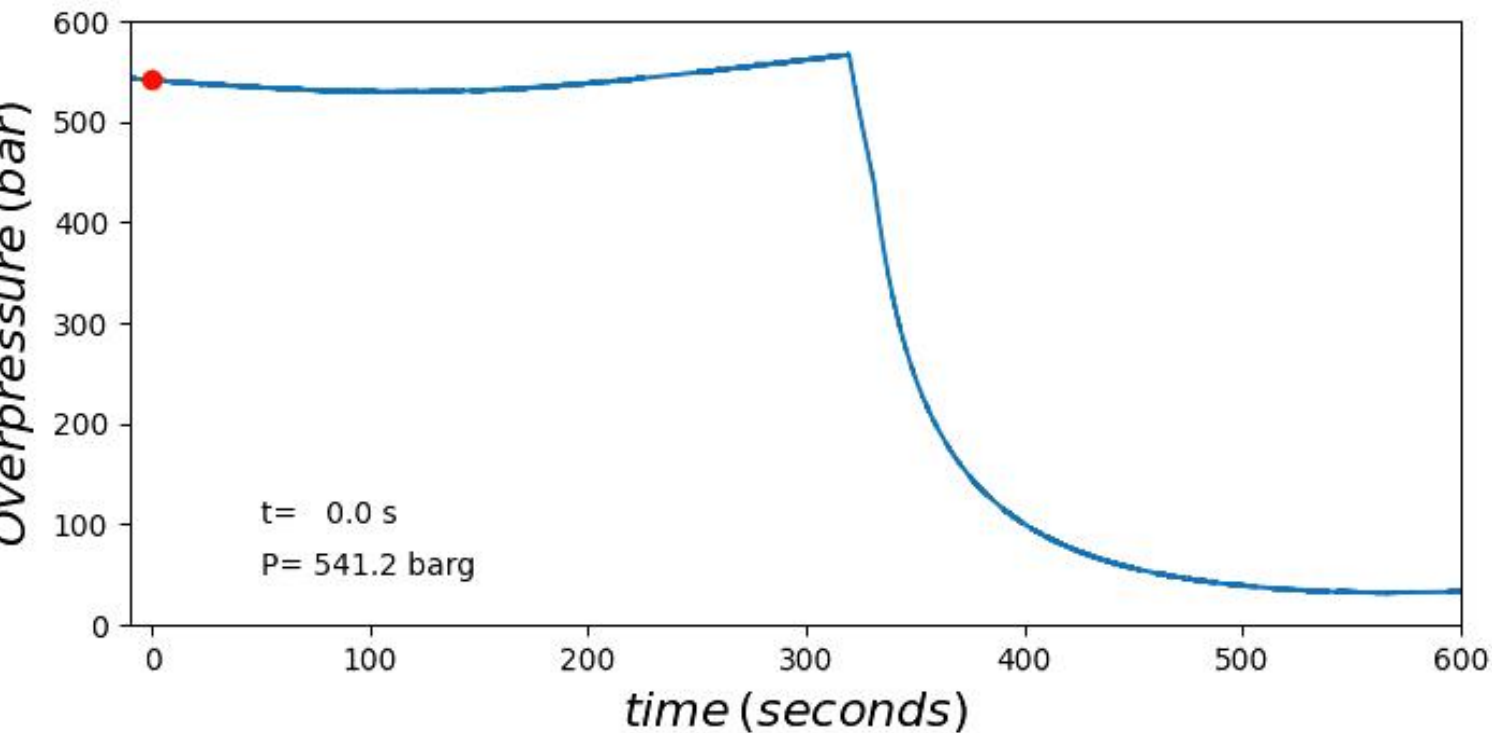
# Performance during fire intervention

# Performance during fire intervention: tanks

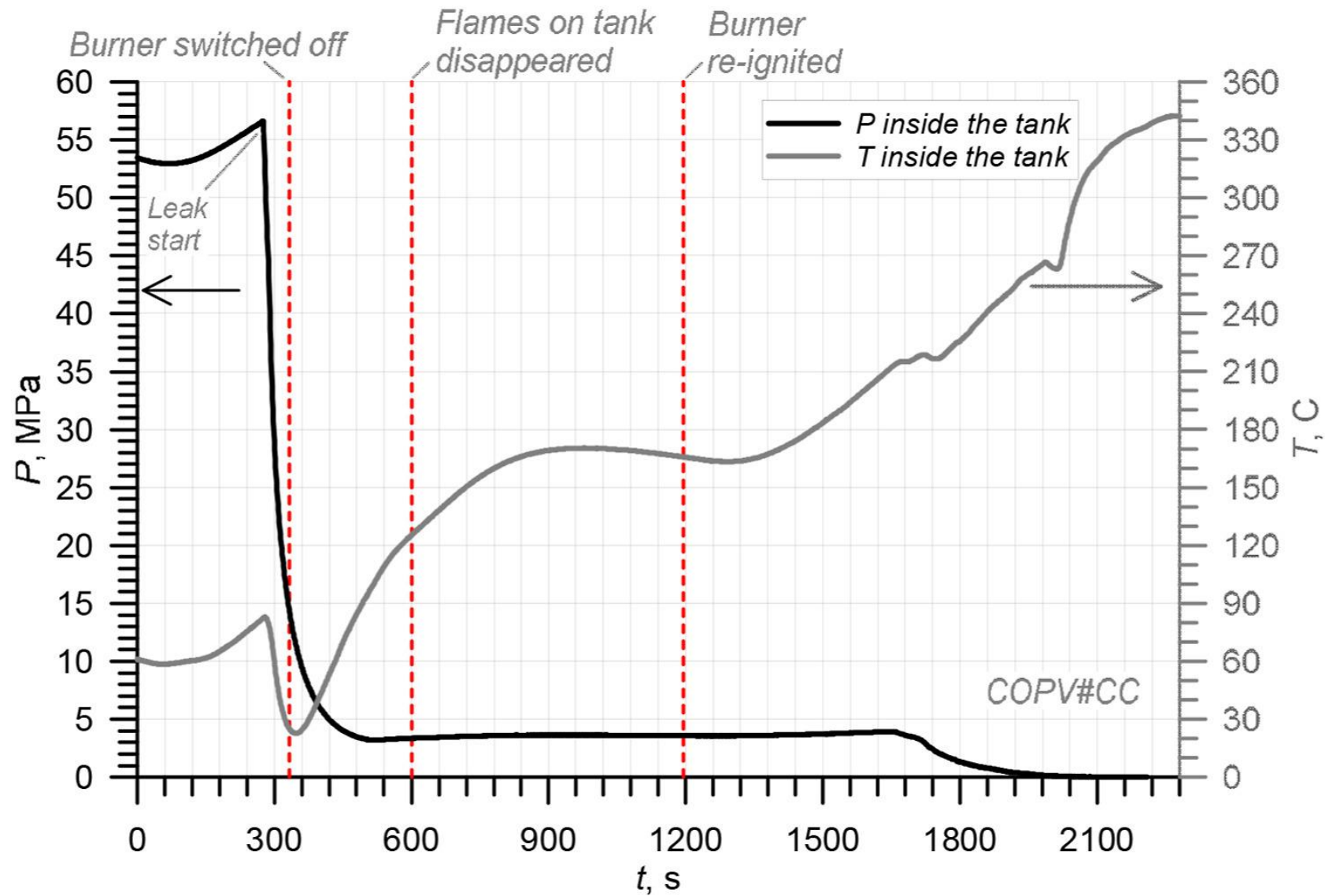
| Prototype | Liner | Layer 1 | Layer 2 | Outside D increase* | Fire scenario        |
|-----------|-------|---------|---------|---------------------|----------------------|
| COPV#CC   | L1    | CFRP#1  | CFRP#2  | 2%                  | Removal from a fire  |
| COPV#CB-1 | L1    | CFRP#1  | BFRP    | 2%                  | Removal from a fire  |
| COPV#CB-2 | L2    | CFRP#1  | BFRP    | 0%                  | Water supply to fire |
| COPV#CB-3 | L1    | CFRP#1  | BFRP    | 0%                  | Water supply to fire |
| COPV#CB-4 | L2    | CFRP#1  | BFRP    | 2%                  | Water supply to fire |
| COPV#CB-5 | L2    | CFRP#1  | BFRP    | 0%                  | Water supply to fire |



Removal from a fire and  
fire re-ignition

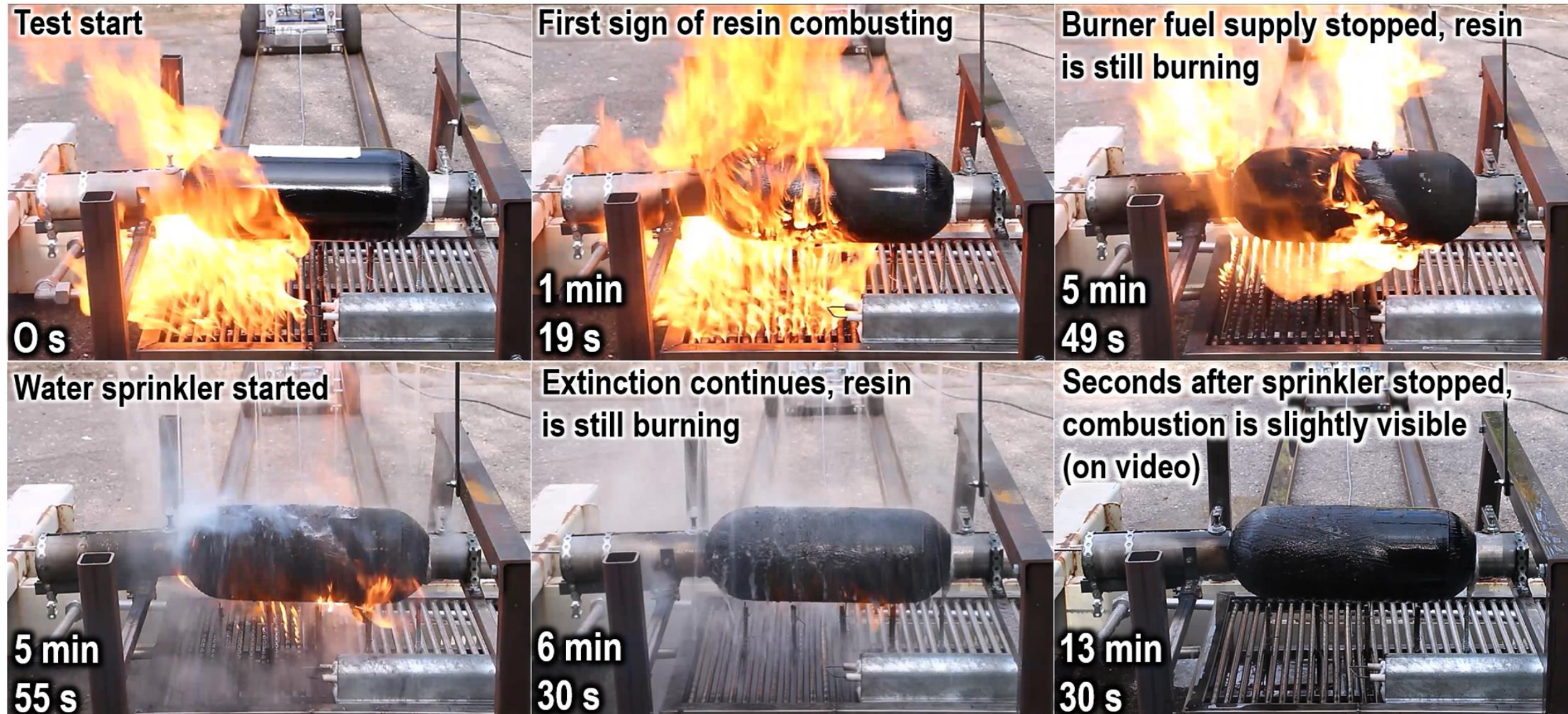


# Removal from a fire and fire re-ignition



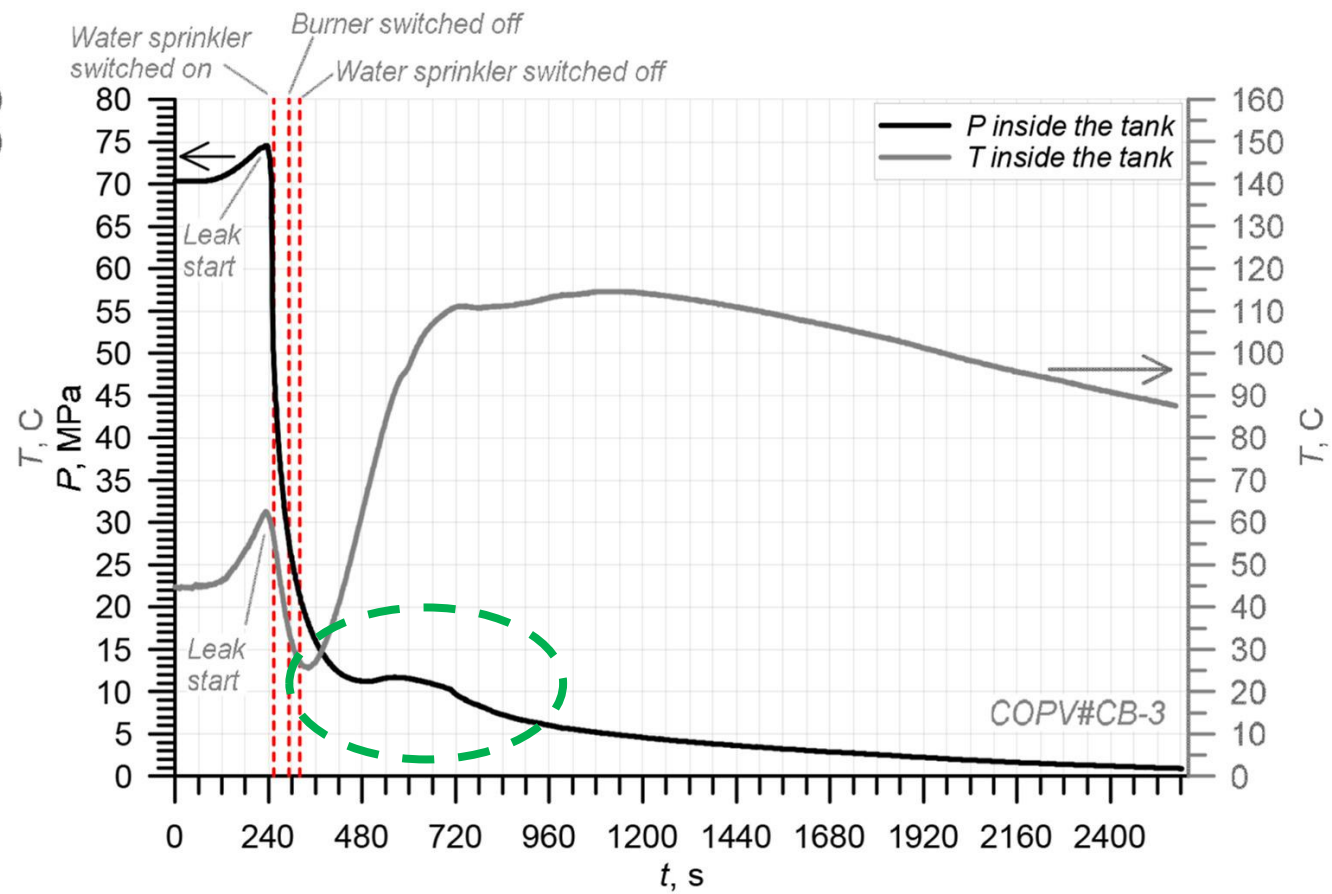
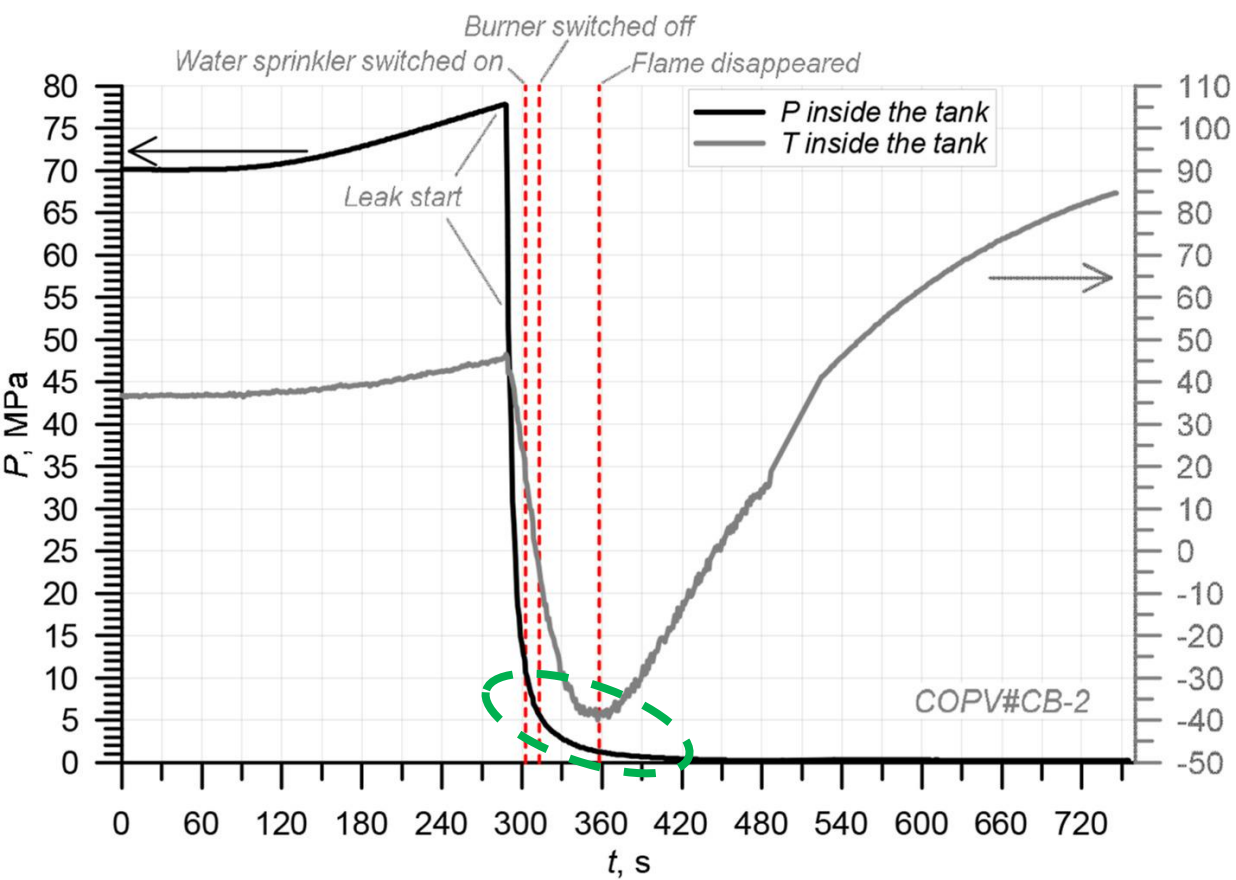


# Fire extinction – series 1





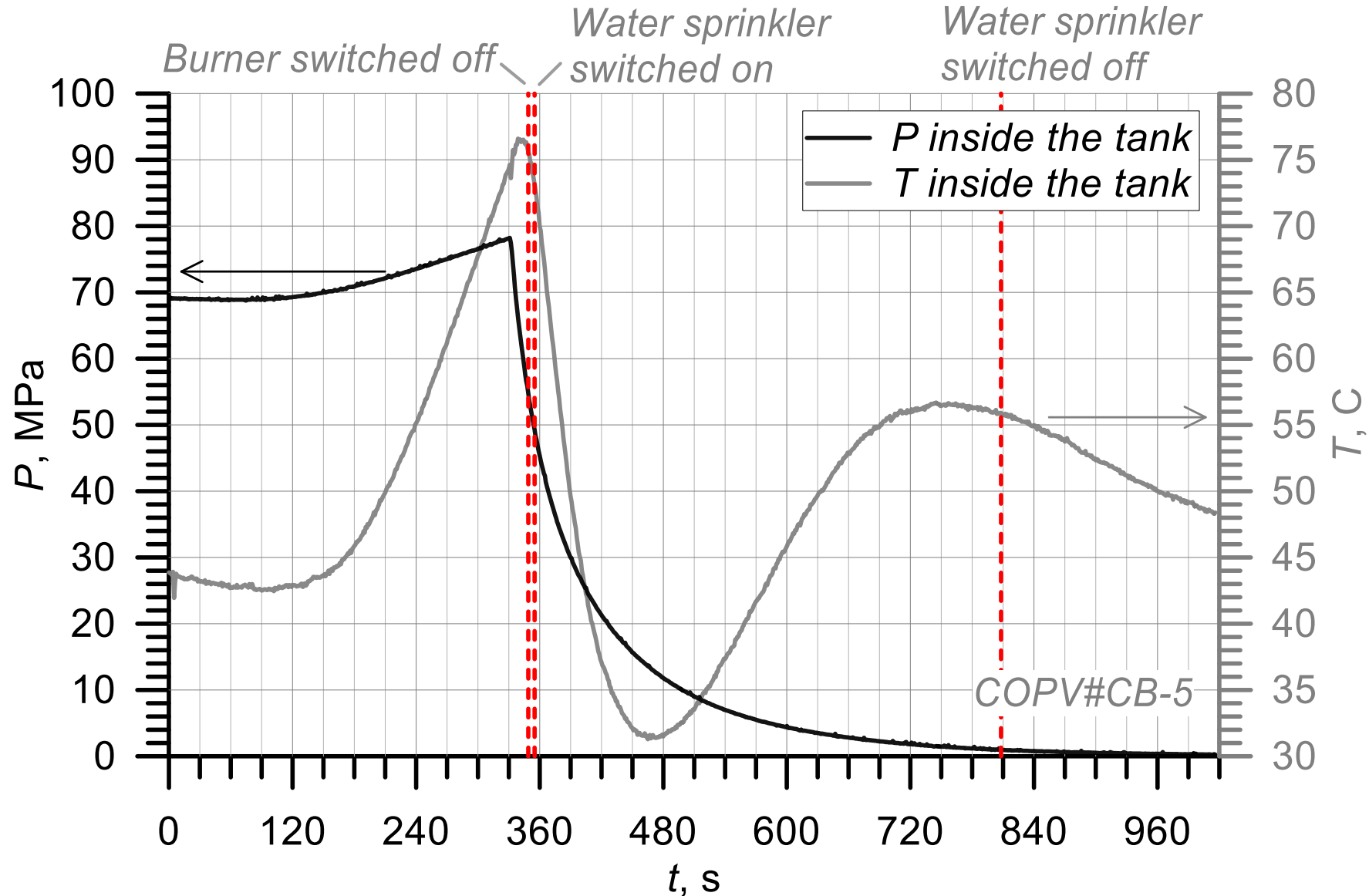
# Fire extinction – series 1



# Fire extinction – series 2



# Fire extinction – series 2





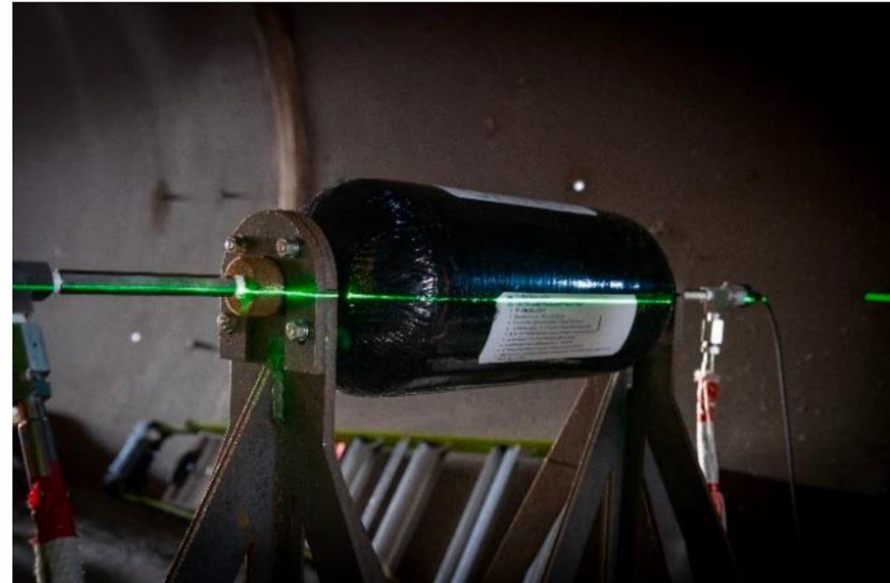
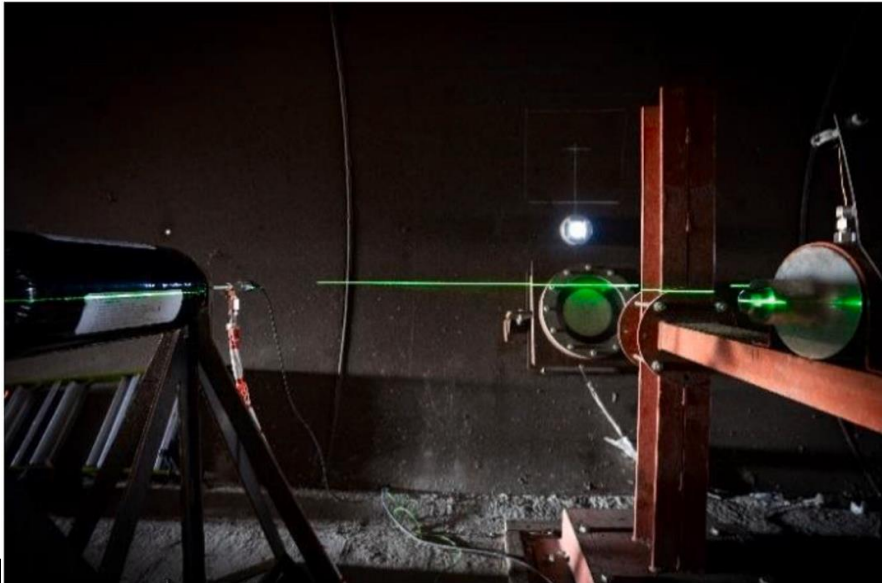
# Validation under extreme impinging 70 MPa hydrogen jet fire conditions

# 70 MPa impinging jet fire test

| Prototype   | Liner | Layer 1 (FRP) | Layer 2 (TPL) | Outside D increase |
|-------------|-------|---------------|---------------|--------------------|
| COPV#CB-1   | HDPE  | CFRP          | BFRP          | 0%                 |
| COPV#CB-2** | HDPE  | CFRP          | BFRP          | 2%                 |

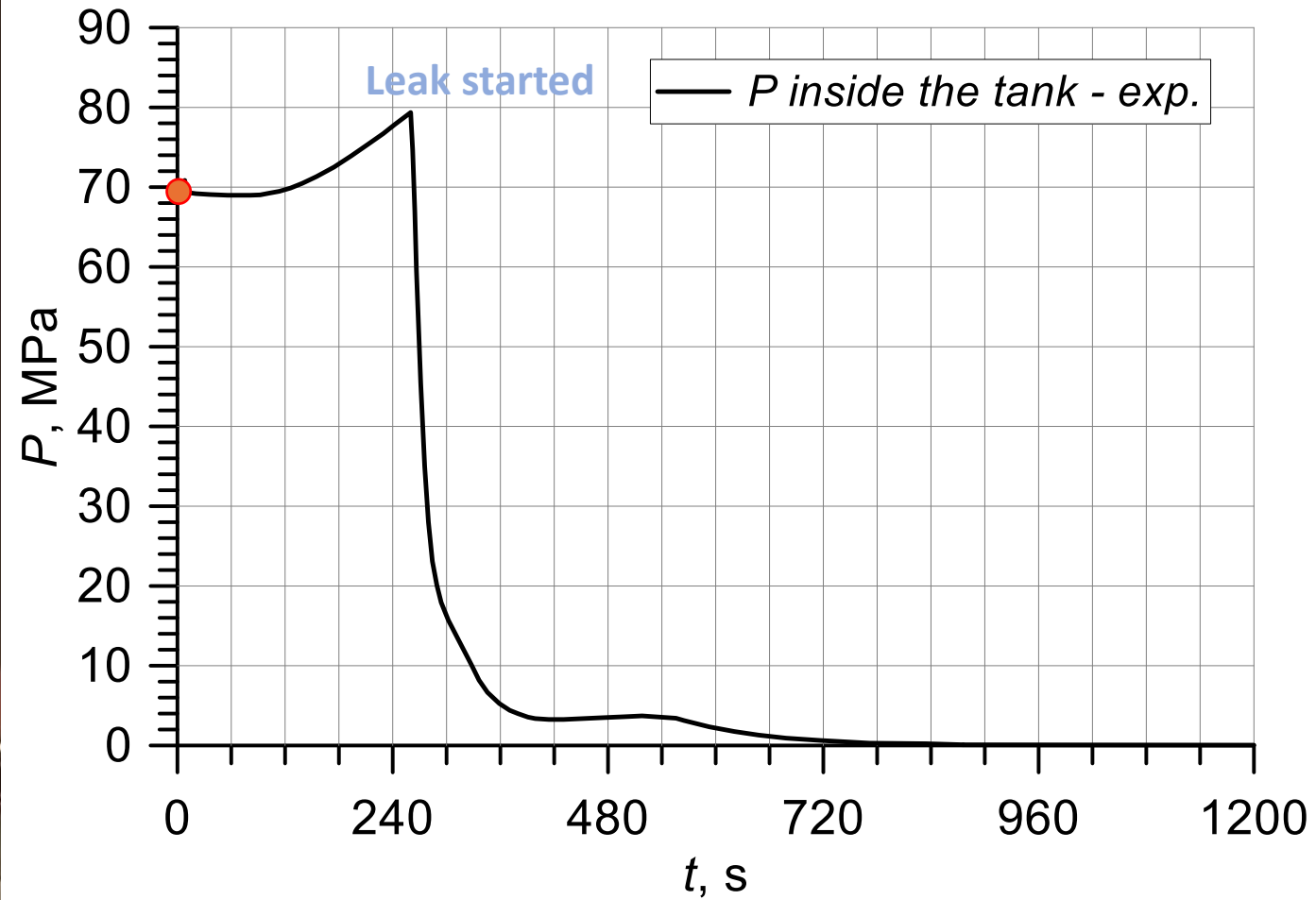


# 70 MPa impinging jet fire test





# 70 MPa impinging jet fire test

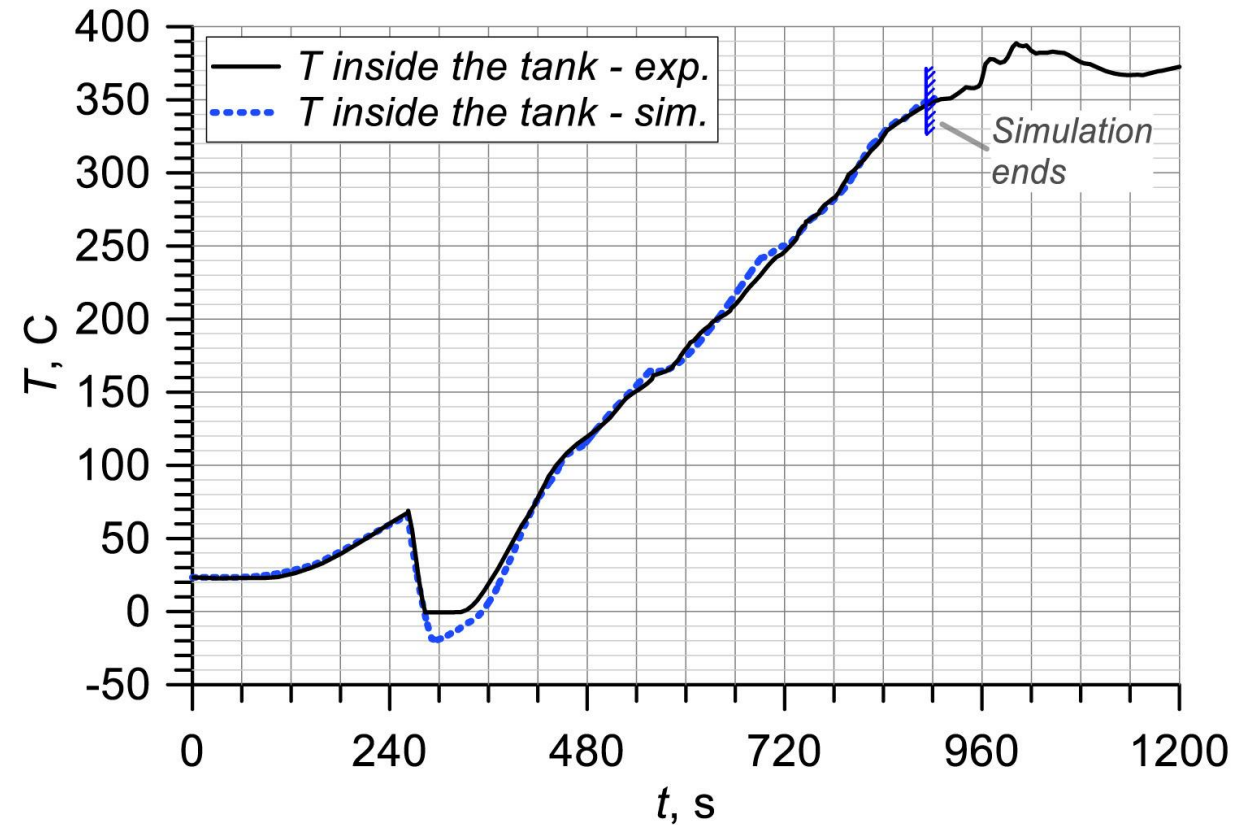
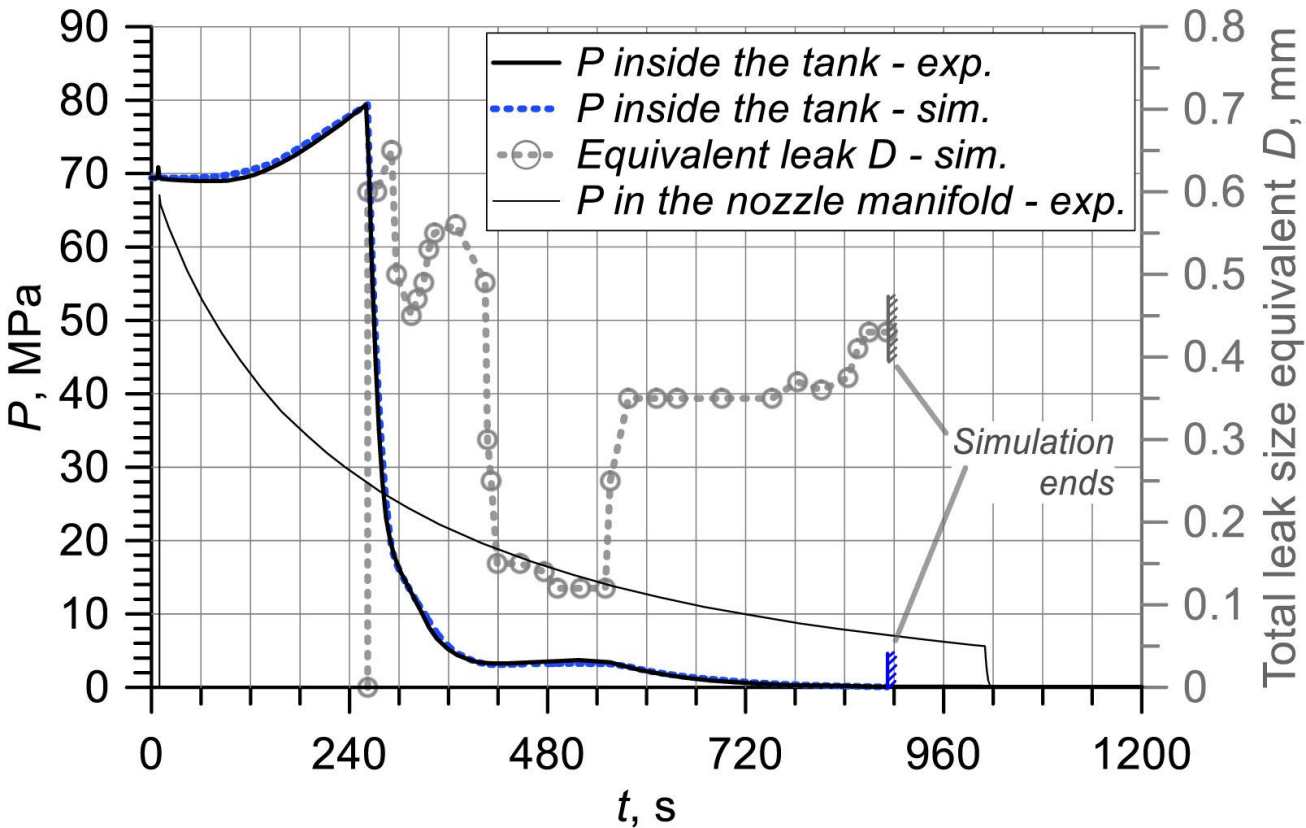








# 70 MPa impinging jet fire test



# Unprecedented level of safety

- No devastating consequences of tank rupture in a fire:
  - *No blast wave*
  - *No fireball*
  - *No projectiles*
  - *No pressure peaking phenomenon*
  - *No long flames*
  - *No loss of life and property due to tank rupture*
- Tank is explosion free in a fire at any SoC up to 100%.
- TPRD-less tank withstands any fire, including a localised fire!
- Standard tank-TPRD system will not withstand localised fire. It will rupture if TPRD is blocked from a fire, if response time of TPRD is comparatively large. Additional safety issues for conformable tanks (with thinned composite wall).

Testing of the TPRD-less tank prototypes confirmed that the customers could have hydrogen-powered vehicles with unprecedented level of safety.

- The fire extinction does not interrupt hydrogen release, i.e. firefighters can conduct their interventions at accident scenes as before.
- The hazards and risks of hydrogen vehicles could be eliminated or reduced drastically: no blast wave, no fireball, no long flames, no pressure peaking phenomenon.
- The “self-venting containers” are becoming a part of GTR#13 regulation.



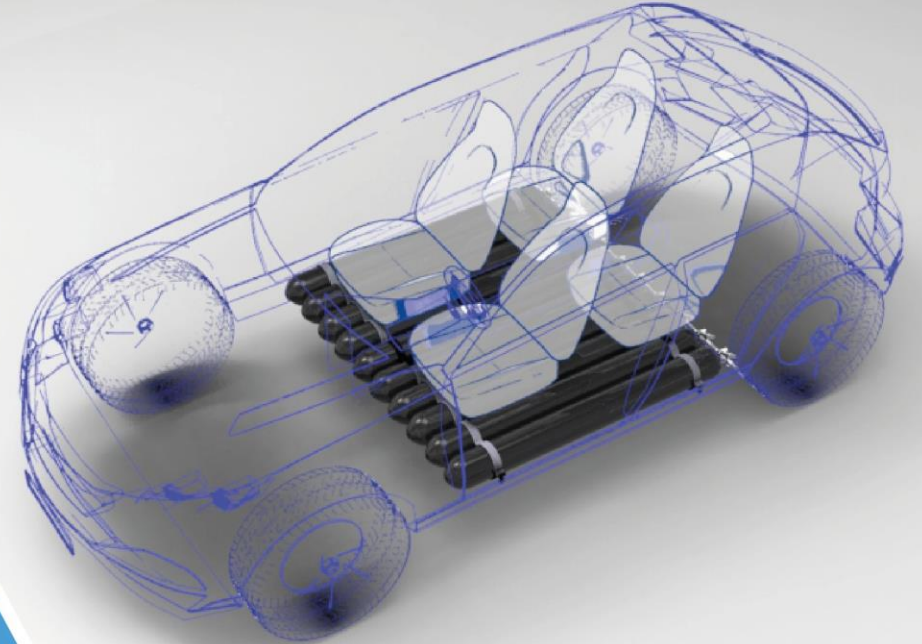
# THANK YOU



This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.

# Design of self-venting (TPRD-less) tank: liner (HDPE vs PA), composite

Stakeholder's workshop of SH2APED project  
26-27 September 2024  
S. Kashkarov, D. Makarov, V. Molkov



# PA vs HDPE: pros and cons

| Property                                   | PA                                                                                                     | HDPE                                    |
|--------------------------------------------|--------------------------------------------------------------------------------------------------------|-----------------------------------------|
| Weight                                     | 1120-1140 kg/m <sup>3</sup>                                                                            | 930~970 kg/m <sup>3</sup> (19% lighter) |
| Melting T (essential for $\mu$ LNB tank )  | 150~190°C                                                                                              | 110~132°C (40% lower)                   |
| Permeability                               | No win of PA over HDPE, HDPE permeation makes less than 8% of the “standard” leaks through connections |                                         |
| Increase in $\mu$ LNB tank size            | Up to 20 mm inter-axis increase                                                                        | No size increase                        |
| Hygroscopic (moisture absorption) property | High                                                                                                   | Low                                     |
| Good vibration damping                     | No                                                                                                     | Yes                                     |

## References:

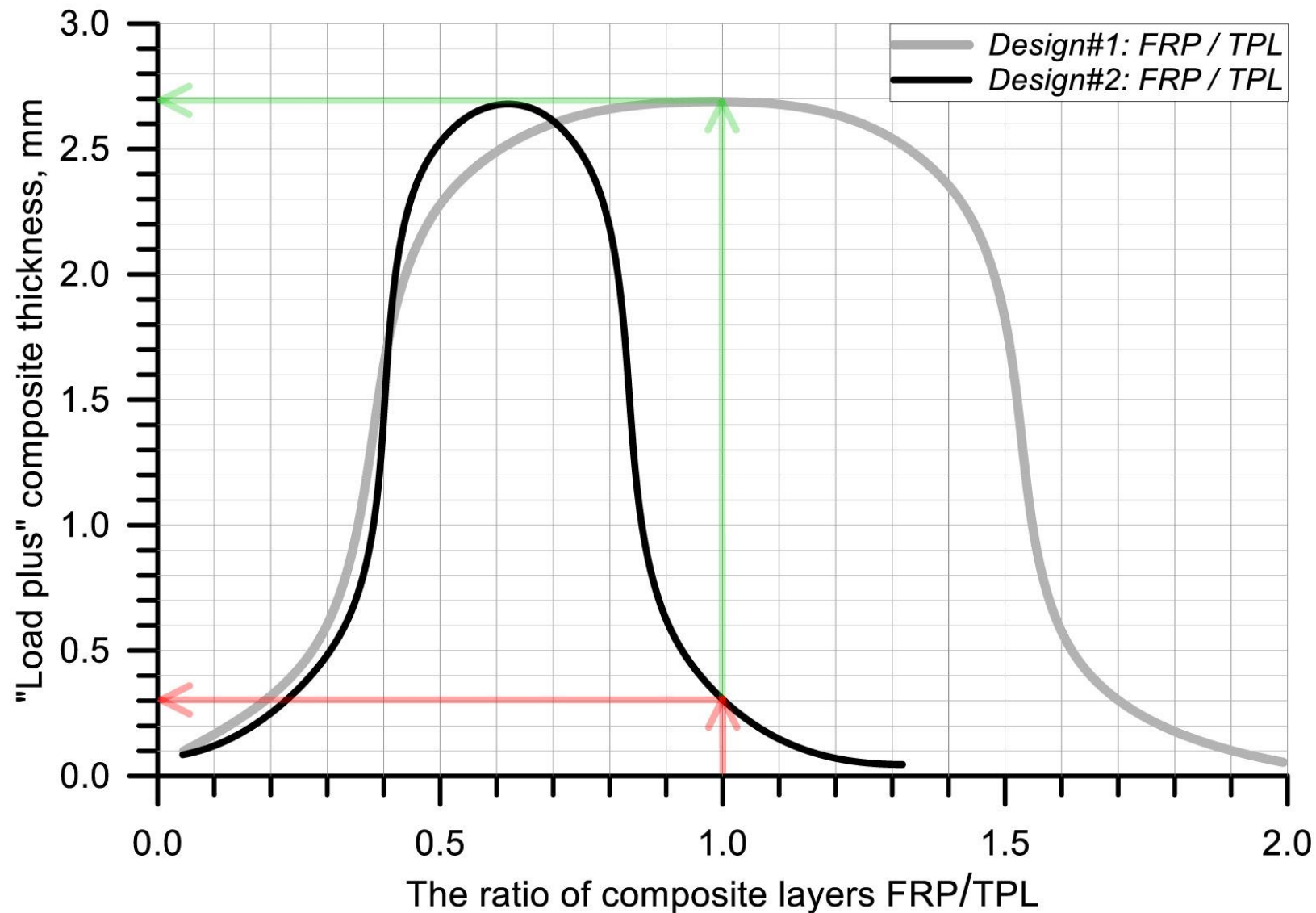
[https://www.acmeplastics.com/what-is-hdpe#:~:text=The%20density%20of%20HDPE%20can,\(low%2Ddensity%20polyethylene\)](https://www.acmeplastics.com/what-is-hdpe#:~:text=The%20density%20of%20HDPE%20can,(low%2Ddensity%20polyethylene))

<https://omnexus.specialchem.com/selection-guide/polyamide-pa-nylon/key-properties>

- Targeting PA liner because of the need to increase the temperature above 85C for fuelling:
  - **NOT A PROBLEM** - Ulster University has a unique fuelling tool that will provide protocol time-efficient and avoiding high temperature
- O-ring – as an argument in favour of PA:
  - **IS A POTENTIAL PROBLEM** – will deteriorate after 1 year of use

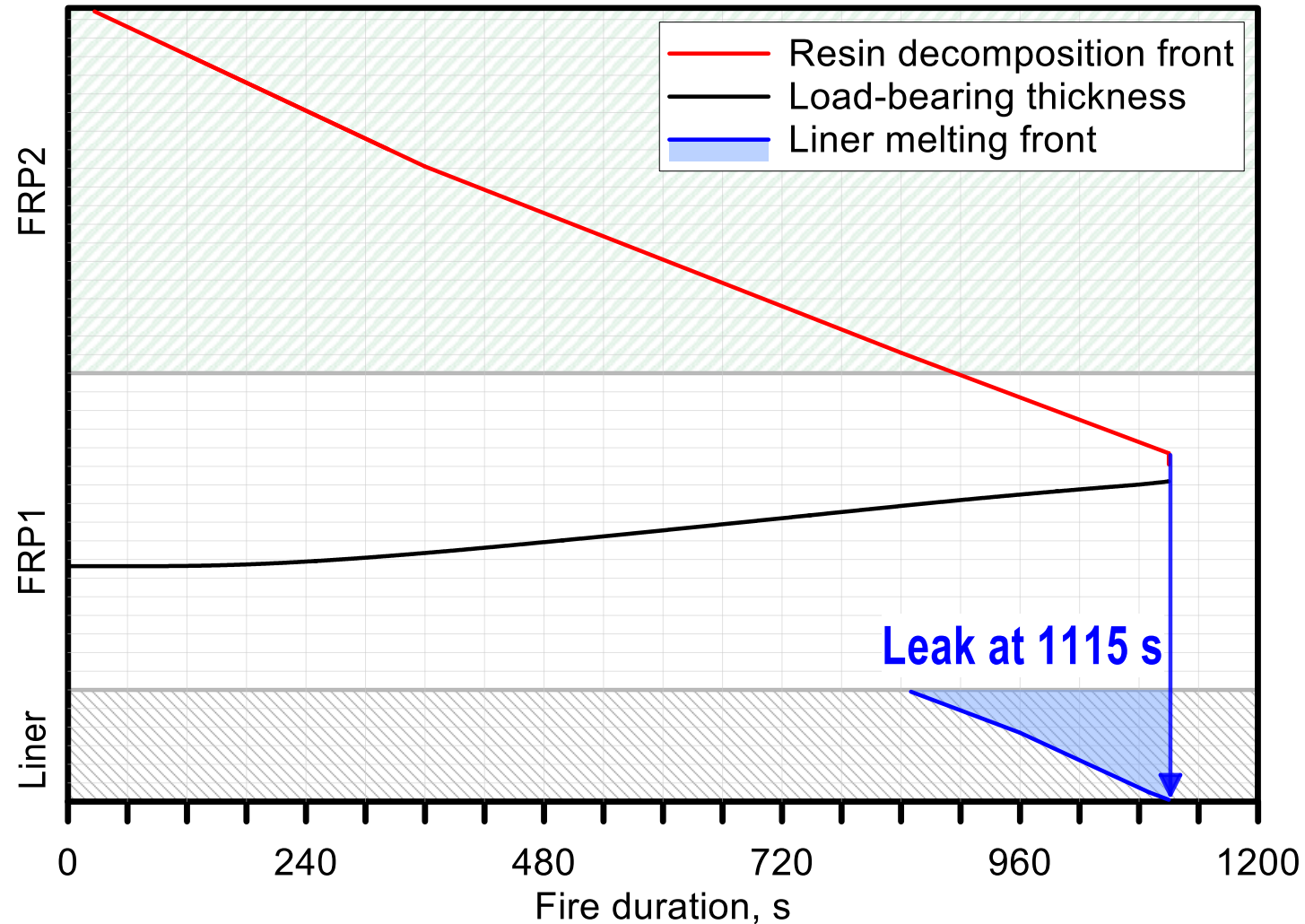


# Optimisation of designs of $\mu$ LNB tanks

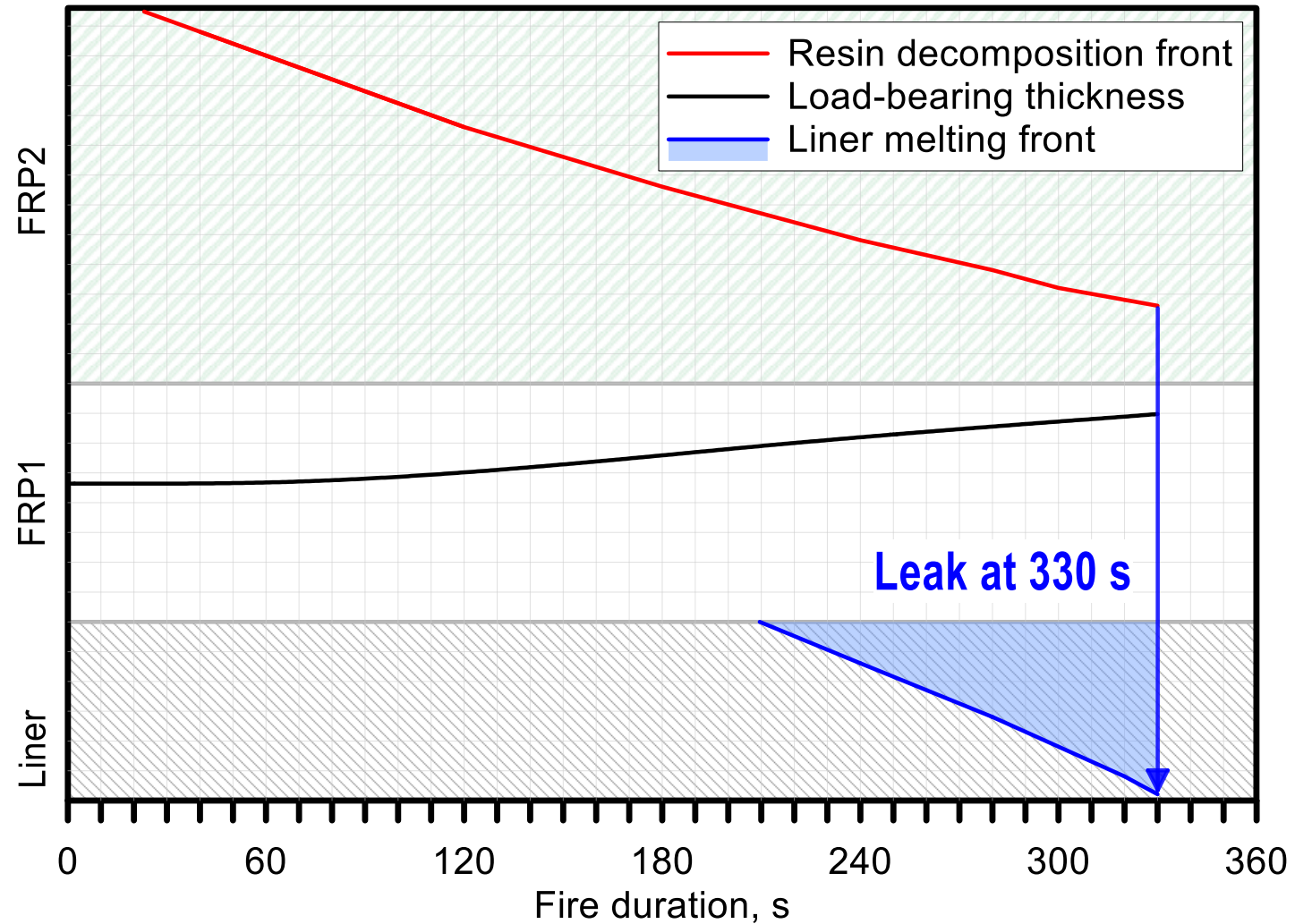


**Example of the designs with PA liner**

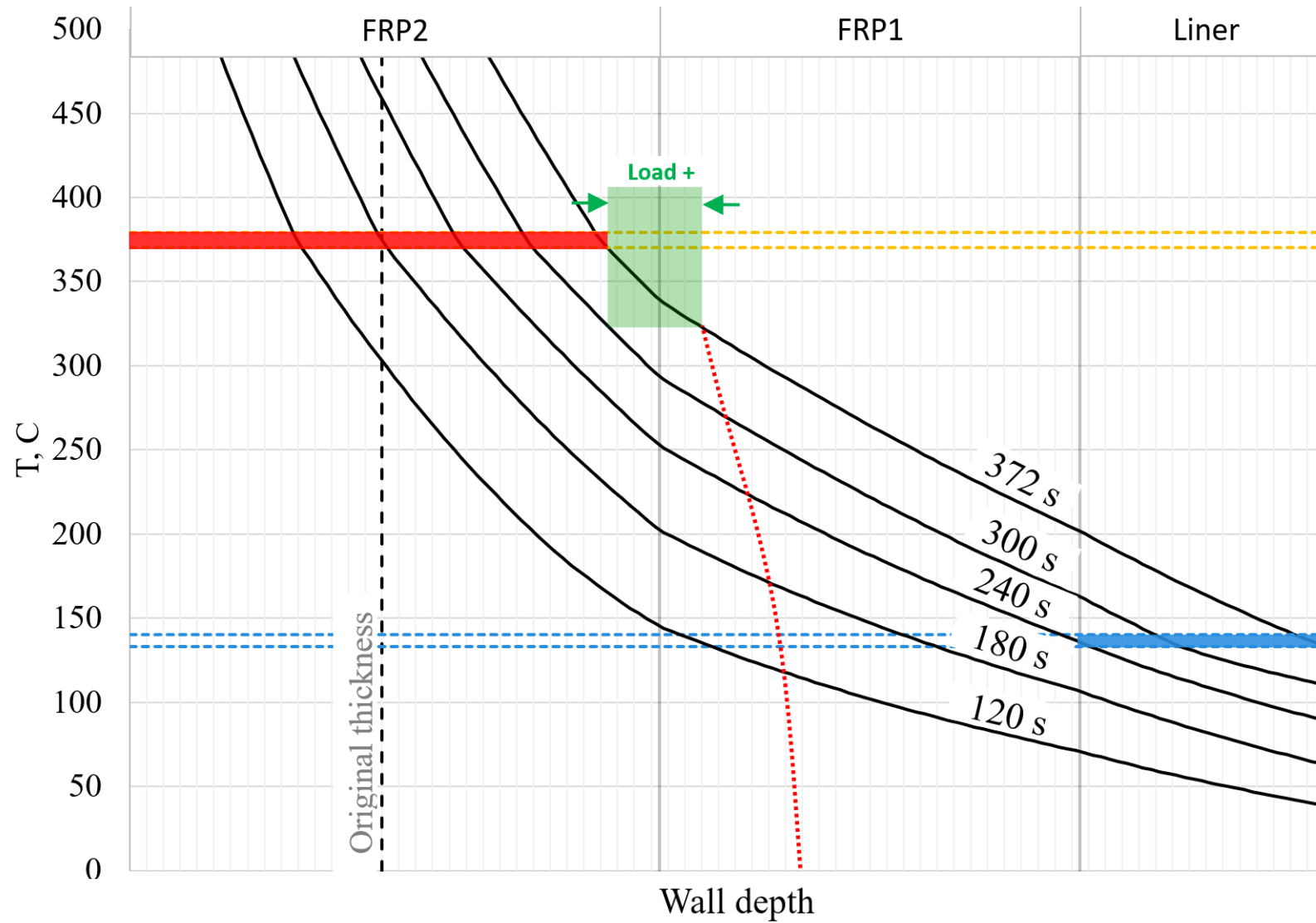
# $\mu$ LNB tank with PA liner in 1 MW/m<sup>2</sup> fire



# $\mu$ LNB tank with HDPE liner in 1 MW/m<sup>2</sup> fire

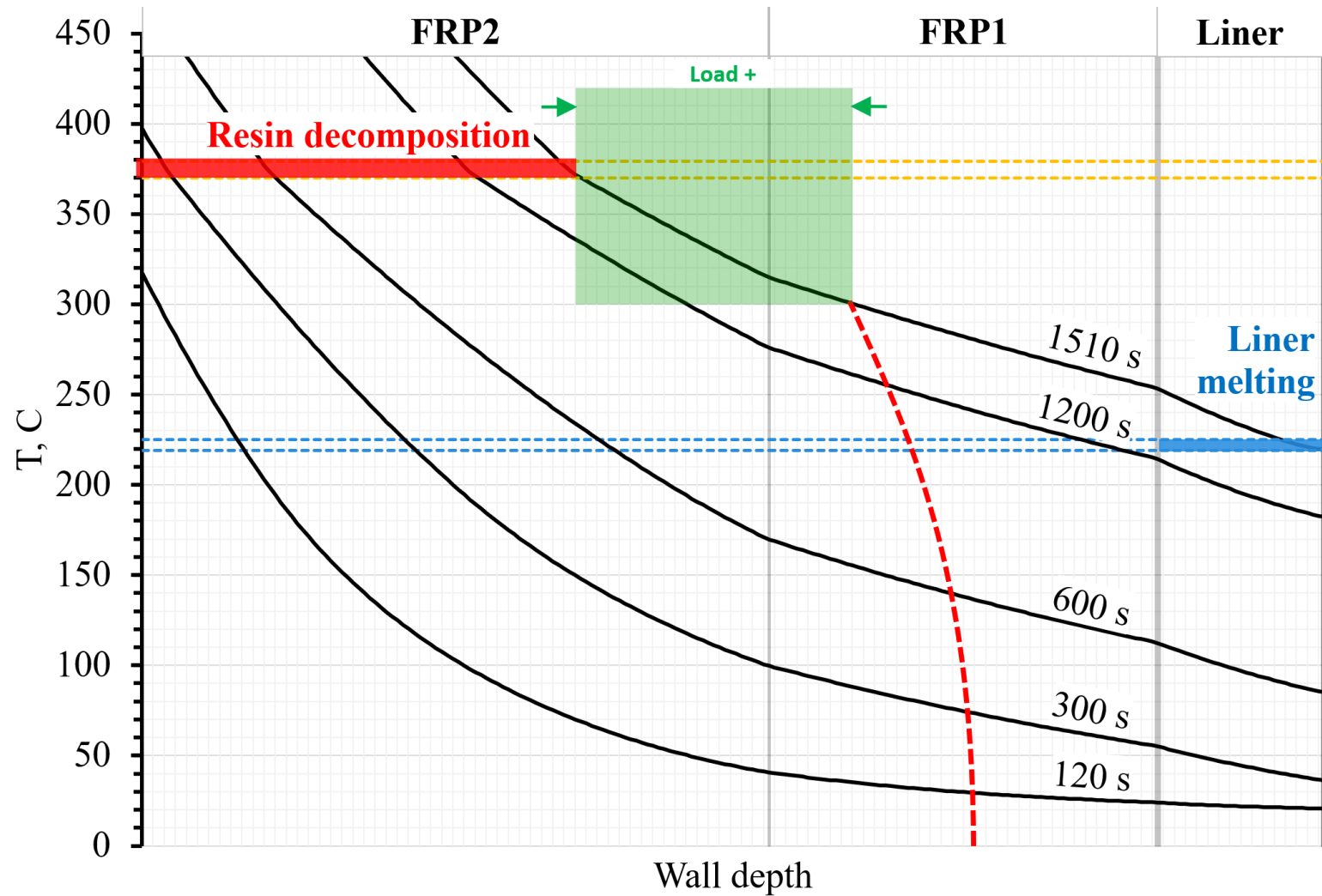


# $\mu$ LNB tank with HDPE liner in 1 MW/m<sup>2</sup> fire

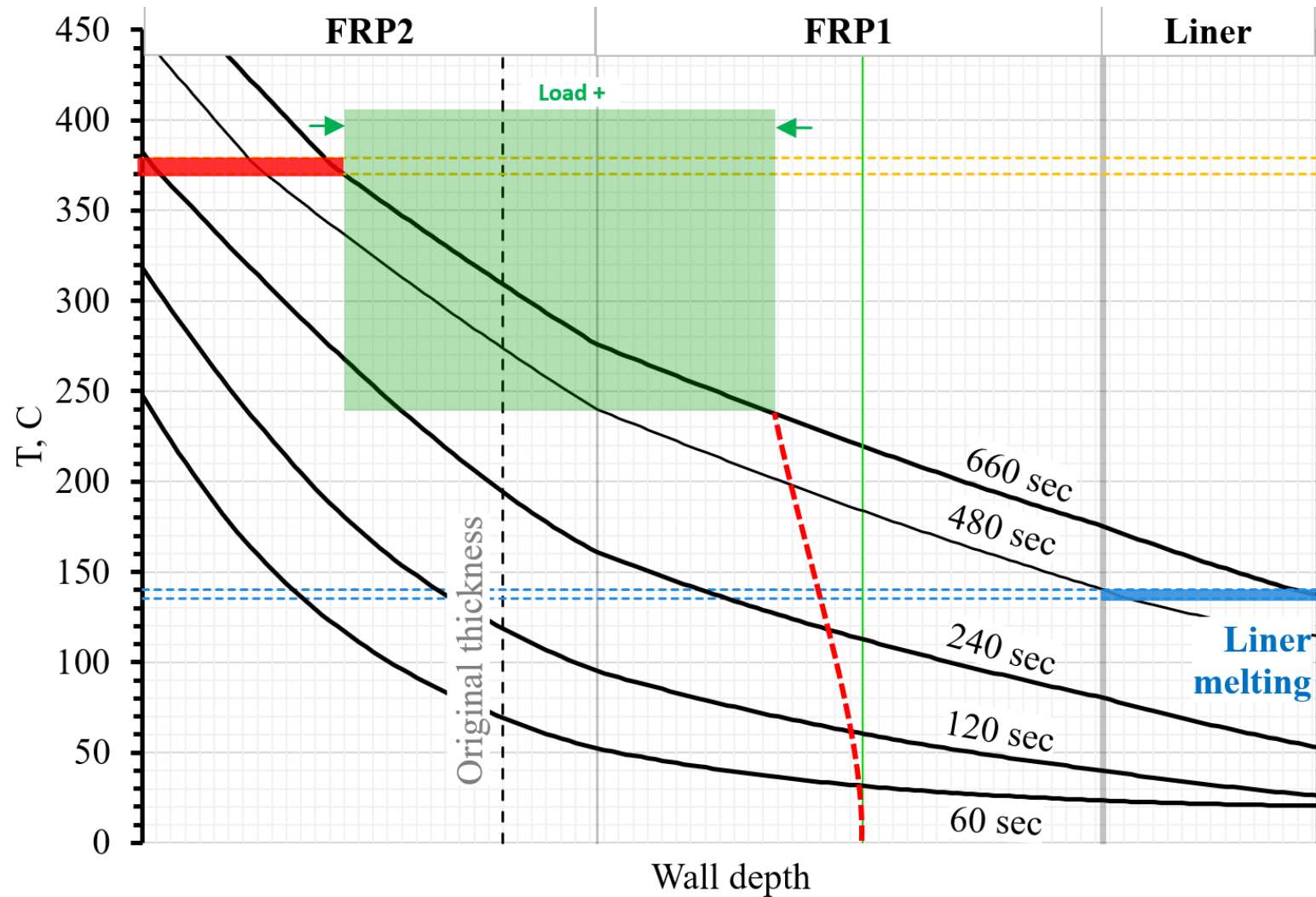




# $\mu$ LNB tank with PA liner in 0.29 MW/m<sup>2</sup> fire



# $\mu$ LNB tank with HDPE liner in 0.29 MW/m<sup>2</sup> fire



# Prototypes with PA & HDPE liners: comparison

| <b>Tank and liner</b> | <b>Weight, kg *</b> | <b>Weight +</b> | <b>Costs, EUR **</b> | <b>Costs+</b> | <b>D+</b> |
|-----------------------|---------------------|-----------------|----------------------|---------------|-----------|
| Original              | 14.18               | 0.0%            | 180.58               | 0.0%          | 0.0%      |
| μLNB,<br>HDPE liner   | 17.28               | 21.8%           | 182.29               | 0.9%          | 4.3%      |
| μLNB,<br>PA6 liner    | 25.03               | 76.4%           | 297.62               | 64.8%         | 14.4%     |

Notes: \* - total weight, including bosses (and TPRD only for standard tank), and hydrogen; \*\* - costs of composite materials only.

- The use of HDPE liner for conformable self-venting tanks allows for the reduction of the weight, diameter and cost of the tanks, compared to those with PA liner.
- Compared to the standard tank, the self-venting tanks with HDPE and PA liners provide:
  - *Increase of the weight by 21.8% and 76.4% respectively,*
  - *Increase of cost – by 0.9% and 64.8% respectively,*
  - *Increase of diameter – by 4.3% and 14.4% respectively.*
- The use of PA liner also shortens the Load+ thickness by almost twice (safety concern).



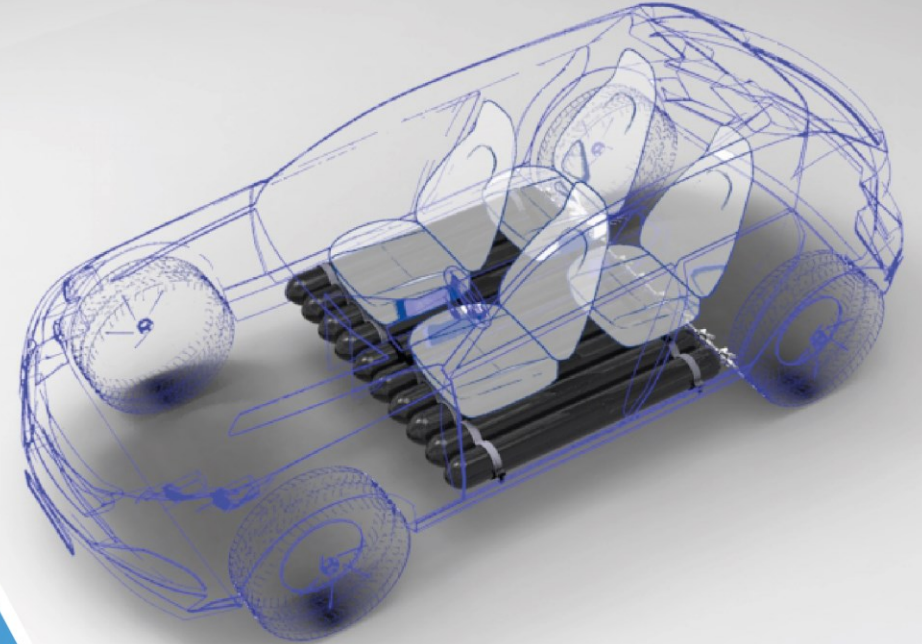
# THANK YOU



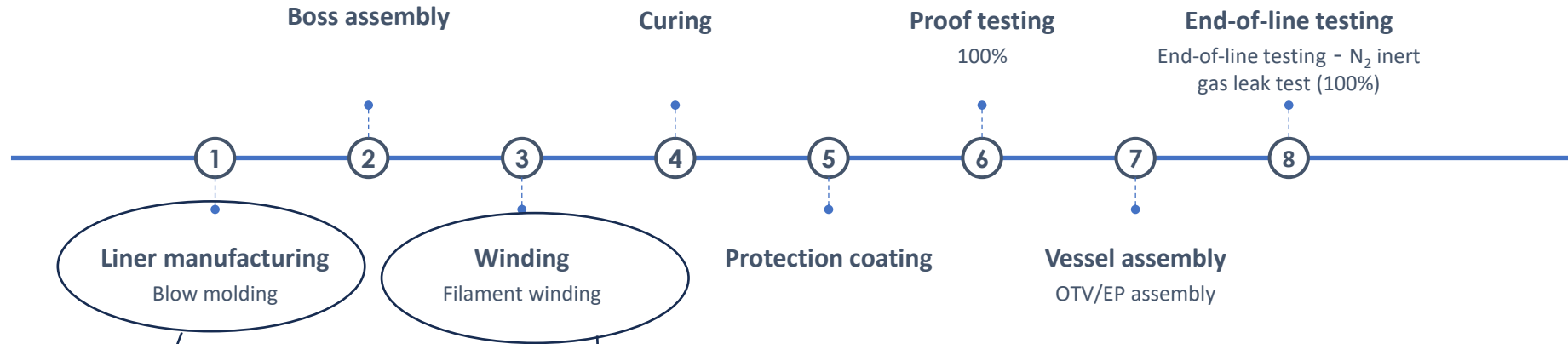
This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.

# Manufacturing of Self venting system

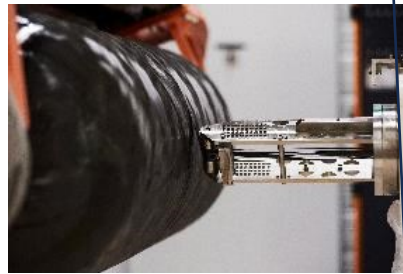
STAKEHOLDER's Workshop Brussel  
September 26<sup>th</sup> – 27<sup>th</sup>, 2024



# Overview vessel manufacturing process



Blow molding



Winding



Curing



Vessel assembly & EoL testing

Specific BM trial done (low thickness liner)

Additional winding step: glass fibre layers added

# μLNB Liner Blow-Molding

- Specific blow molding trial done; same mold, machine and material as on standard vessels, but:
- Target: lower wall thickness compared to the standard vessels (to allow quicker melting of PA6)



BM machine





- The composite vessel comprised 10 additional GF layers
- Winding time  $\mu$ LNB vessel is 2x winding time of a standard vessel
- A specific endcap tool was put in place for the production of the vessel
- Outer diameter : 160mm  
*+22mm compared to the standard vessel*
- Weight of the vessel : 21.2kg  
*+11kg compared to the standard vessel*

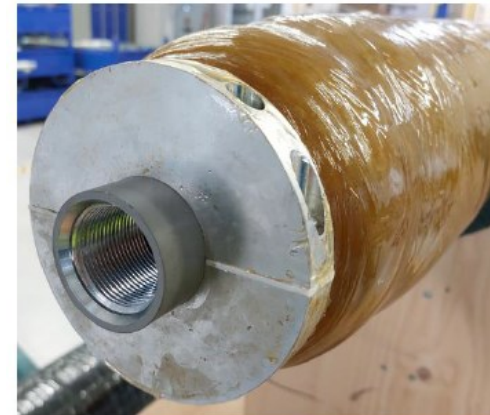


Figure 2: Endcap tooling for  $\mu$ LNB vessel development

# Overview test results final vessel at Plastic Omnium

## Plastic Omnium internal vessel validation results for $\mu$ LNB vessel

### ✓ Burst test

| Vessel - final   | Test  | Result (internal target: >1700bar) |
|------------------|-------|------------------------------------|
| Vessel $\mu$ LNB | Burst | Okay 1762 bar                      |
| Vessel $\mu$ LNB | Burst | Okay 1791 bar                      |
| Vessel $\mu$ LNB | Burst | Okay 1722 bar                      |



### ✓ Ambient cycling test

| Vessel – final   | Test            | Result             |
|------------------|-----------------|--------------------|
| Vessel $\mu$ LNB | Ambient Cycling | Okay 22.000 cycles |



19 Vessels produced within the project

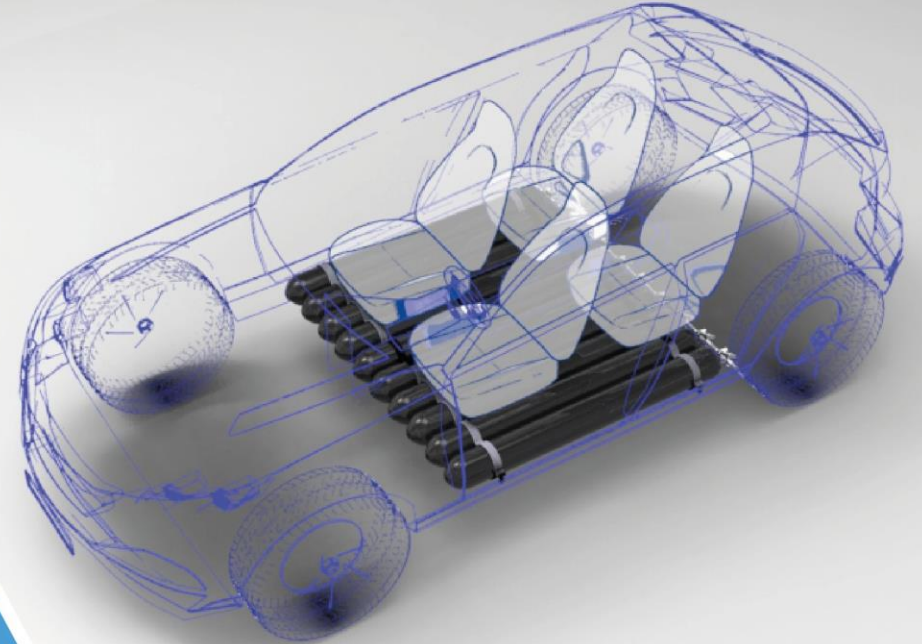
Contact: [bjorn.criel@opmobility.com](mailto:bjorn.criel@opmobility.com)



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# Fire resistance of standard and self-venting tanks in a smouldering and hydrogen jet fire

Stakeholder's workshop of SH2APED project  
26-27 September 2024  
S. Kashkarov, D. Makarov, V. Molkov

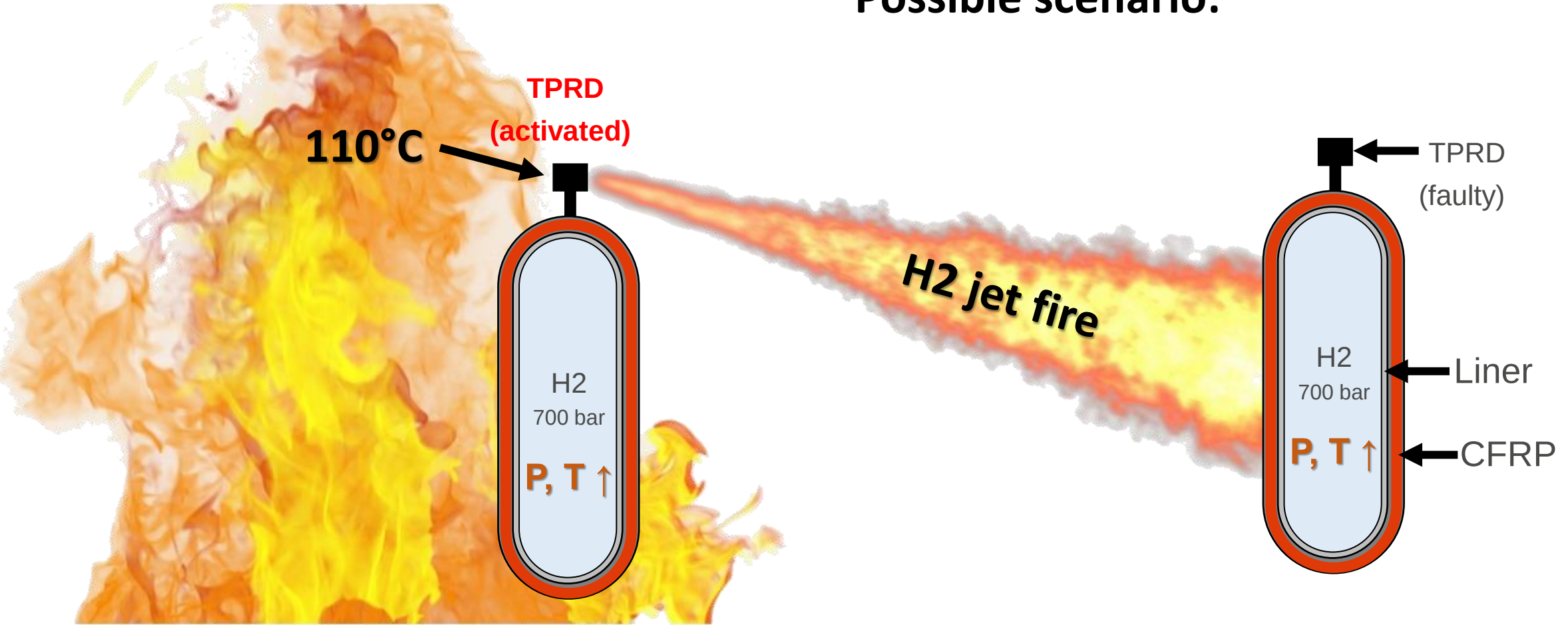




# Impinging jet fire and the performance of a conformable tank

# Jet fire impingement

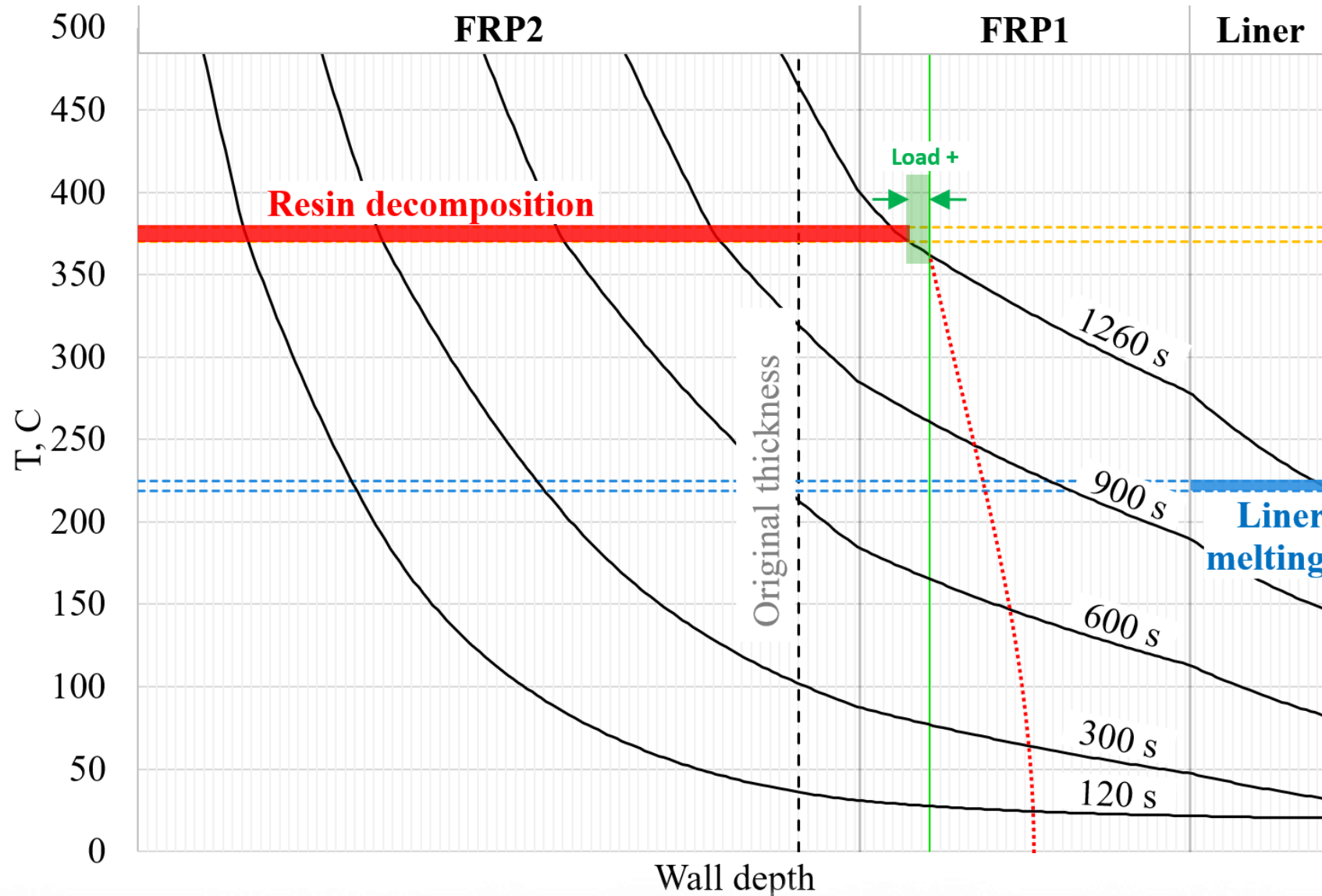
## Possible scenario:



# Jet fire impingement on standard $\mu$ LNB tank



# Jet fire: conformable $\mu$ LNB tank (PA liner)

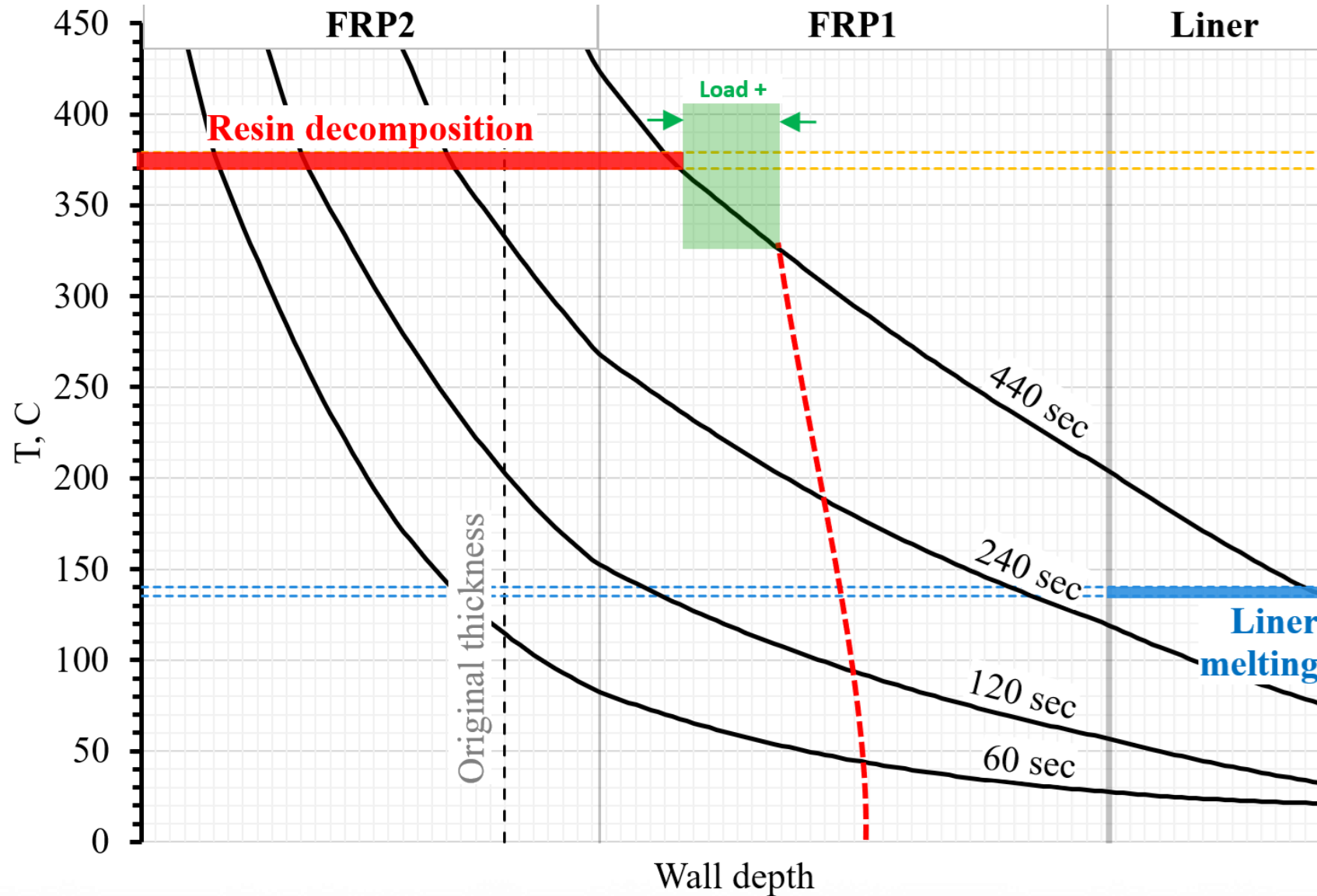


**Tank leak  
(no rupture)  
at 1260 s  
(21 min)**

**Jet fire impingement onto a conformable tank with PA requires D increase by 14%**



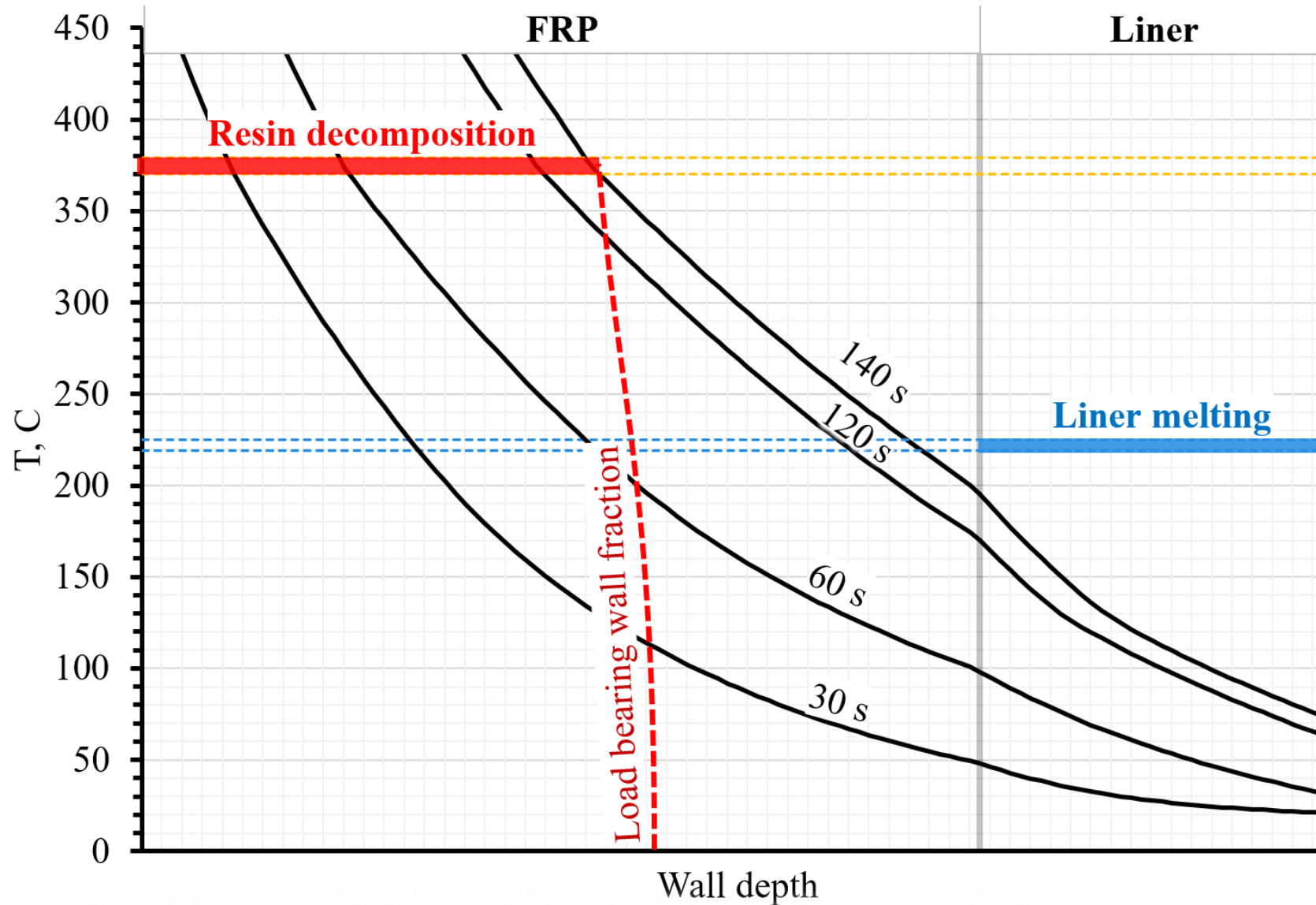
# Jet fire: conformable $\mu$ LNB tank (HDPE)



Tank leak  
(no rupture)  
at 440 s  
(7 min 20 s)

Jet fire impingement onto a conformable tank with HDPE requires D increase by 4%

# Jet fire: conformable unprotected standard tank (PA)



**Tank rupture  
at 140 s  
(2 min 20 s)**

**Exposure of a standard conformable tank with faulty TPRD to a jet fire**

# Towards the smouldering fire and the performance of a conformable tank



# Smouldering fires

## CNG garbage trucks explosions in the USA



Reference:

■ [https://www.youtube.com/watch?v=CpmWPEhlaiU&ab\\_channel=CleanFuelsOhio](https://www.youtube.com/watch?v=CpmWPEhlaiU&ab_channel=CleanFuelsOhio)



# Smouldering fires

## CNG garbage trucks explosions in the USA:

- “...natural-gas powered garbage truck began smouldering... neighbour was recording just as the truck exploded”,
- “...garbage truck exploded after catching fire ... and blasted a hole in the front of a nearby house”. “A total of four houses were damaged in the explosion”.



### References:

- <https://www.today.com/video/caught-on-camera-natural-gas-powered-garbage-truck-explodes-609780803613>.
- [https://www.nj.com/mercer/2016/01/garbage\\_truck\\_explosion\\_damages\\_hamilton\\_house.html](https://www.nj.com/mercer/2016/01/garbage_truck_explosion_damages_hamilton_house.html).

# Smouldering fires

- Smouldering fire temperatures peaks vary from 500°C to 700°C.
- Temperatures above 250-350°C, i.e. within the range of resin thermal degradation temperatures, can cause a tank rupture.



## References:

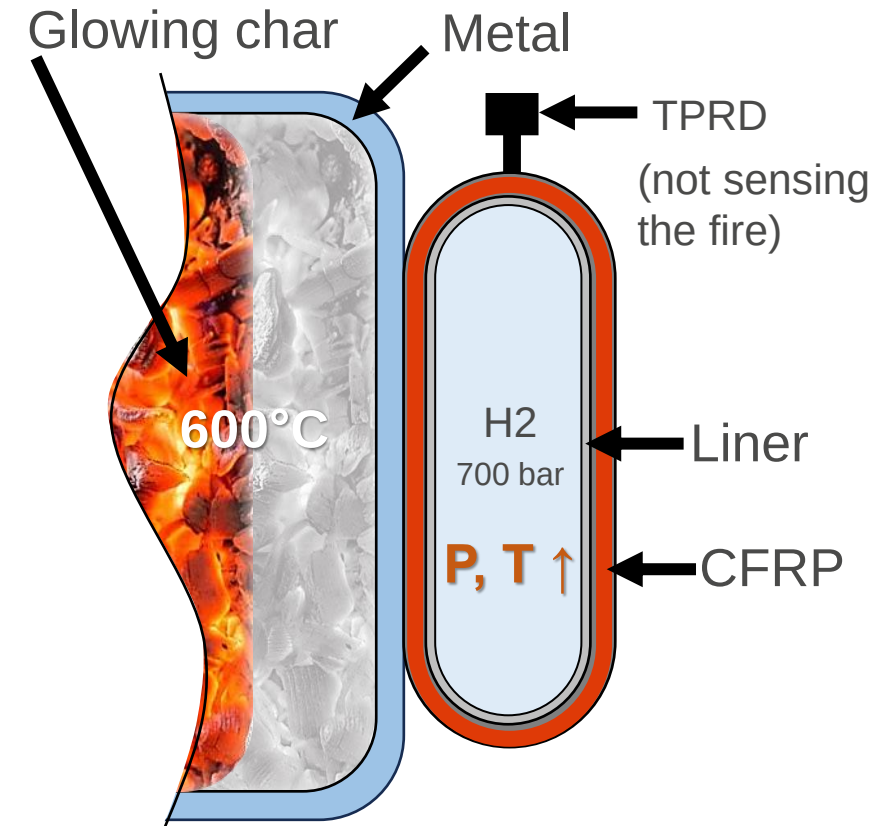
- Rein G, Cleaver N, Ashton C, Pironi P, Torero JL. The severity of smouldering peat fires and damage to the forest soil. CATENA 2008;74:304–9. <https://doi.org/10.1016/j.catena.2008.05.008>.
- Watts AC, Kobziar LN. Smoldering Combustion and Ground Fires: Ecological Effects and Multi-Scale Significance. Fire Ecol 2013;9:124–32. <https://doi.org/10.4996/fireecology.0901124>.

# Smouldering fires

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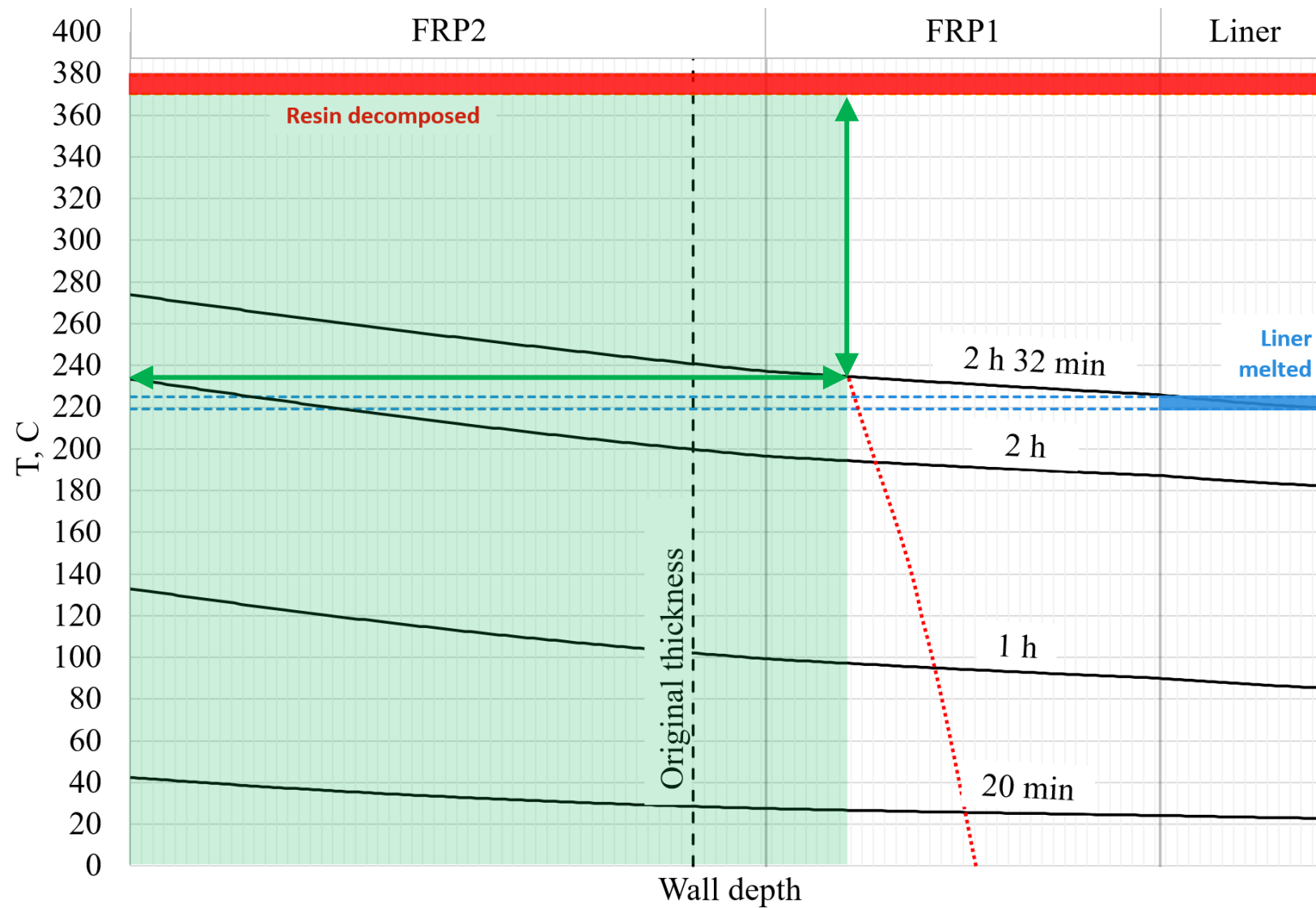
## Possible scenario:



### References:

- Rein G, Cleaver N, Ashton C, Pironi P, Torero JL. The severity of smouldering peat fires and damage to the forest soil. CATENA 2008;74:304–9. <https://doi.org/10.1016/j.catena.2008.05.008>.
- Watts AC, Kobziar LN. Smoldering Combustion and Ground Fires: Ecological Effects and Multi-Scale Significance. Fire Ecol 2013;9:124–32. <https://doi.org/10.4996/fireecology.0901124>.

# Self-venting tank in a smouldering fire





# Real-world and laboratory-scale 'conventional' fires, and the performance of a conformable tank

# Propane burner

HRR=138 kW, A=0.7095 m<sup>2</sup>,  
**HRR/A=194.5 kW/m<sup>2</sup>**



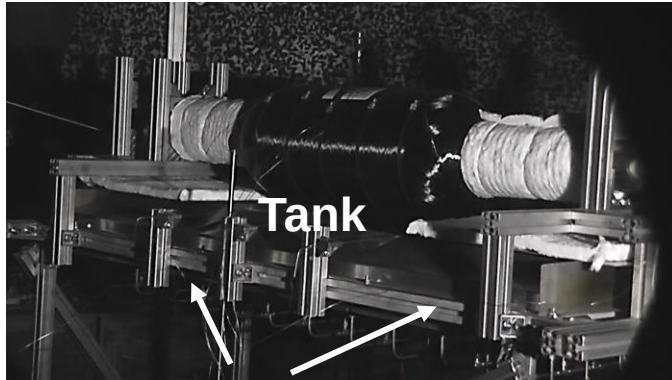
HRR=215 kW, A=0.7095 m<sup>2</sup>,  
**HRR/A=303.03 kW/m<sup>2</sup>**



- HRR=292 kW, A=0.7095 m<sup>2</sup>,  
**HRR/A=411.56 kW/m<sup>2</sup>**



# Premixed methane-air burner



HRR=165 kW, A=0.2672 m<sup>2</sup>,  
HRR/A=617.5 kW/m<sup>2</sup>



# Propane burner: under-vehicle tank



HRR=265 kW, A=0.406 m<sup>2</sup>  
HRR/A=652.7 kW/m<sup>2</sup>





# Propane burner: stand-alone tank



HRR=370 kW, A=0.251 m<sup>2</sup>  
**HRR/A=1471.4 kW/m<sup>2</sup>**



# Heptane pool fire burner No.1



HRR=1500 kW, A=0.72 m<sup>2</sup>  
HRR/A=2083.3 kW/m<sup>2</sup>



# Heptane pool fire burner No.2

HRR=4100 kW, A=0.96 m<sup>2</sup>

HRR/A=4270.8 kW/m<sup>2</sup>



# Hydrogen burner



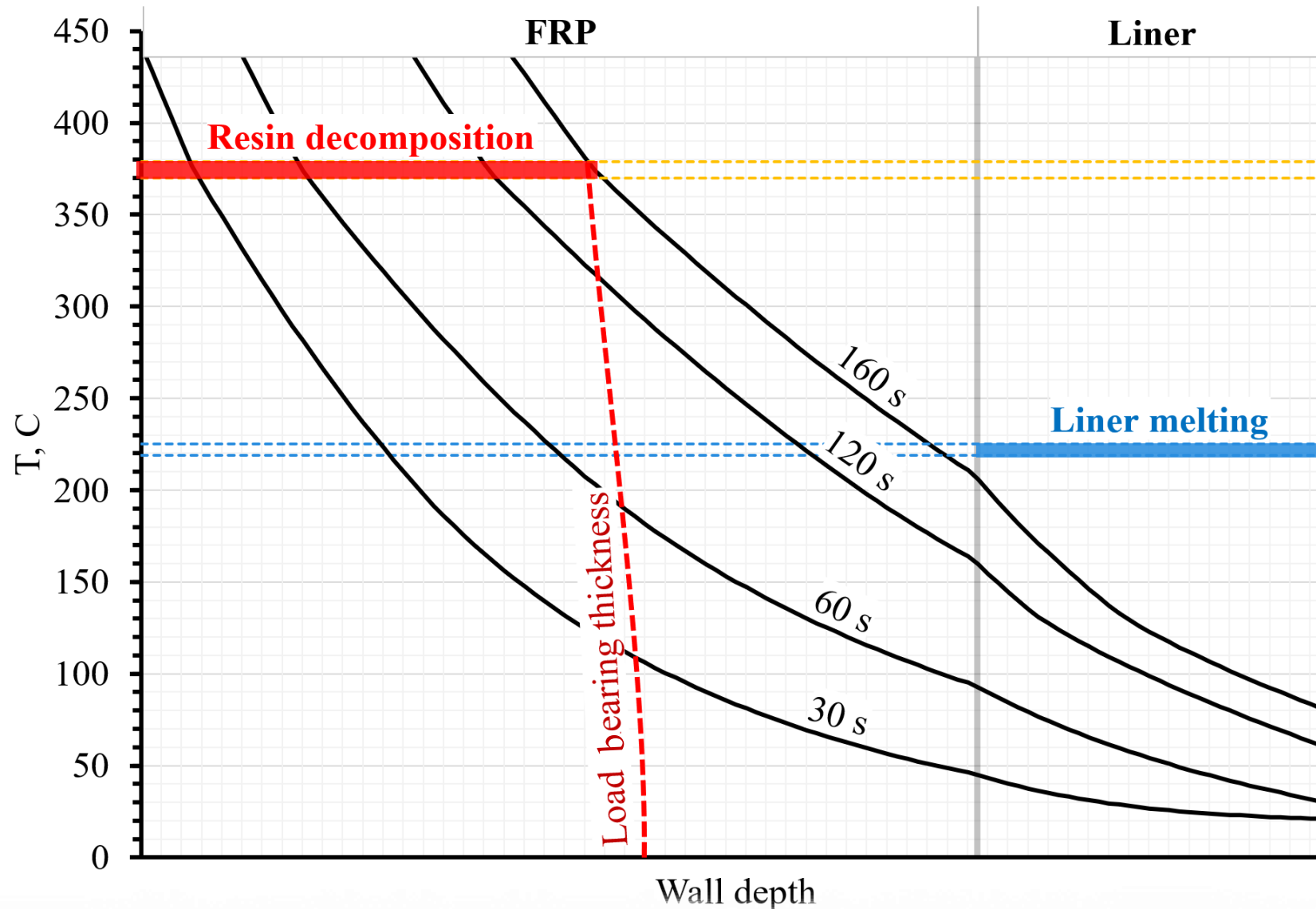
HRR=719.76 kW, A=0.09 m<sup>2</sup>

**HRR/A=7997.3 kW/m<sup>2</sup>**



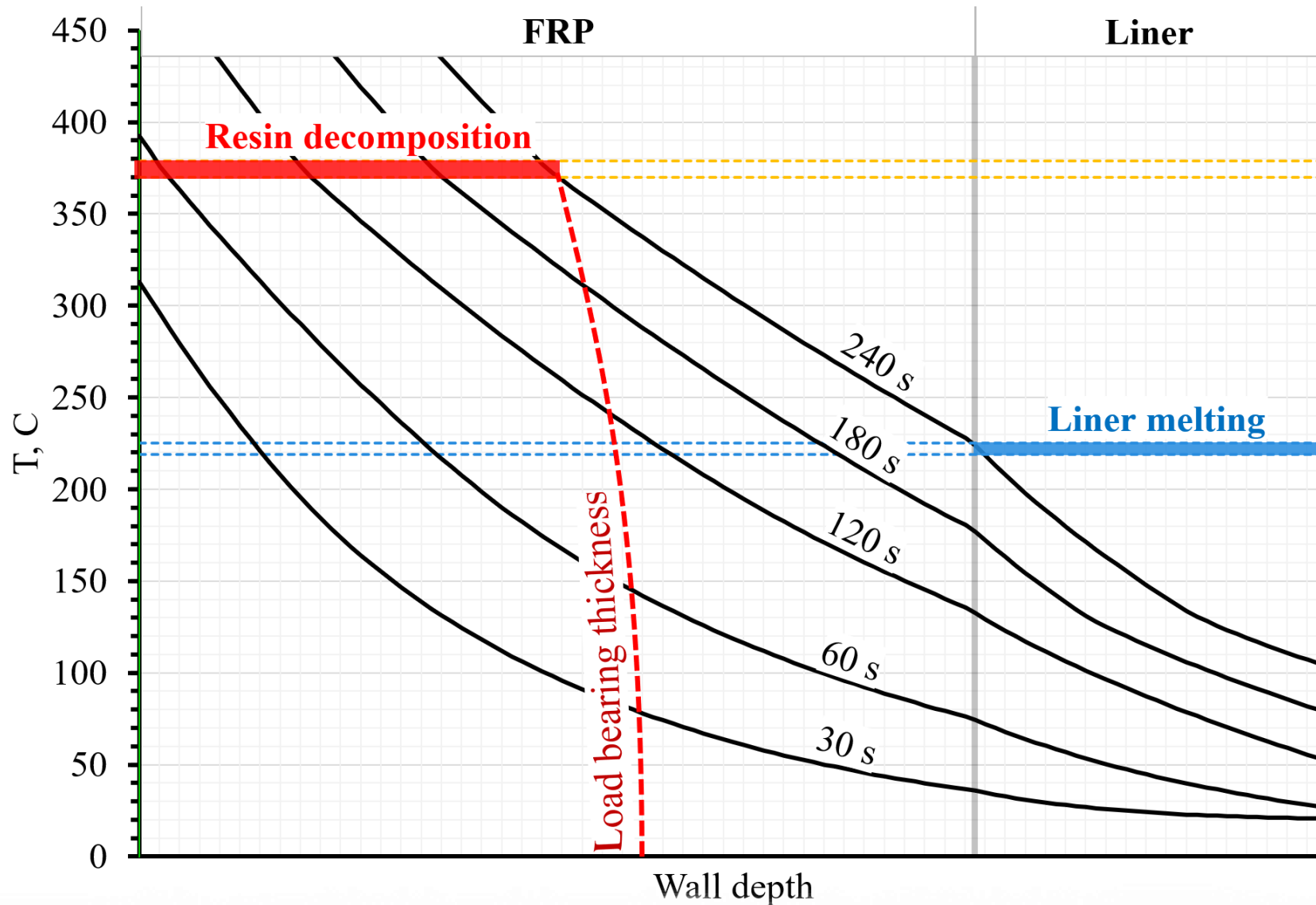


# Unprotected standard tank, fire HRR/A = 1 MW/m<sup>2</sup>



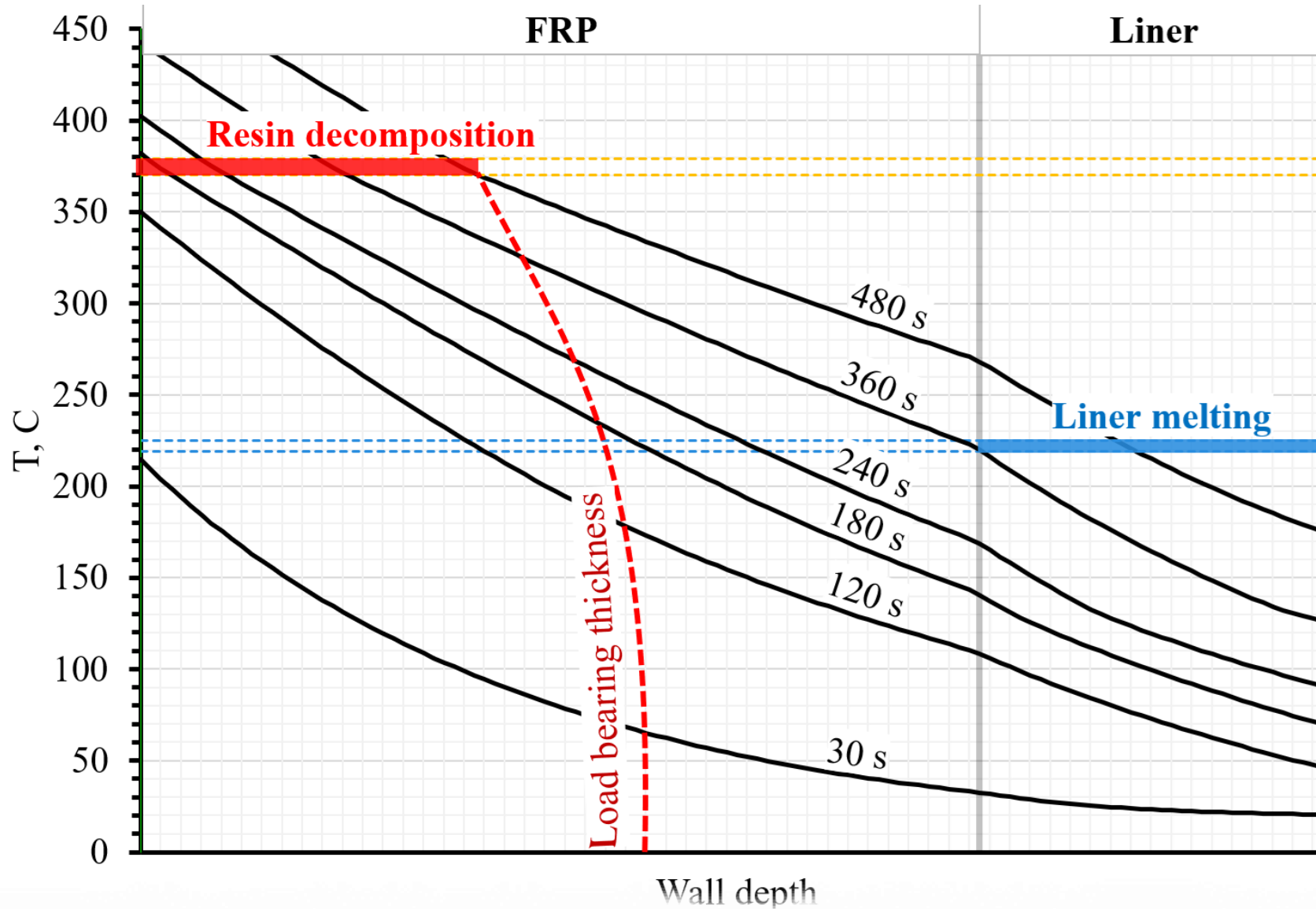
**Exposure of a standard conformable tank with faulty TPRD to a fire**

# Unprotected standard tank, fire HRR/A = 0.62 MW/m<sup>2</sup>



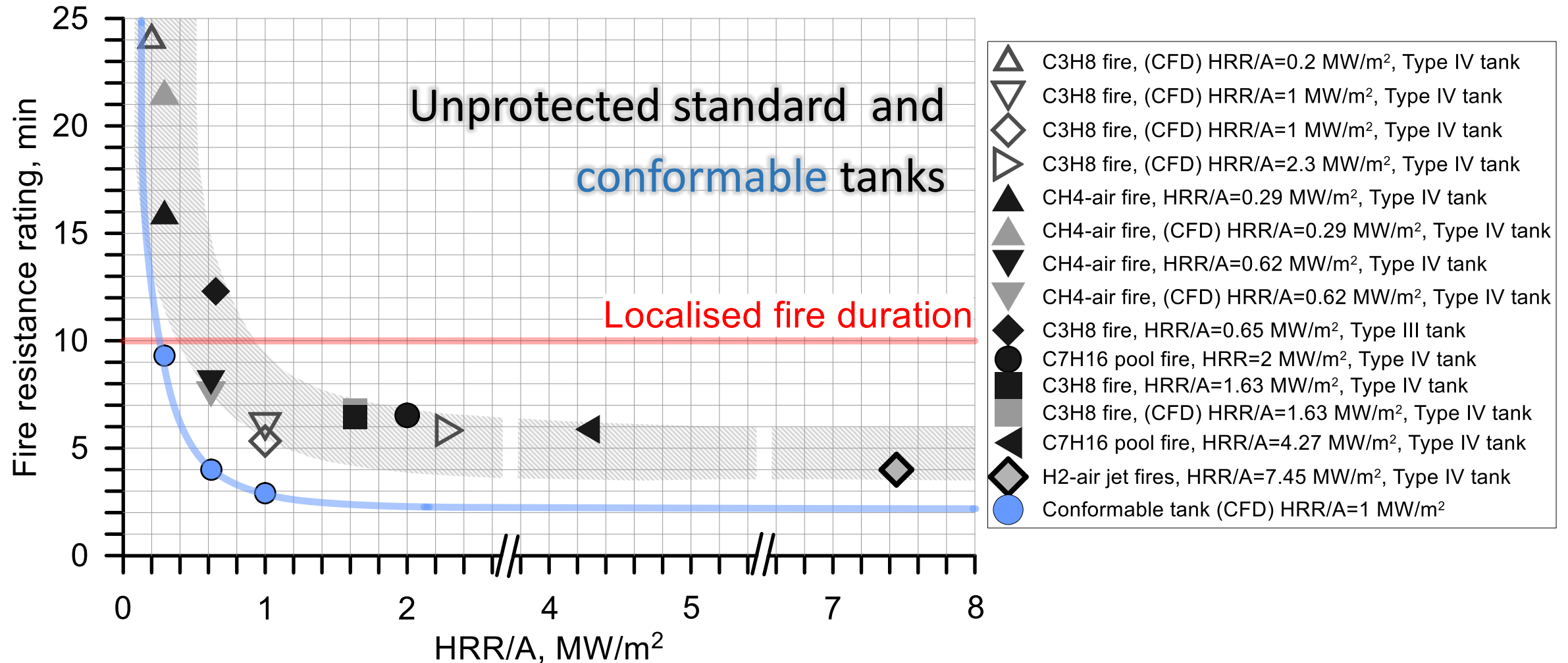
**Exposure of a standard conformable tank with faulty TPRD to a fire**

# Unprotected standard tank, fire HRR/A = 0.29 MW/m<sup>2</sup>



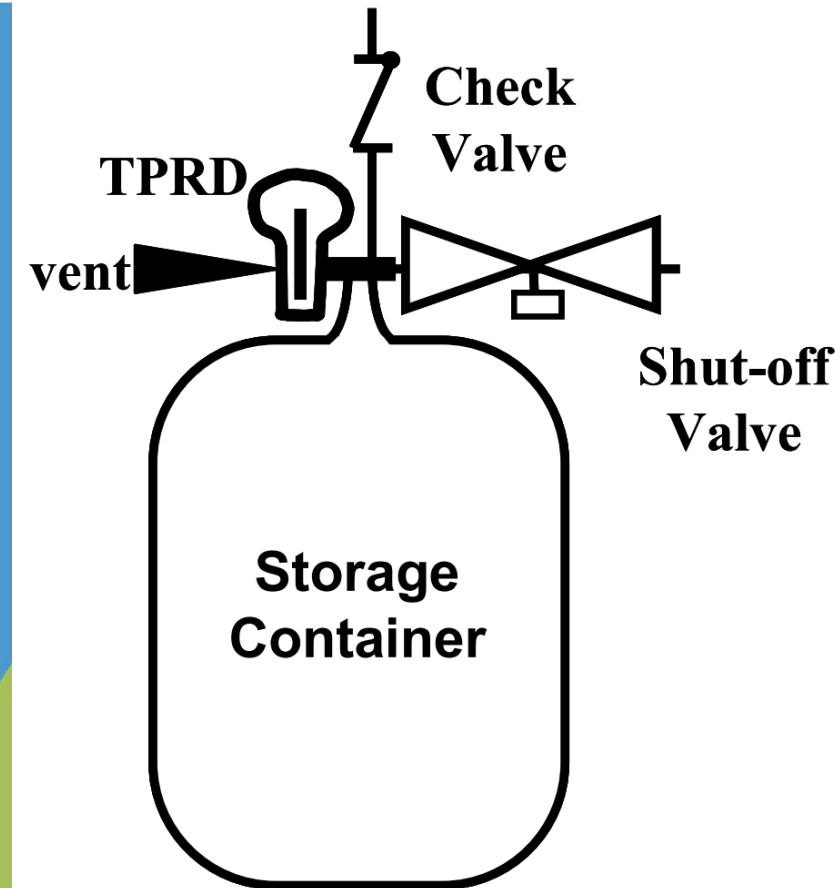
**Exposure of a standard conformable tank with faulty TPRD to a fire**

# FRR of tanks vs HRR/A of the fire sources

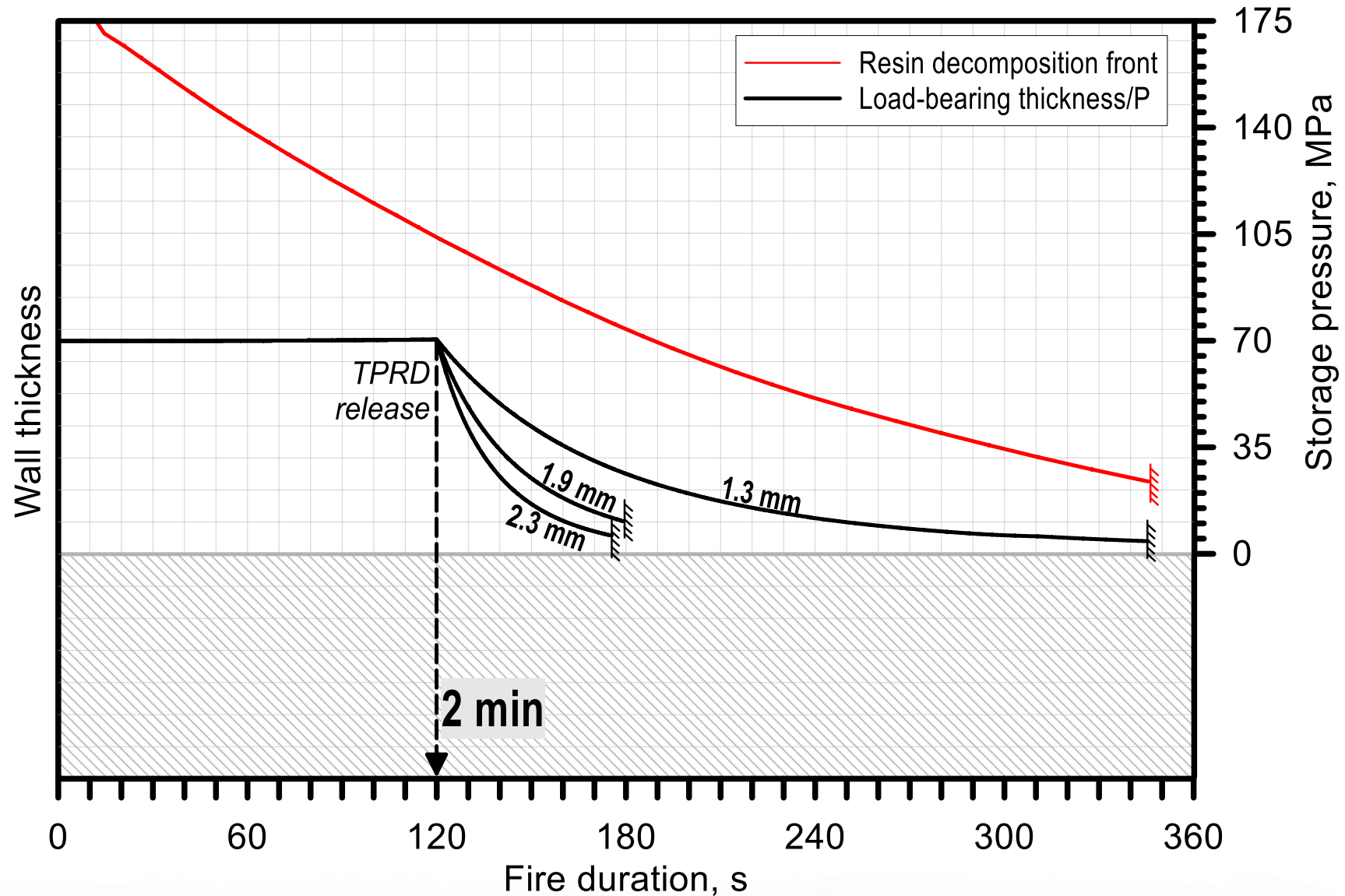




# Performance of the system conformable tank-TPRD in a real-world fire

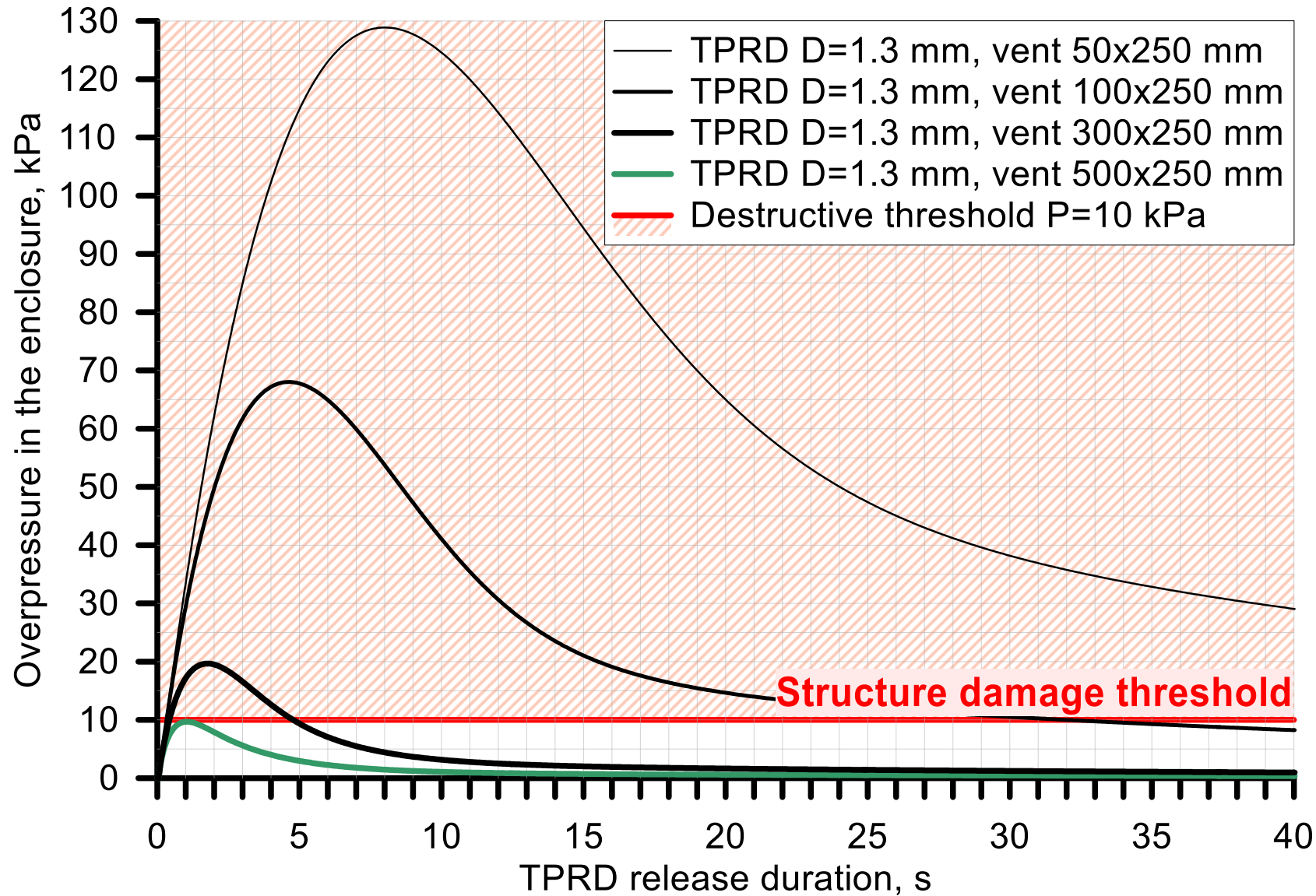


# Unprotected tank-TPRD system (1 MW/m<sup>2</sup>)



**Exposure of a standard conformable tank-TPRD system to a fire**

# Pressure peaking phenomenon (TPRD release)



- When exposed to jet fires, conformable tanks exhibit a shorter FRR (approximately 20% shorter compared to a diffusion fire with  $HRR/A = 1 \text{ MW/m}^2$ ).
- Micro-leak-no-burst technology is effective for impinging jets and prevents tank rupture.
- The use of an HDPE liner (compared to PA) allows for a reduction in diameter to +4%, from +14%, respectively.
- An initial assessment of the performance of a self-venting tank exposed to a smoldering fire demonstrated the safest performance with a 100% Load+ (assuming a faulty TPRD).
- It was found that a TPRD with a diameter of 1.3 mm is sufficient to prevent the rupture of a CHSS with 9 conformable tanks.
- However, a TPRD of 1.3 mm can lead to a pressure-peaking phenomenon, necessitating an increase in vent size from one brick size (50 x 250 mm) to ten brick sizes (500 x 250 mm). Self-venting tanks eliminate this problem.



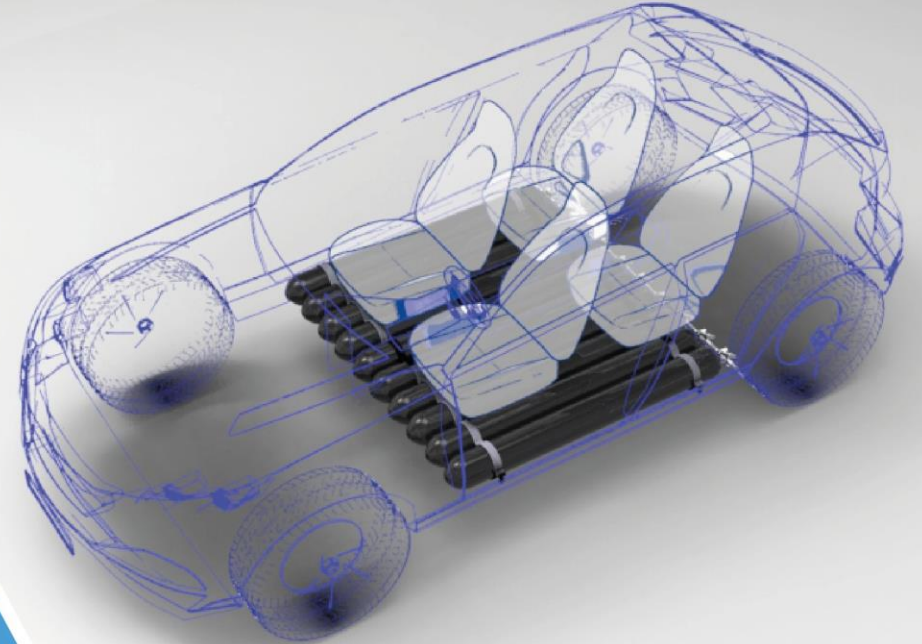
# THANK YOU



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# Performance of an onboard conformable hydrogen storage system in a vehicle fire incident

Stakeholder's workshop of SH2APED project  
26-27 September 2024  
S. Kashkarov, D. Makarov, V. Molkov



# Fuel spill fires

- The Norwegian incident in the tunnel with the gasoline spill of 225 m<sup>2</sup> produced the maximum 1.96 MW/m<sup>2</sup>.
- Ingason and Li estimated HRR/A of 0.8-1 MWm<sup>2</sup> in their experimental work on gasoline spill fires.
- The experimental studies of Li et. al. on fire in tunnels demonstrated HRR/A up to 1.8 MW/m<sup>2</sup>.



## References:

- Ingason H, Li YZ. Spilled liquid fires in tunnels. *Fire Saf J* 2017;91:399–406. <https://doi.org/10.1016/j.firesaf.2017.03.065>.
- Bratt tunnel årsak til at brannen spredte seg raskt over 500 meter 2016. <https://www.bt.no/nyheter/lokalt/i/88k9d/bratt-tunnel-aarsak-til-at-brannen-spredte-seg-raskt-over-500-meter> (accessed July 21, 2023).
- Li J, Tian Y, Li Y, Zhao Y, Huang Y. Numerical and Experimental Study on the Effects of the Slope on the Critical Velocity in Titled Tunnels. *Procedia Eng* 2017;205:1864–70. <https://doi.org/10.1016/j.proeng.2017.10.265>.



# Possible fuel spill fire scenario



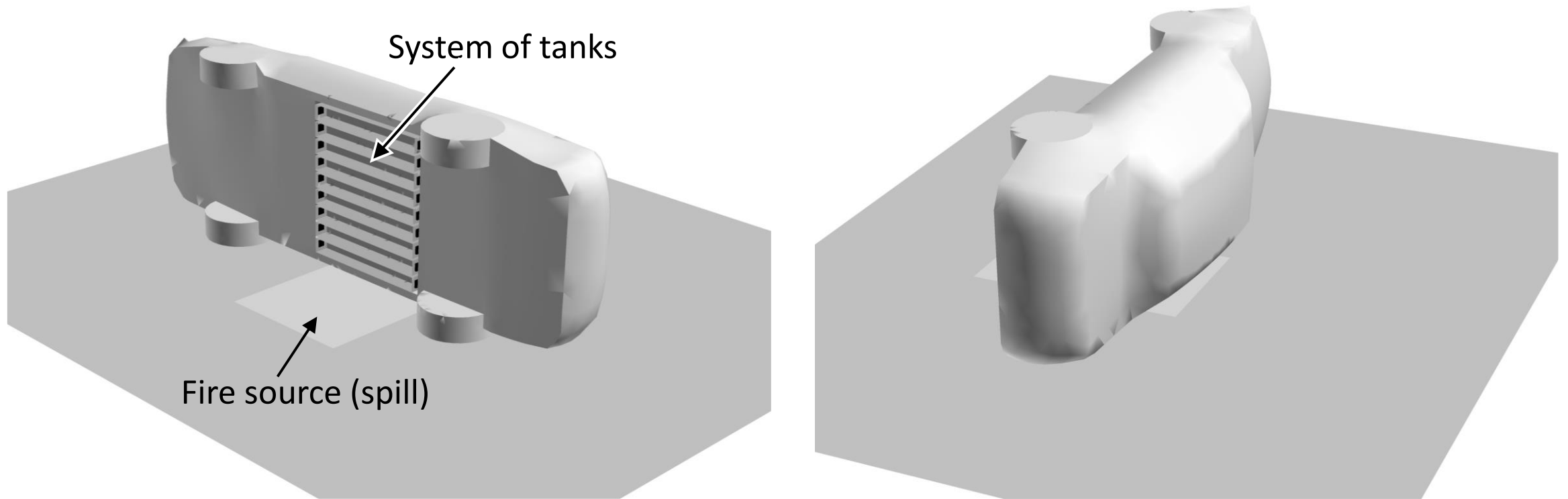
## References:

- Vernon H. Passengers run for their lives after bus catches fire in Argentina. Independent 2023. <https://www.independent.co.uk/tv/news/passengers-flee-bus-fire-argentina-b2394755.html> (accessed August 18, 2023).
- Rumpf-Whitten S. Passengers on Argentina bus run for their lives after public bus becomes engulfed in flames. Yahoo News 2023. <https://news.yahoo.com/passengers-argentina-bus-run-lives-040422535.html> (accessed August 18, 2023).
- BBC. Watch moment passengers flee after bus catches fire. BBC News 2023. <https://www.bbc.co.uk/news/av/world-latin-america-66529625> (accessed August 18, 2023).



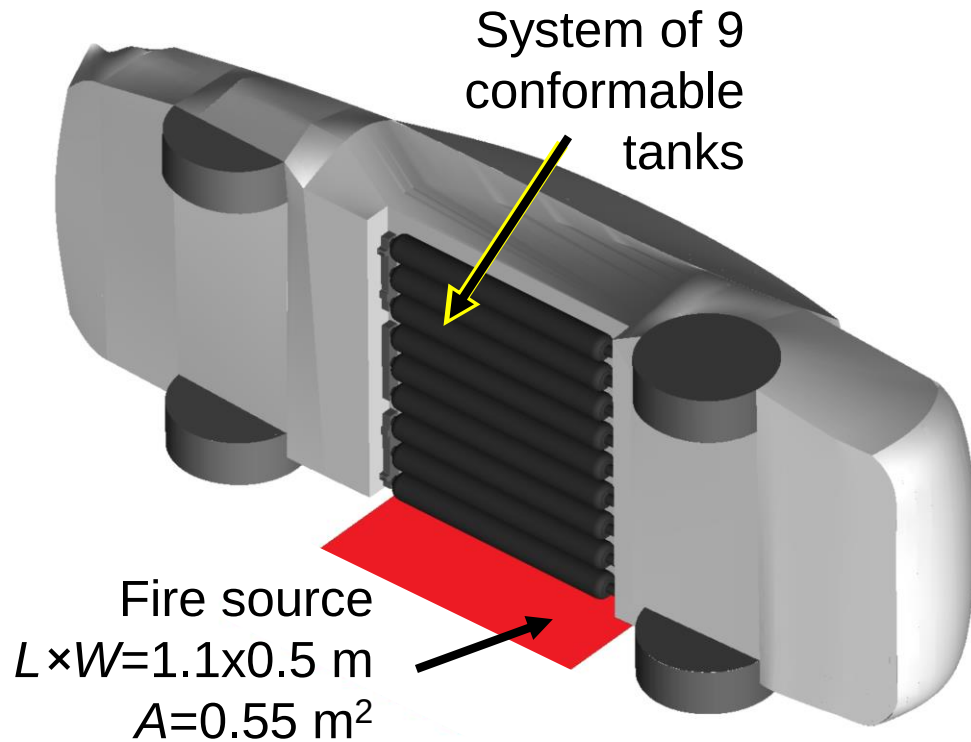
# Problem formulation

- 3D CFD simulations: system of 9 onboard tanks in metal box in a fire
- Overturned car assumed, as a result of an incident

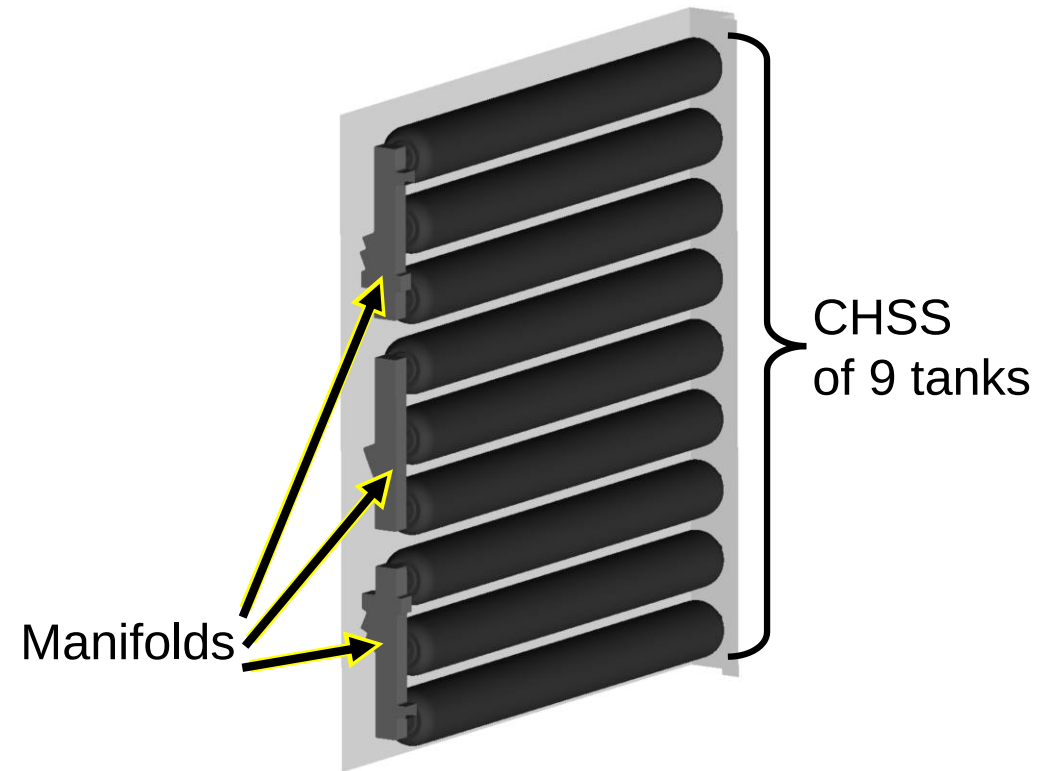


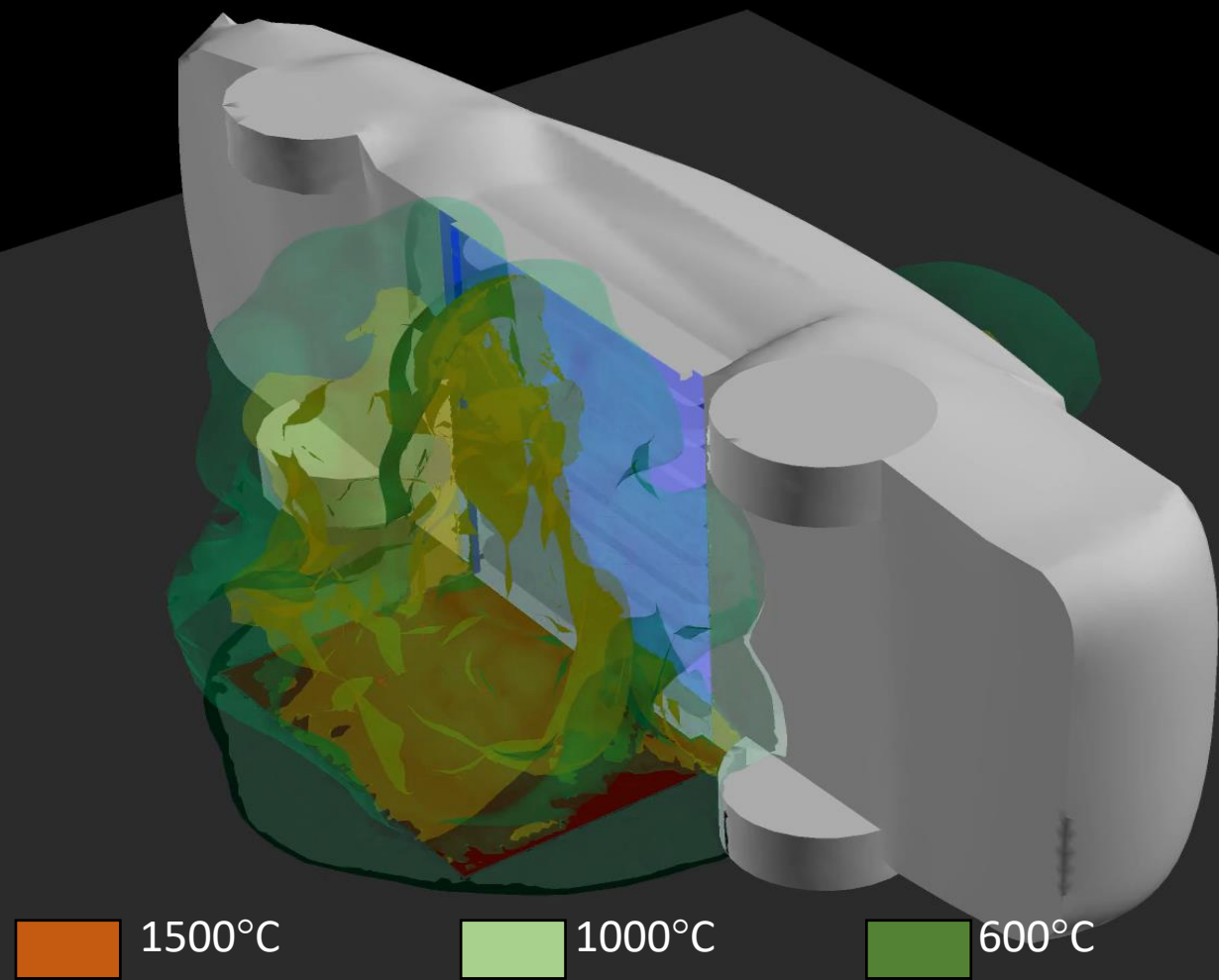
# Problem formulation

Car fire: geometry of the overturned car and “spill”

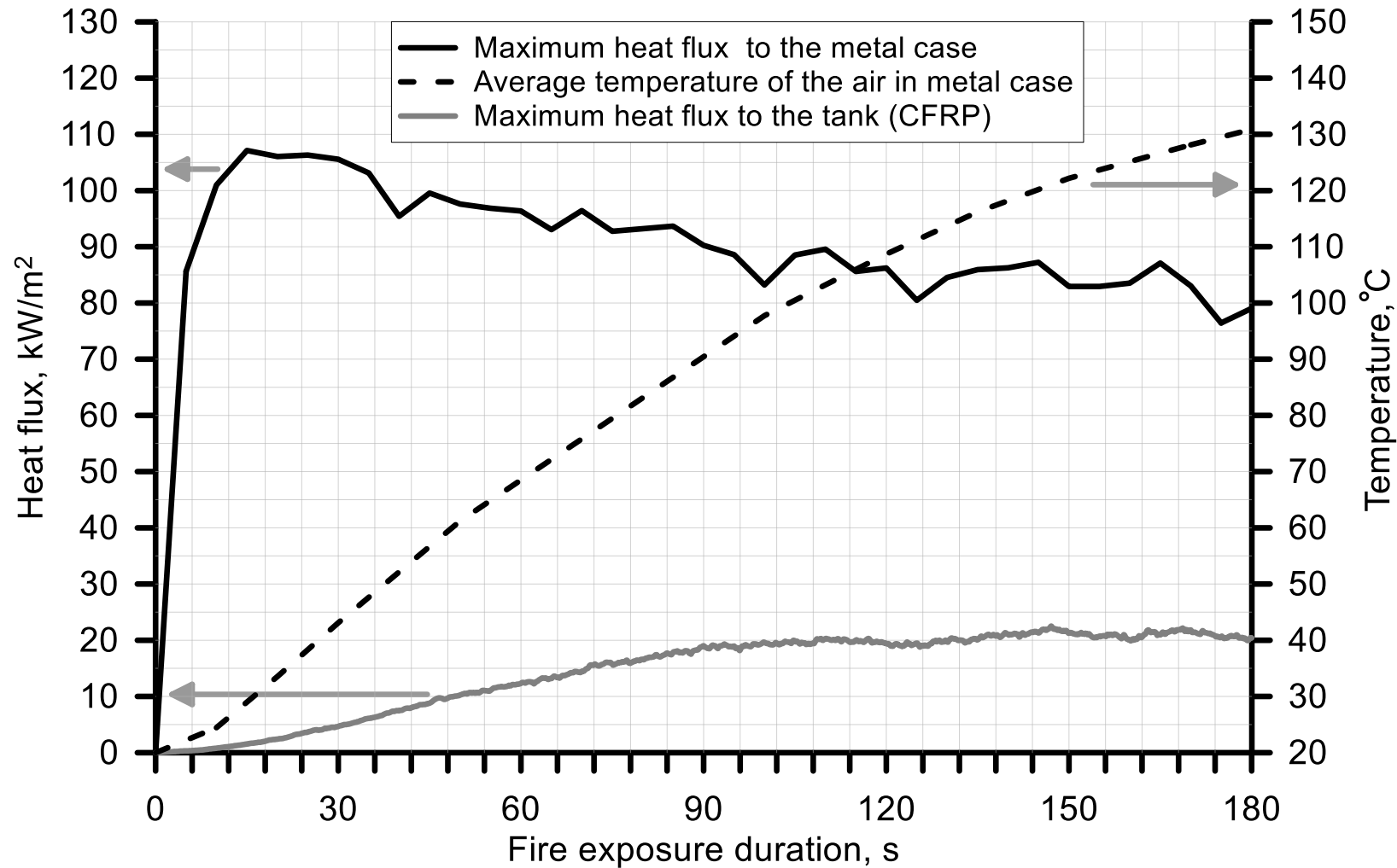


Car fire: geometry of the system of conformable tanks



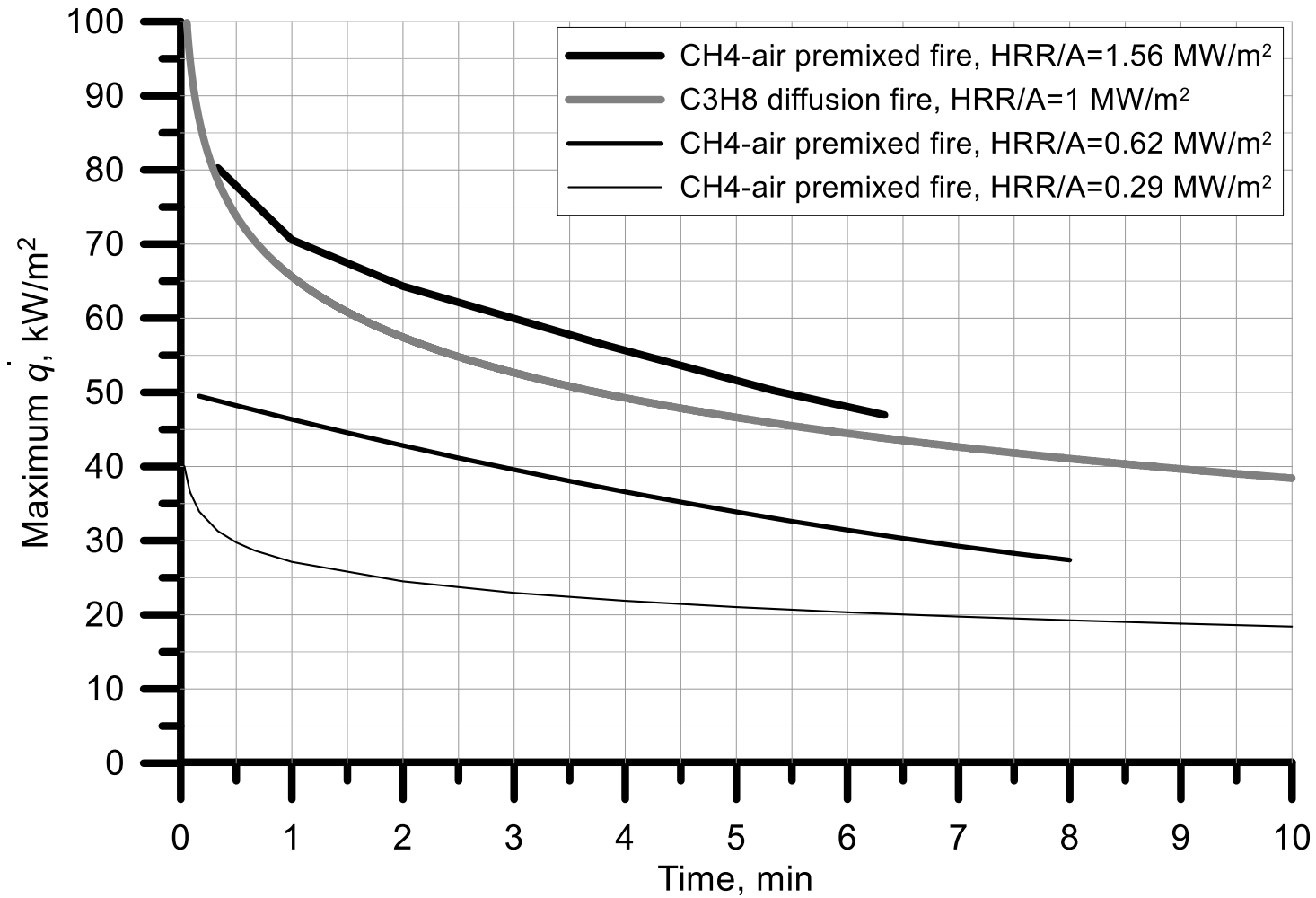


# Heat fluxes and temperatures

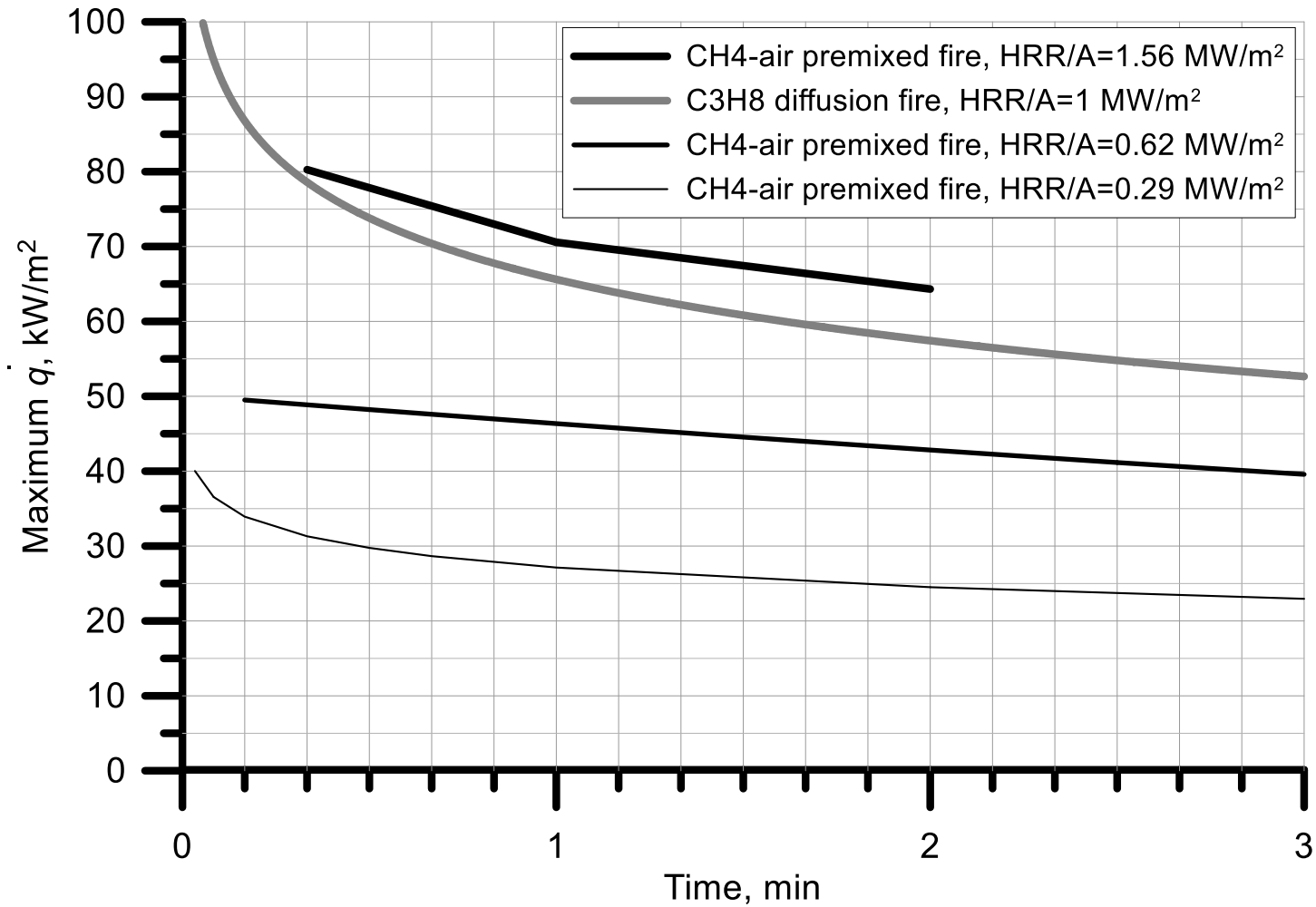




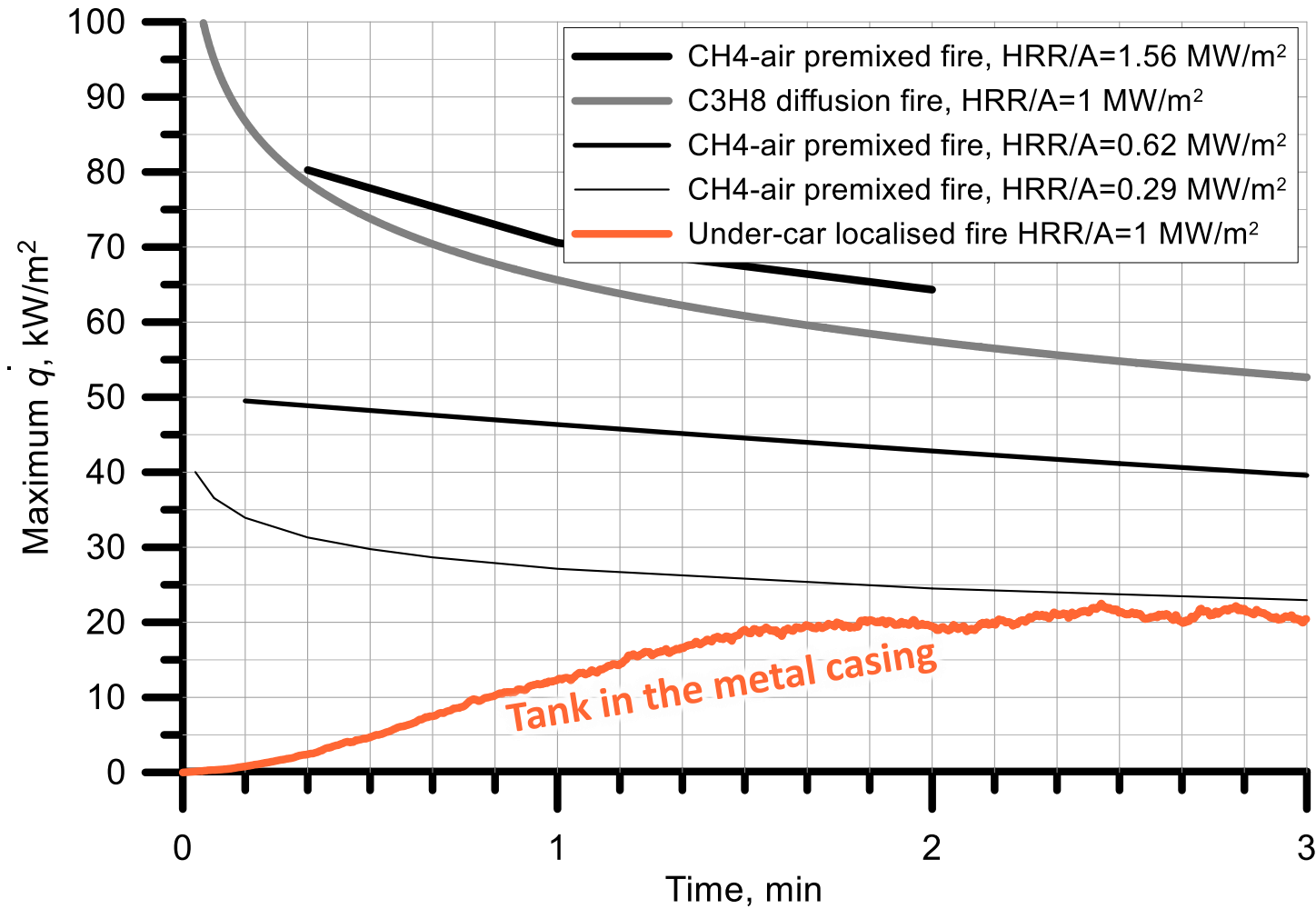
# Heat fluxes to the tank



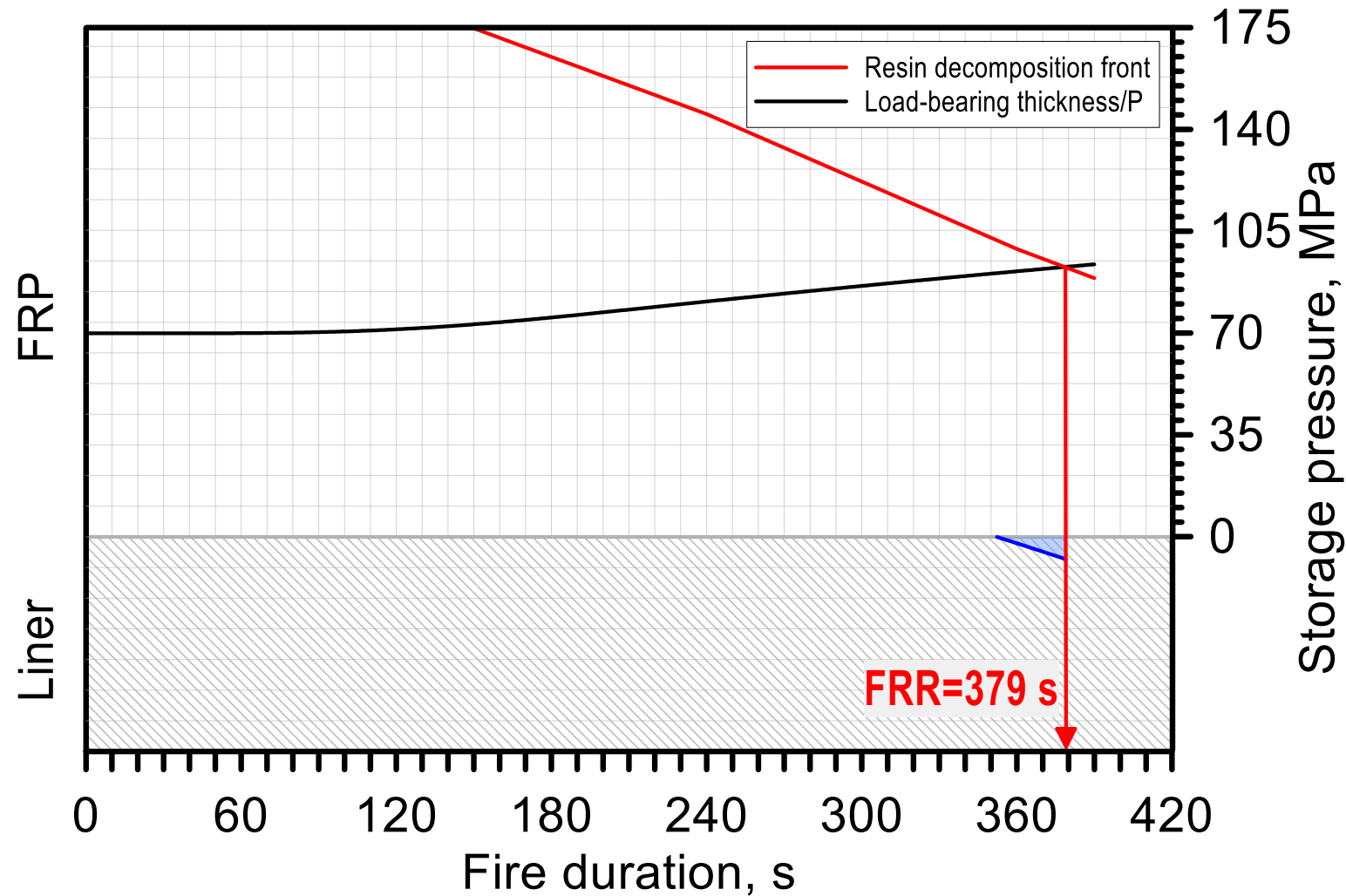
# Heat fluxes to the tank



# Heat fluxes to the tank

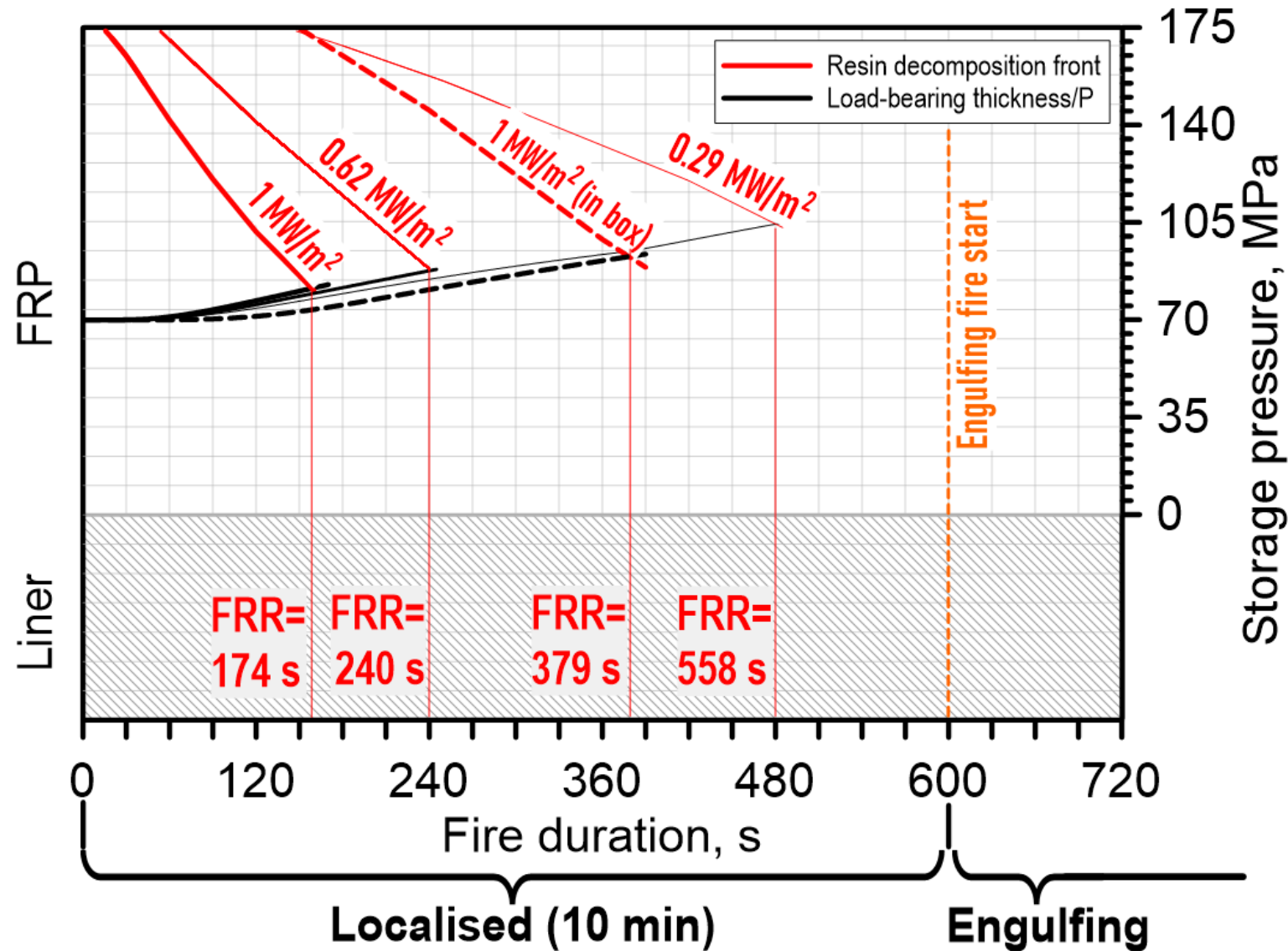


# FRR of the tank in metal casing

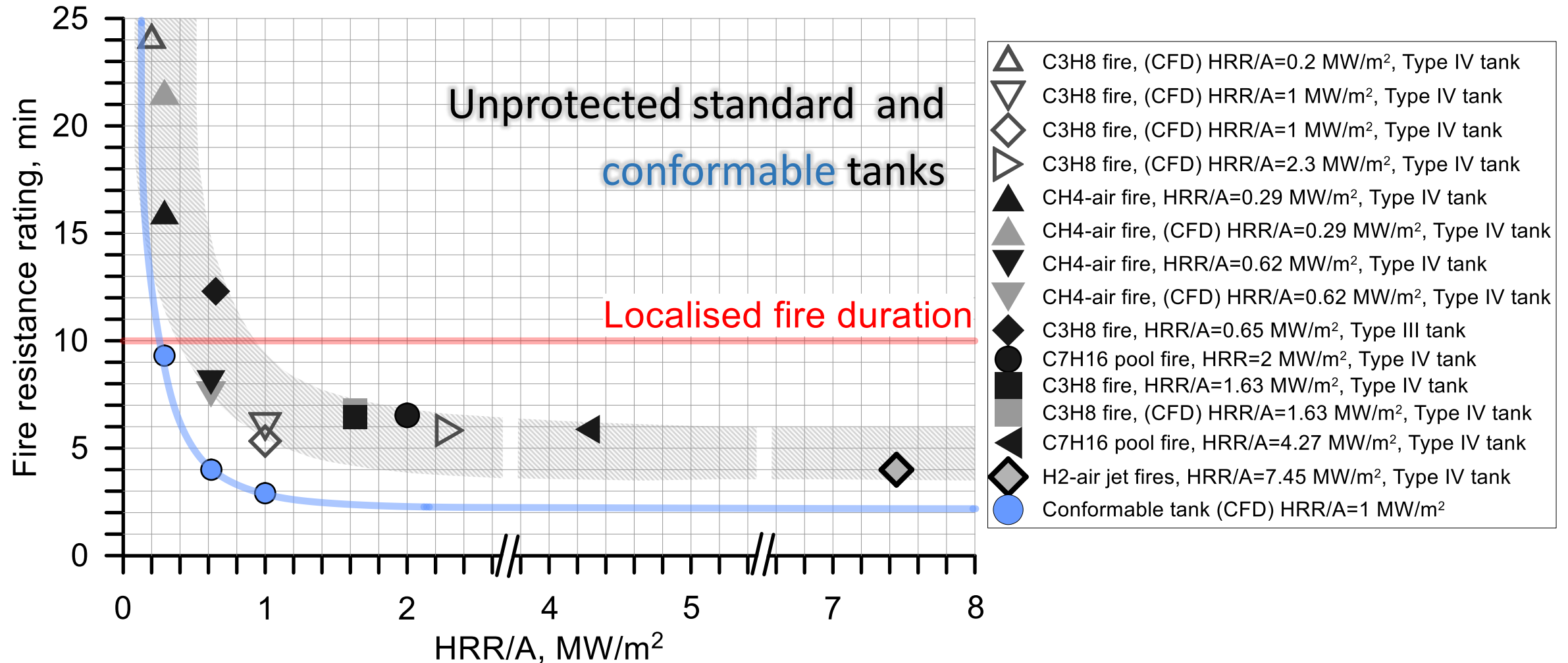




# FRR of the unprotected and protected tanks

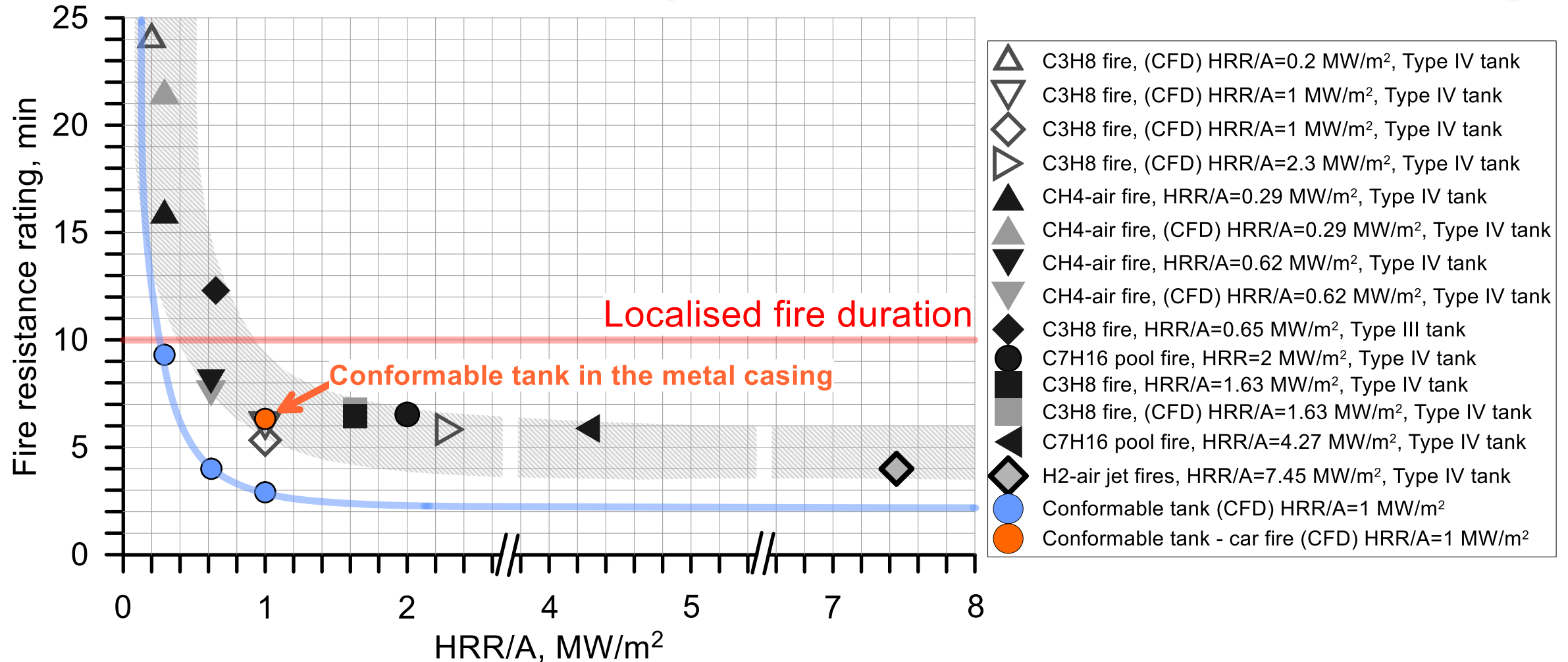


# FRR of tanks vs HRR/A of the fire sources



# FRR of tanks vs HRR/A of the fire sources

Standard and **conformable** unprotected tanks and tanks in a metal casing



- The FRR of conformable tanks appears to be ~3 min, at a fire HRR/A=1 MW/m<sup>2</sup>. This is significantly (2-3 times) shorter than FRR of standard tanks (with L/D=2~5) of 6-8 min.
- This imposes a greater risk of hydrogen tank rupture as such FRR is comparable with the TPRD activation delay time, i.e. in some cases, e.g. remote localised fire, the TPRD may fail to release hydrogen and the tank could rupture catastrophically.
- The presence of the metal casing is able to extend the FRR by more than a factor of 2, which is favorable when designing the CHSS package. However, it does not exclude tank rupture.



# THANK YOU



This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.

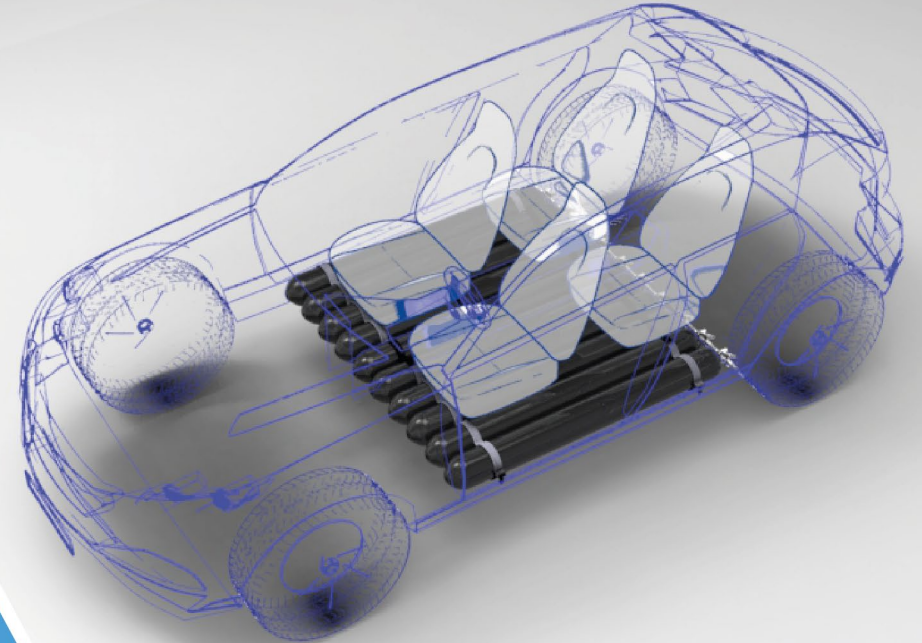


Storage of Hydrogen  
Alternative Pressure Enclosure Development



# TPRD as a safety device: underground parking

Stakeholder's workshop of SH2APED project  
26-27 September 2024, Brussels, Belgium  
V. Shentsov, D. Cirrone, D. Makarov



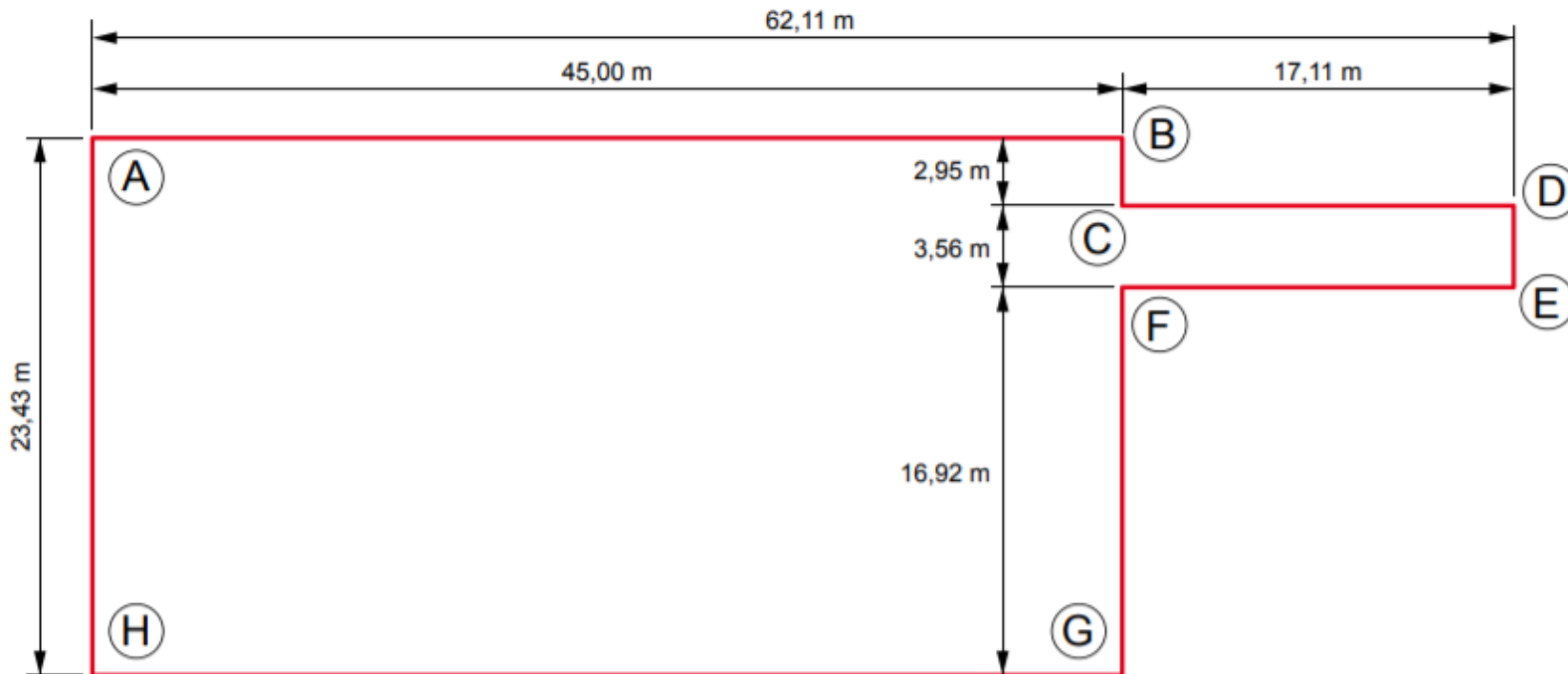
[www.sh2aped.eu](http://www.sh2aped.eu)

Underground parking generally equipped with mechanical systems to fulfil the ventilation requirements according to BS 7346-7:2013.

- Requirements in normal working conditions:
  - 6 air changes per hour (ACH) in the main parking area
  - 10 ACH in the zones where vehicles may stop with running engines
  
- Requirements in the event of fire:
  - Provide 10 ACH
  - Maintain velocity lower than 5 m/s in the escape routes to not impede the occupants escape

# Underground car park layout

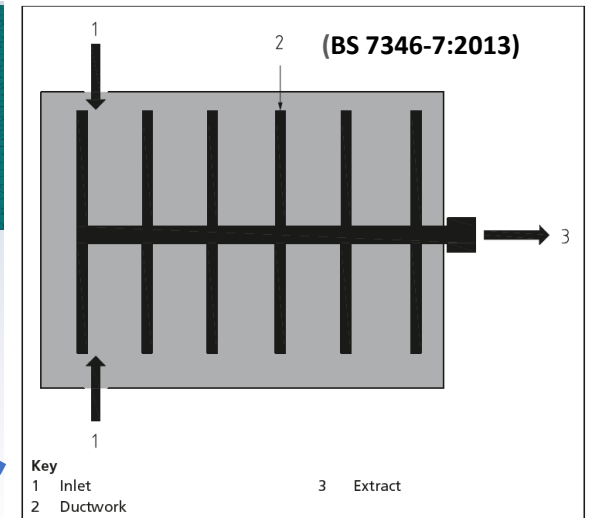
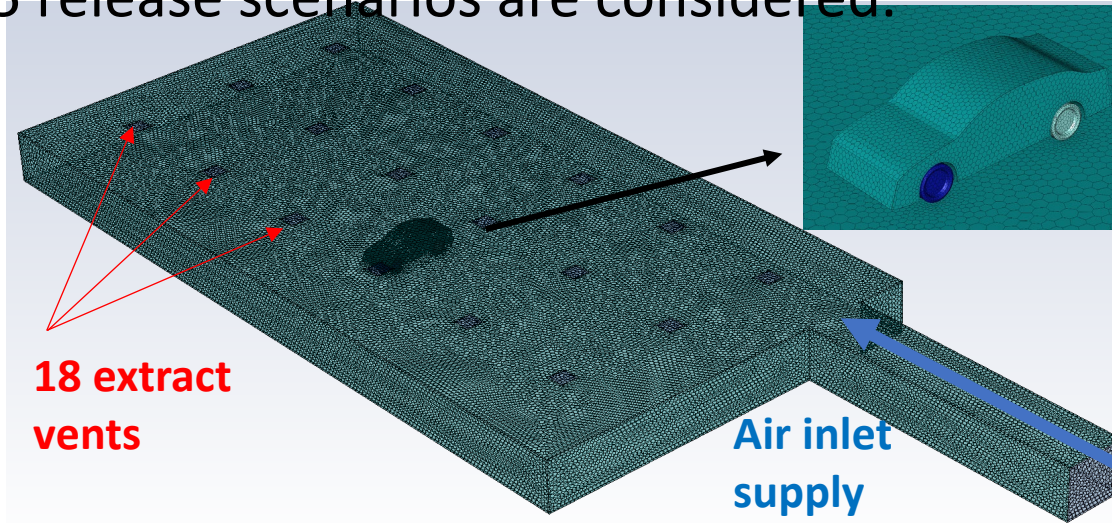
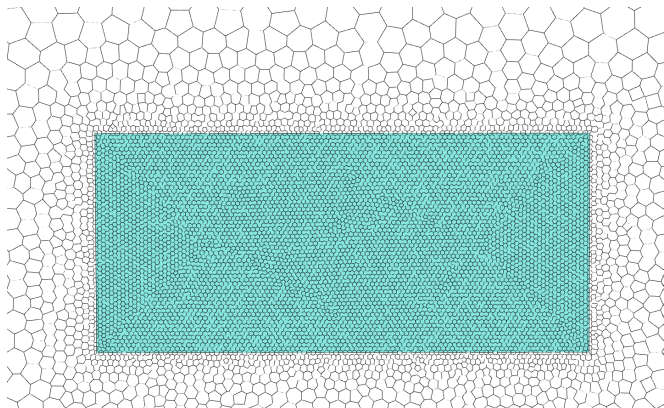
Real underground car park in St. Martnes Latem (Gent, Belgium).



| Parameter              | Value |
|------------------------|-------|
| Width, m               | 23.5  |
| Length, m              | 45    |
| Height, m              | 3     |
| Volume, m <sup>3</sup> | 3346  |



- **Numerical details:** transient formulation, with volumetric source (VS) for blowdown, pressure-based implicit solver, realizable k-e for turbulence, second order upwind scheme for the momentum, species and energy equations. Mesh: 440,000 poly-hex-core CVs.
- **Geometry and ventilation:** ventilation 10 ACH, 18 evenly distributed extraction vents (BS 7346-7:2013)
- **Release scenarios:** 15 release scenarios are considered.



# Unignited release

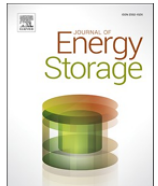
Journal of Energy Storage 68 (2023) 107771



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Journal of Energy Storage

journal homepage: [www.elsevier.com/locate/est](https://www.elsevier.com/locate/est)



Research papers

Effect of TPRD diameter and direction of release on hydrogen dispersion and jet fires in underground parking

V. Shentsov<sup>\*</sup>, D. Cirrone, D. Makarov

Hydrogen Safety Engineering and Research Centre (HySAFER), Ulster University, Shore Road, Newtownabbey BT37 0QB, UK

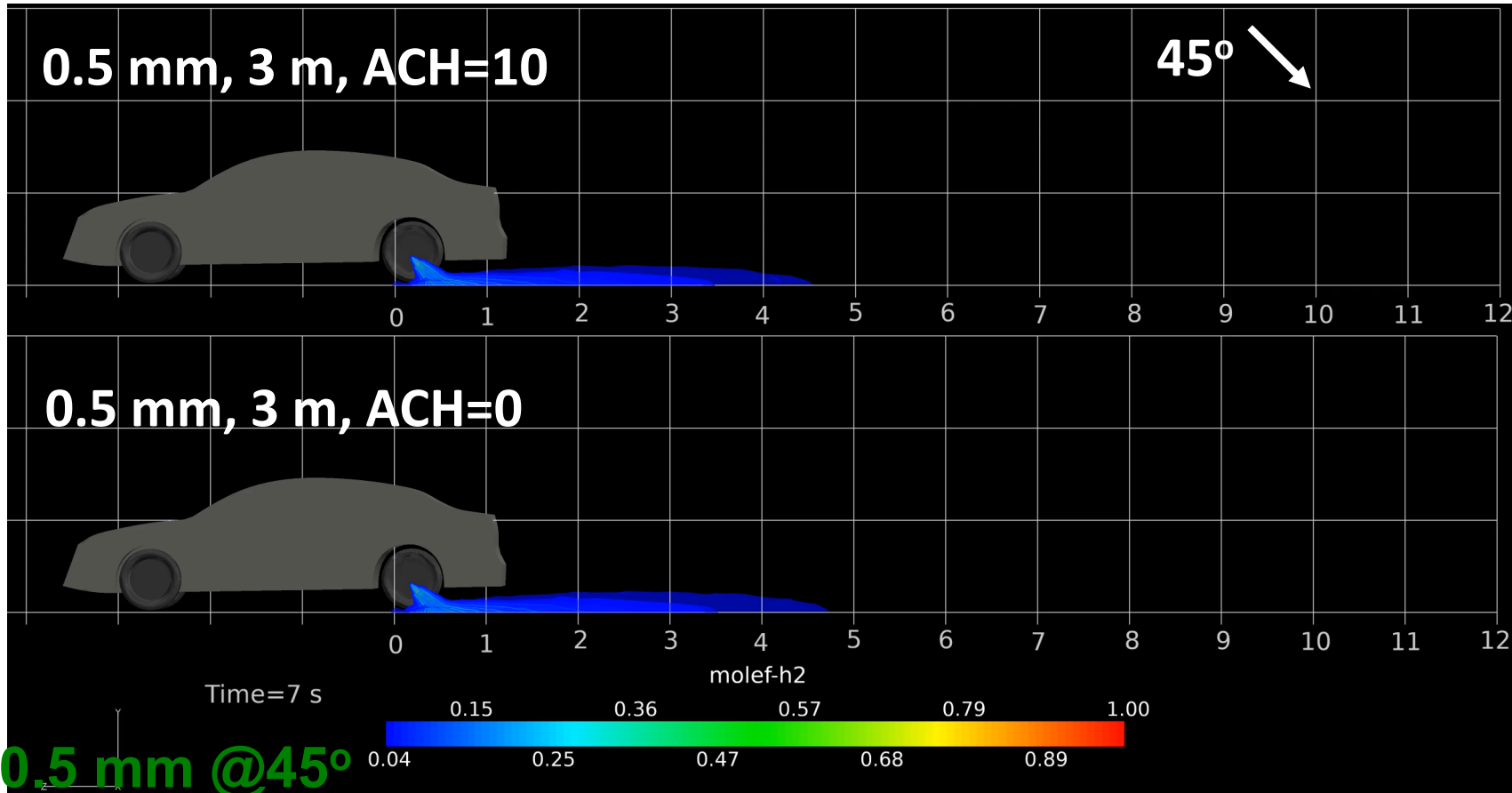


# Unignited release scenarios

| No. | D <sub>TPRD</sub> , mm | ACH | Angle, ° | Obstacle | Ceiling height |                         |
|-----|------------------------|-----|----------|----------|----------------|-------------------------|
| 1   | 0.5                    | 0   | 45       | -        | 3              | Effect of ventilation   |
| 2   | 0.5                    | 10  | 45       | -        | 3              |                         |
| 3   | 0.5                    | 10  | 0        | -        | 3              |                         |
| 4   | 0.5                    | 10  | 30       | -        | 3              |                         |
| 5   | 0.5                    | 10  | 60       | -        | 3              | Effect of TPRD angle    |
| 6   | 0.75                   | 10  | 30       | -        | 3              |                         |
| 7   | 0.75                   | 10  | 0        | -        | 3              |                         |
| 8   | 0.5                    | 10  | 45       | -        | 3              | Effect of TPRD diameter |
| 9   | 0.75                   | 10  | 45       | -        | 3              |                         |
| 10  | 1.0                    | 10  | 45       | -        | 3              |                         |
| 11  | 2.0                    | 10  | 45       | -        | 3              |                         |
| 12  | 0.75                   | 0   | 45       | -        | 2.1            | Limiting scenario       |
| 13  | 0.5                    | 0   | 45       | +        | 2.1            |                         |
| 14  | 0.75                   | 0   | 45       | +        | 2.1            |                         |
| 15  | 0.75                   | 0   | 45       | -        | 3              |                         |
| 16  | 0.75                   | 10  | 45       | -        | 2.1            |                         |

Effect of ceiling height

# Effect of ventilation $D_{TPRD}=0.5$

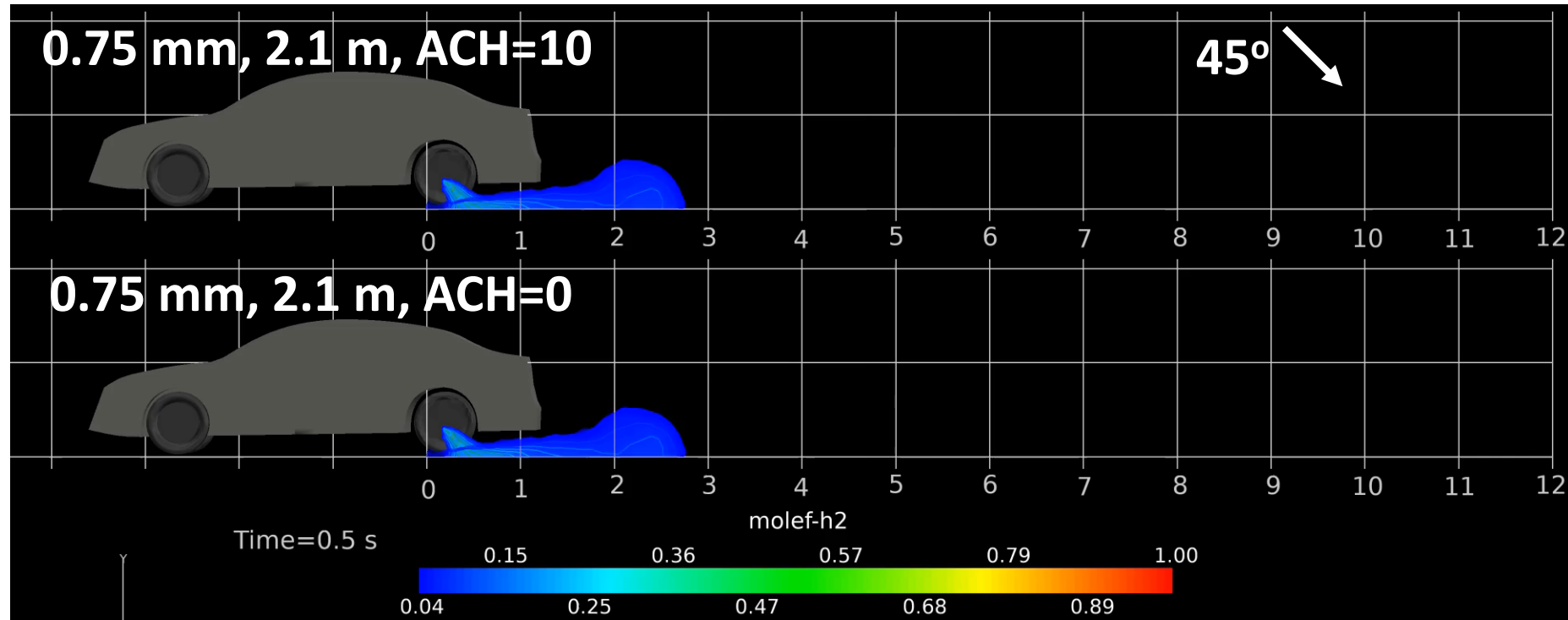


## Release from 0.5 mm @45°

- does not create layer
- ceiling height does not effect the decay
- ventilation reduces the decay by about 20%



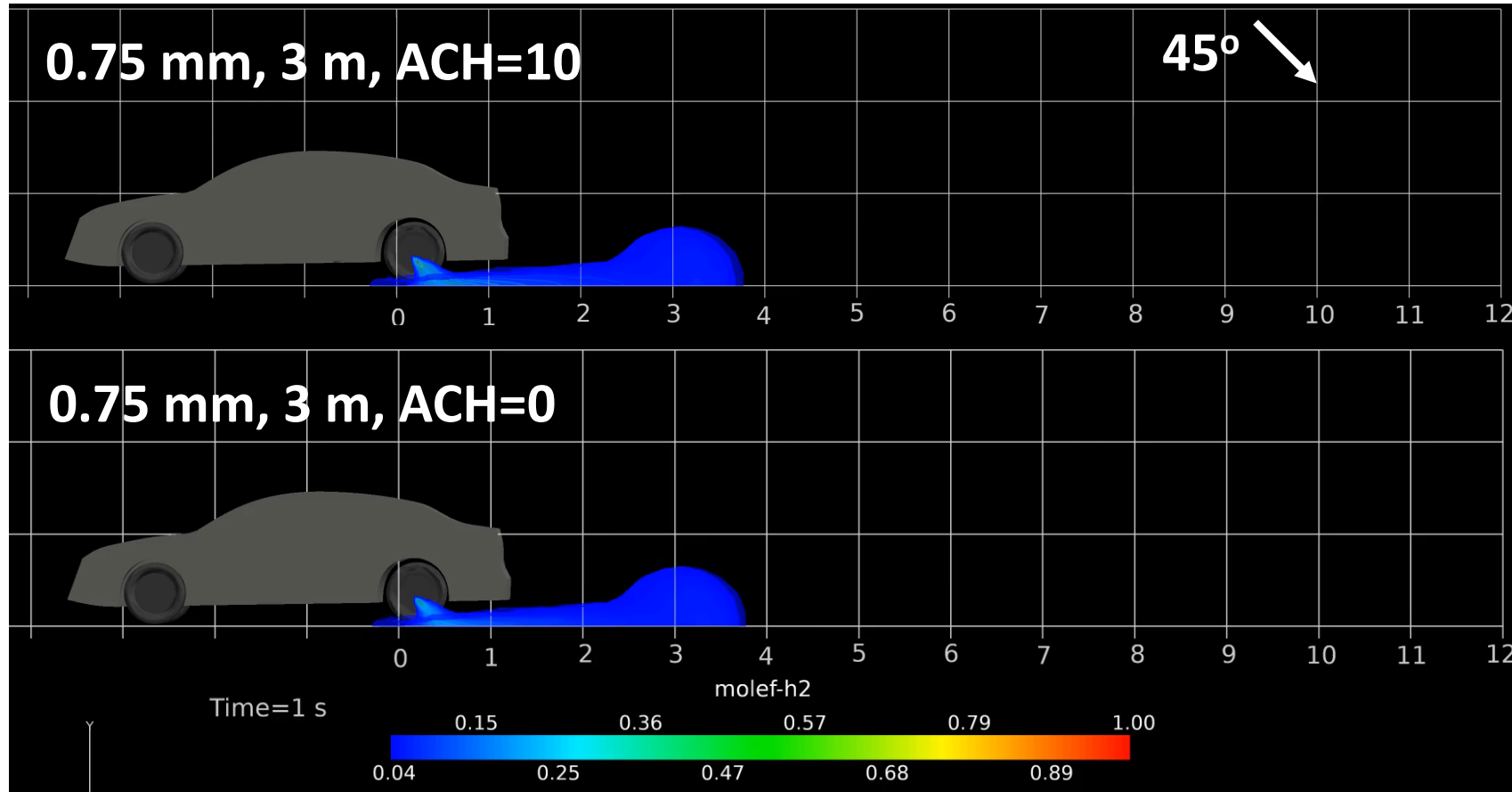
# Effect of ventilation $D_{TPRD}=0.75$



## Release from 0.75 mm @45°

- does not create layer
- ceiling height does not effect the decay
- ventilation reduces the decay by about 20%

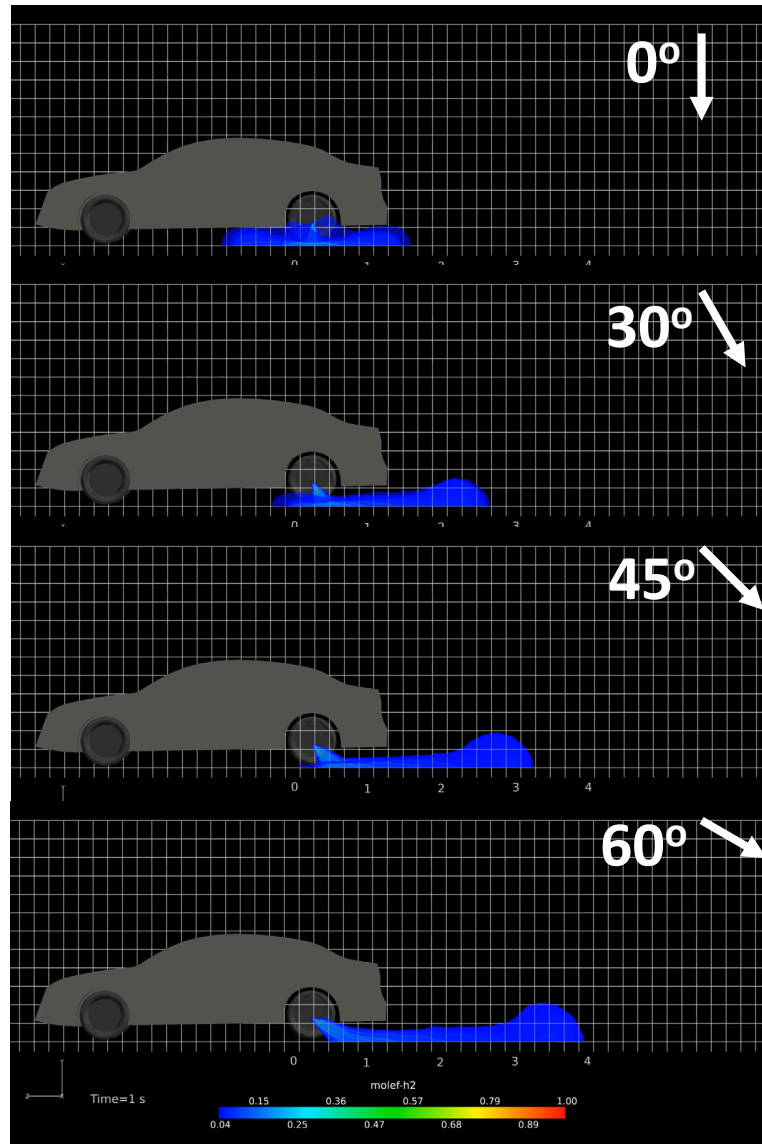
# Effect of ventilation $D_{TPRD}=0.75$



## Release from 0.75 mm @45°

- does not create layer
- ceiling height does not effect the decay
- ventilation reduces the decay by about 20%

# Effect of release angle $D_{TPRD}=0.5\text{mm}$



Tank 70 MPa,  $V=62.4\text{ L}$

$TPRD=0.5\text{ mm}$

$ACH=10$

Comparison of hazard distance at  $t=60\text{ s}$

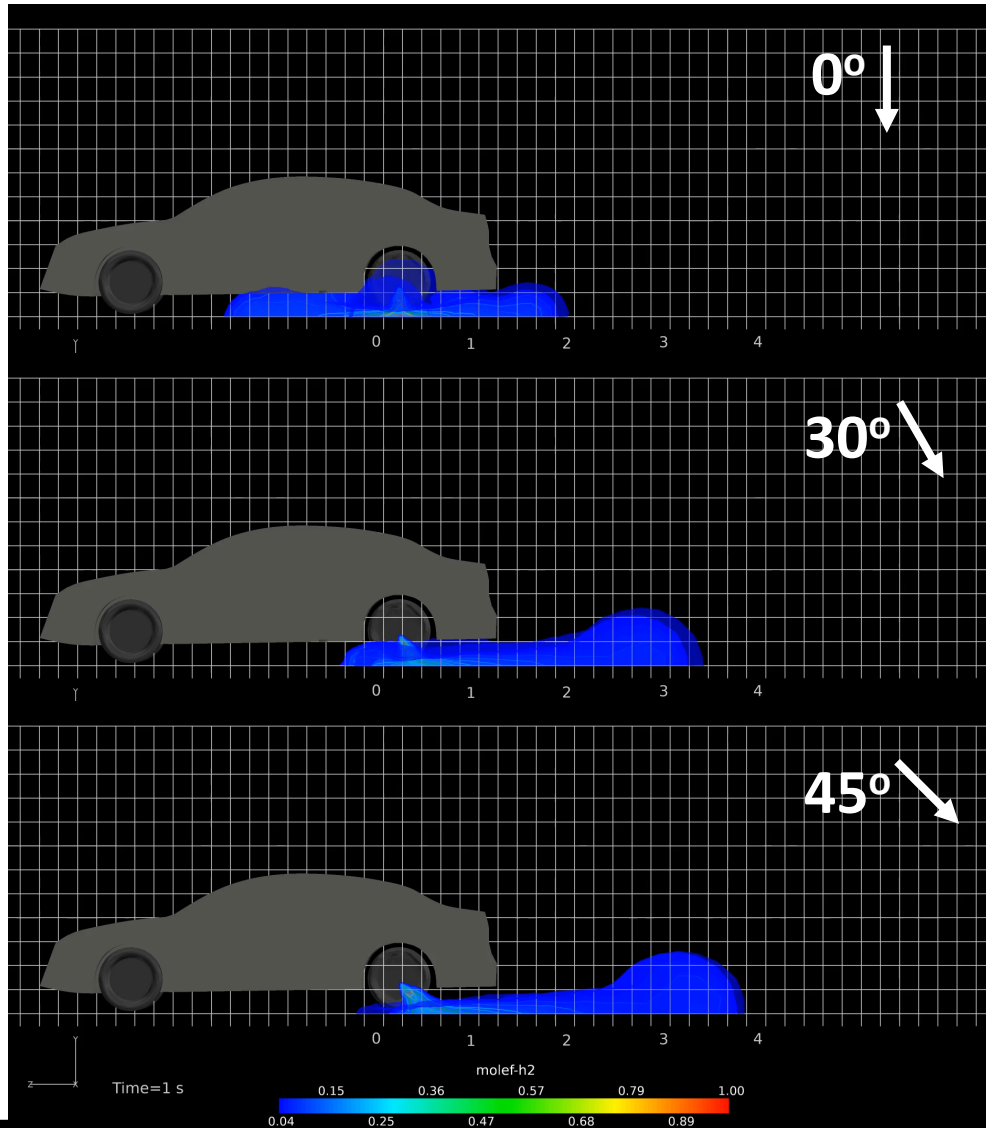
## Release at 0°

- Evacuation problem in case of fire
- Flammable layer formation

## Release at 45°

- Shortest decay distance to 4% at 60 s

# Effect of release angle $D_{TPRD}=0.75$ mm



Tank 70 MPa, V=62.4 L  
TPRD=0.75 mm  
ACH=10

## Release at 0°

- Evacuation problem in case of fire
- Flammable layer formation

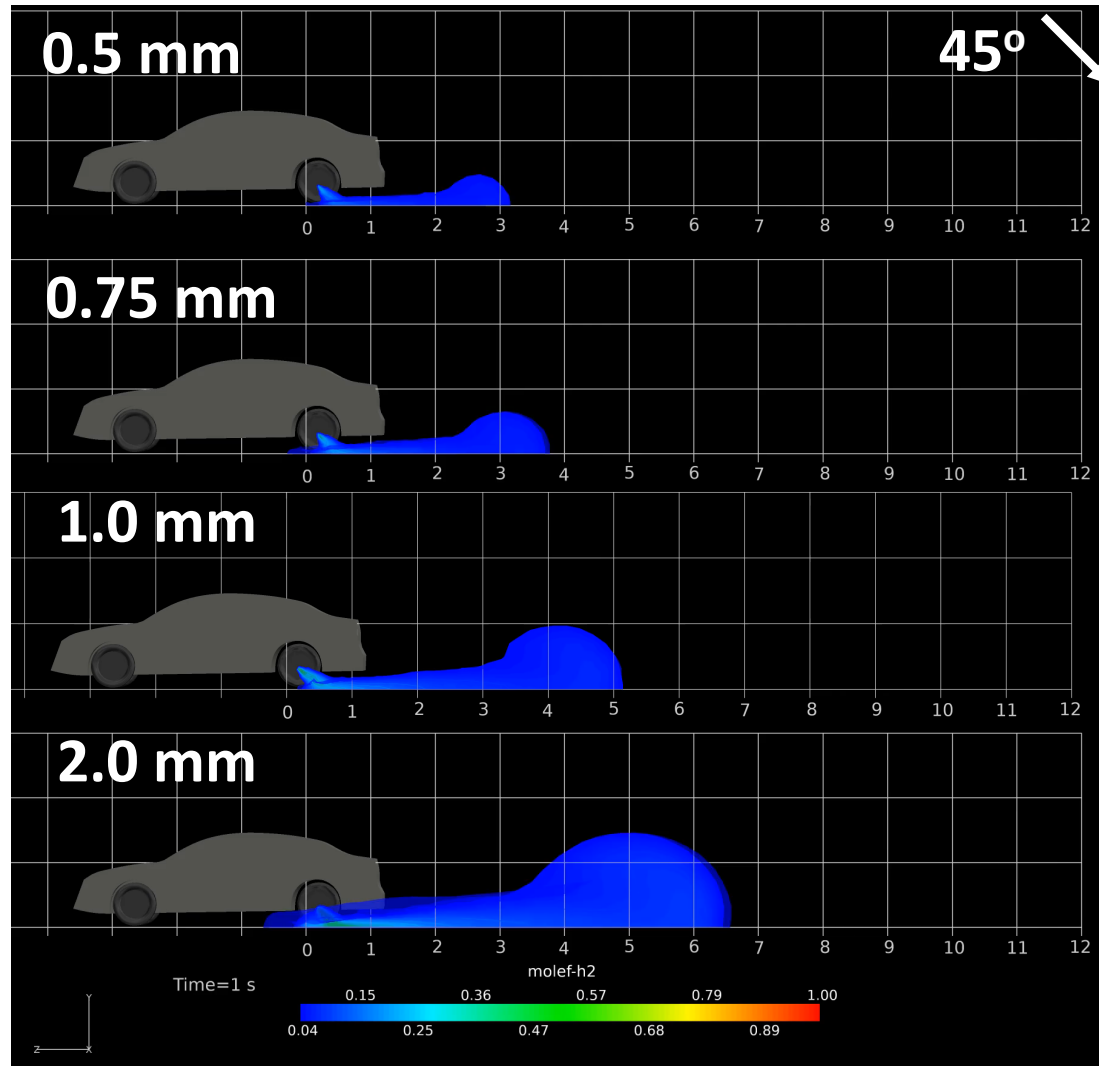
## Release at 30°

- Shortest decay distance to 4%



# Results

## Effect of TPRD diameter (video)



### Release from 0.5-1mm

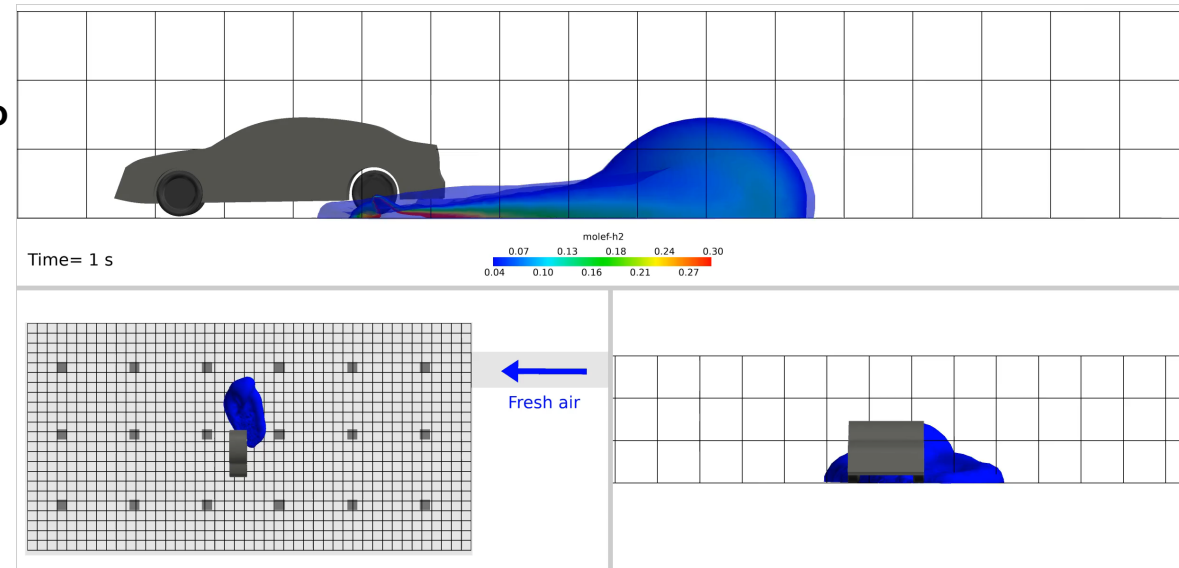
- does not create layer
- 0.5 shortest hazard distance

### Release from 2 mm

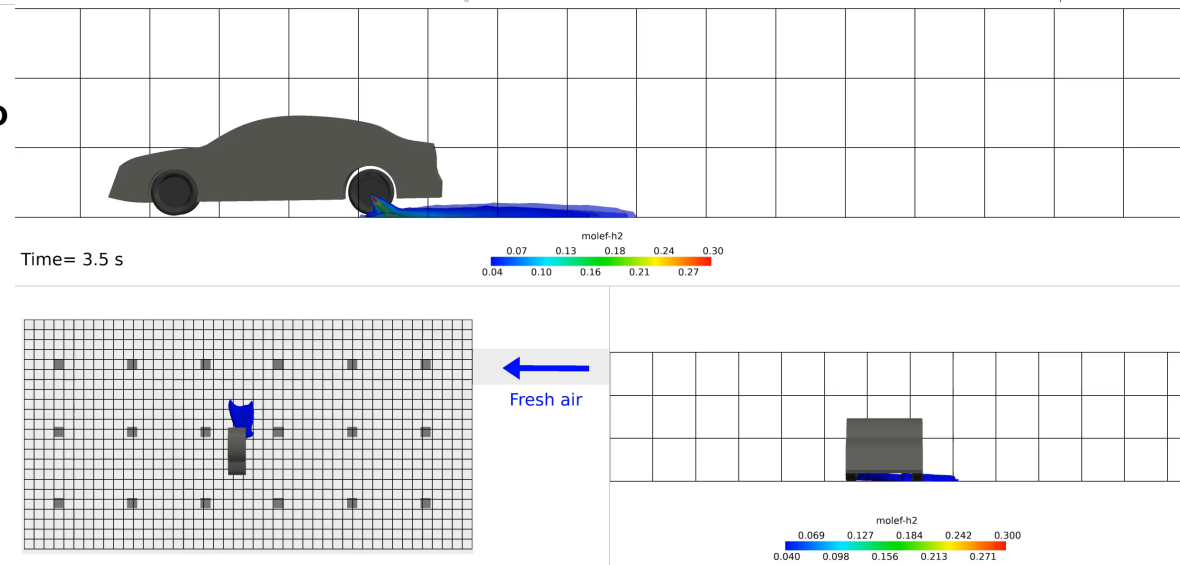
- Long hazard distance
- Evacuation problem in case of fire
- Flammable layer formation

# Effect of TPRD diameter (hazards, 3D video)

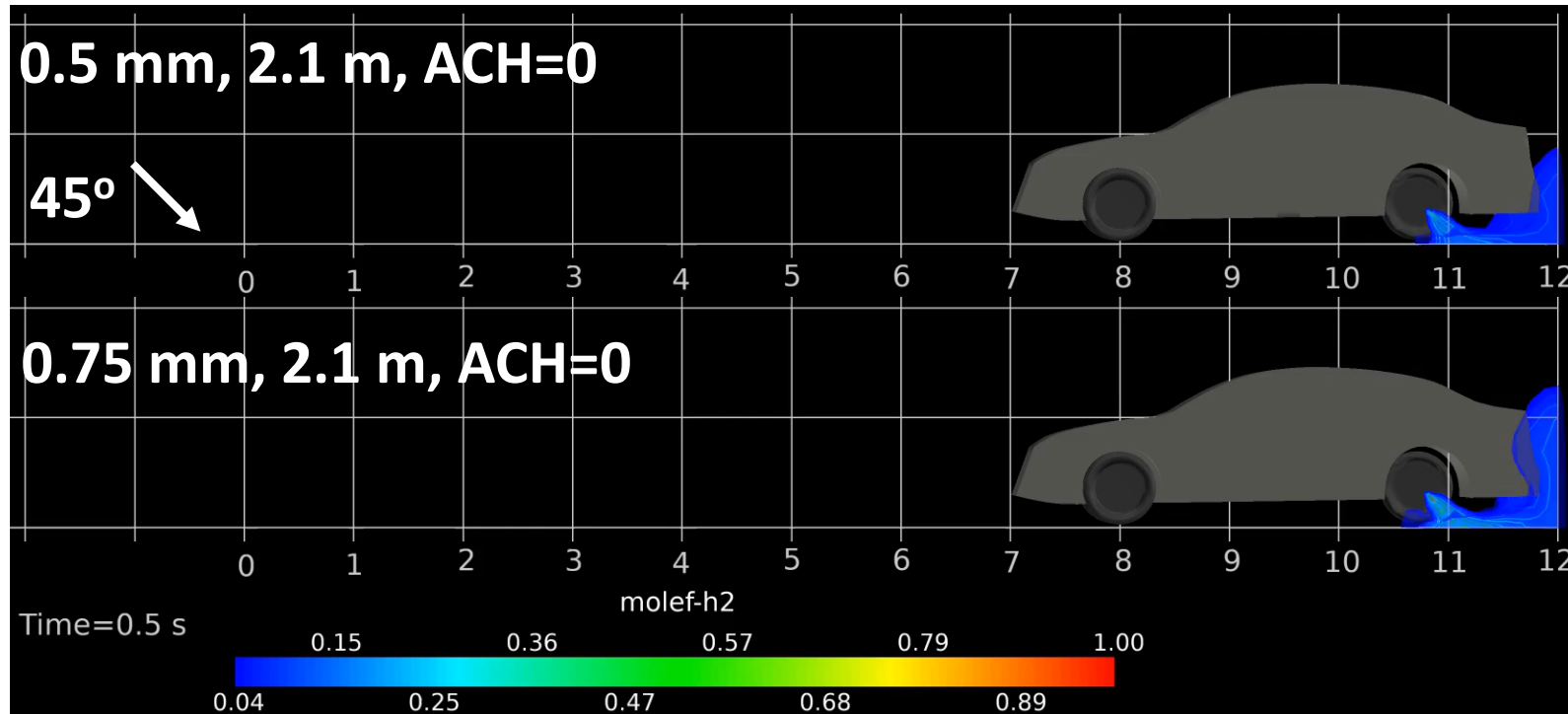
**TPRD=2 mm, 45°**  
70 MPa, 62.4 L  
ACH=10



**TPRD=0.5 mm, 45°**  
700 bar, 62.4 L  
ACH=10



# Effect of obstacle (limiting scenario)



Presence of wall behind, results in formation of flammable mixture regardless of TPRD size.

- Only CFD model could be considered as reliable tool for design of mechanical ventilation in underground parking (especially to account for unsteady phenomena due to blowdown and large volume of parking).
- The ventilation does not affect the decay of concentration for small releases from 0.5 and 0.75 mm TPRDs
- Release downward is subject for formation of flammable layer at the ceiling at considered parking heights even for small TPRDs of 0.5 mm
- TPRD Ø0.5 & 0.75 mm and angels 30-60° doesn't create flammable layer under the ceiling
- The ceiling height does not affect the decay as long as concentration reduces below LFL formation of flammable layer is excluded
- Presence of wall behind, results in formation of flammable mixture regardless of TPRD diameter.
- Releases from TPRD larger than Ø0.75 mm have potential to create flammable layer under ceiling



# Ignited release

- Damage to ventilation system
  - BS 7346-7-2013: Performance recommendations for equipment:
  - “8.2.1 All fans intended to exhaust hot gases used within a car park ventilation system should be tested in accordance with BS EN 12101-3 to verify their suitability for operating at 300 °C for a period not less than 60 minutes (class F300).”
- Harm to people
  - Temperature higher than 70°C according to LaChance (2011).

# Ignited release scenarios

| No.       | D <sub>TPRD</sub> , mm | ACH | Angle, ° | Obstacle | Ceiling height | Start date |
|-----------|------------------------|-----|----------|----------|----------------|------------|
| 1         | 0.5                    | 0   | 45       | -        | 3              | Done       |
| <b>2</b>  | 0.5                    | 10  | 45       | -        | 3              | Done       |
| 3         | 0.5                    | 10  | 0        | -        | 3              | Done       |
| 4         | 0.5                    | 10  | 30       | -        | 3              | Done       |
| 5         | 0.5                    | 10  | 60       | -        | 3              | Done       |
| 6         | 0.75                   | 10  | 30       | -        | 3              | -          |
| 7         | 0.75                   | 10  | 0        | -        | 3              | -          |
| <b>8</b>  | 0.75                   | 10  | 45       | -        | 3              | Done       |
| <b>9</b>  | 1.0                    | 10  | 45       | -        | 3              | Done       |
| <b>10</b> | 2.0                    | 10  | 45       | -        | 3              | Done       |
| 11        | 0.75                   | 0   | 45       | -        | 3              | Done       |
| 12        | 0.5                    | 0   | 45       | Wall     | 2.1            | -          |
| 13        | 0.75                   | 0   | 45       | Wall     | 2.1            | -          |
| 14        | 0.75                   | 0   | 45       | -        | 3              | -          |
| 15        | 0.75                   | 10  | 45       | -        | 2.1            | Done       |
| 16        | 0.5                    | 10  | 45       | -        | 2.1            | Ongoing    |
| 17        | 0.6                    | 10  | 45       | -        | 2.1            | Ongoing    |
| <b>18</b> | 0.6                    | 10  | 45       | -        | 3              | Done       |
| 19        | 0.5                    | 10  | 45       | Wall     | 2.1            | Done       |

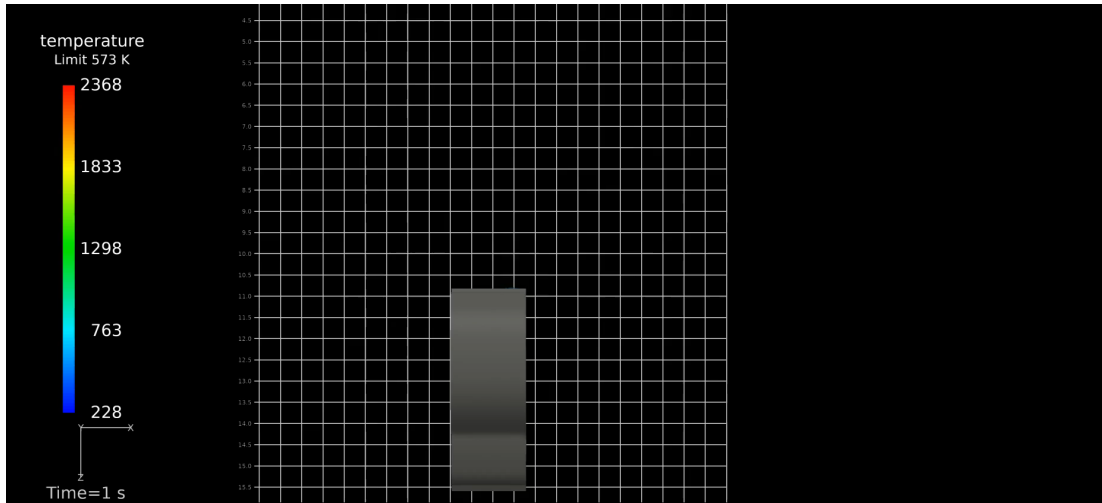
Effect of  
ventilation  
Effect of TPRD  
angle

Effect of TPRD  
diameter: cases  
in bold: 2, 8, 9,  
10, 18

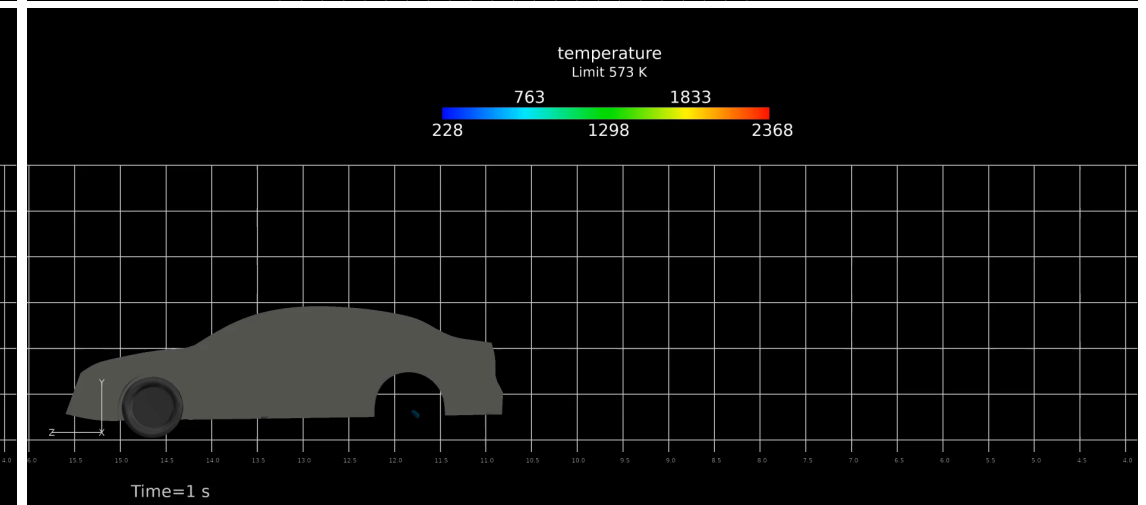
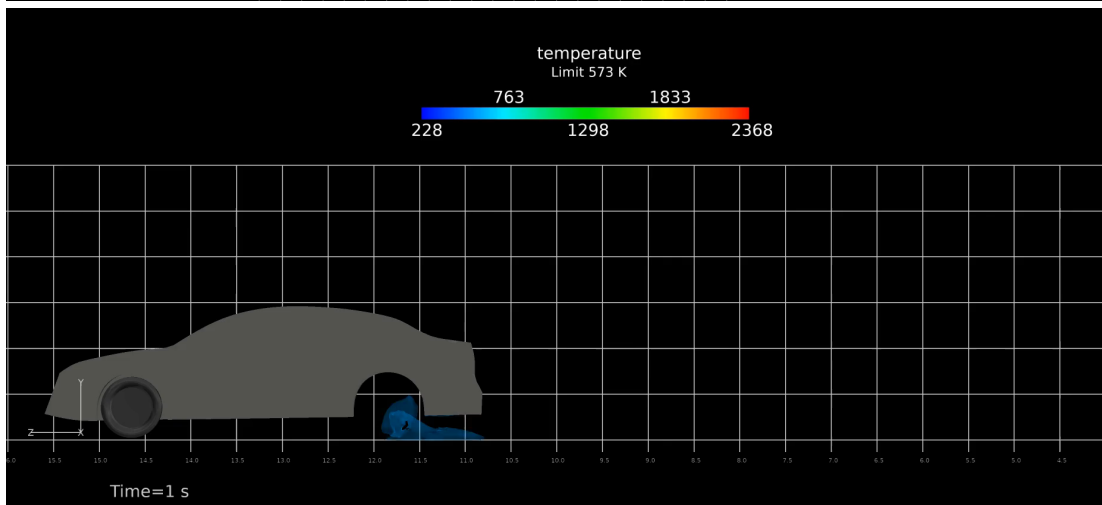
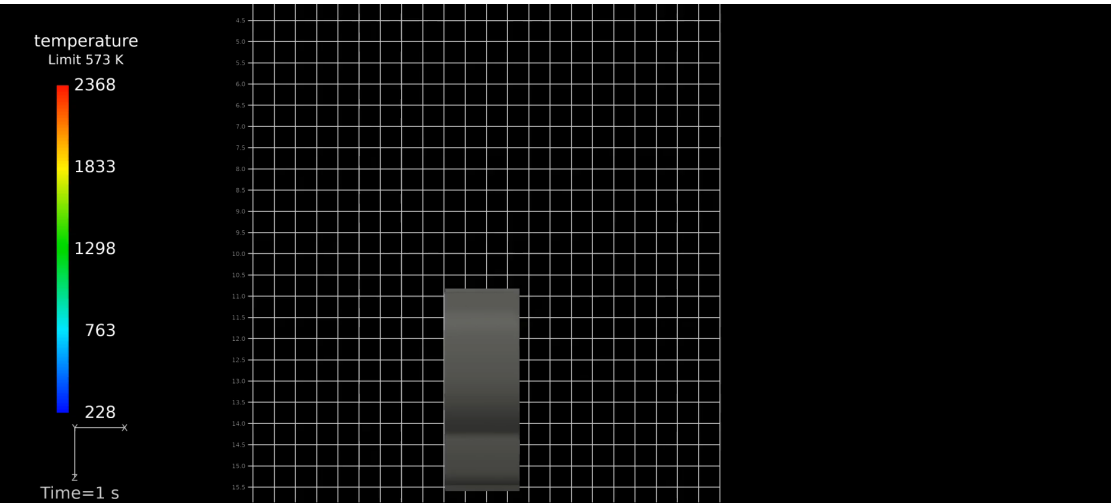
Limiting

# TPRD 0.5mm, 45° - Damage to ventilation system

**0 ACH**



**10 ACH**

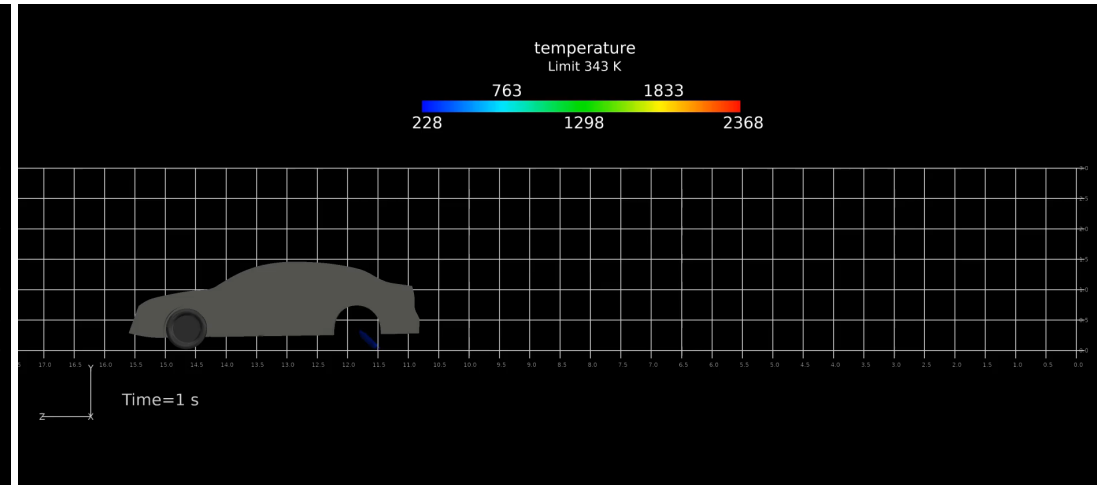
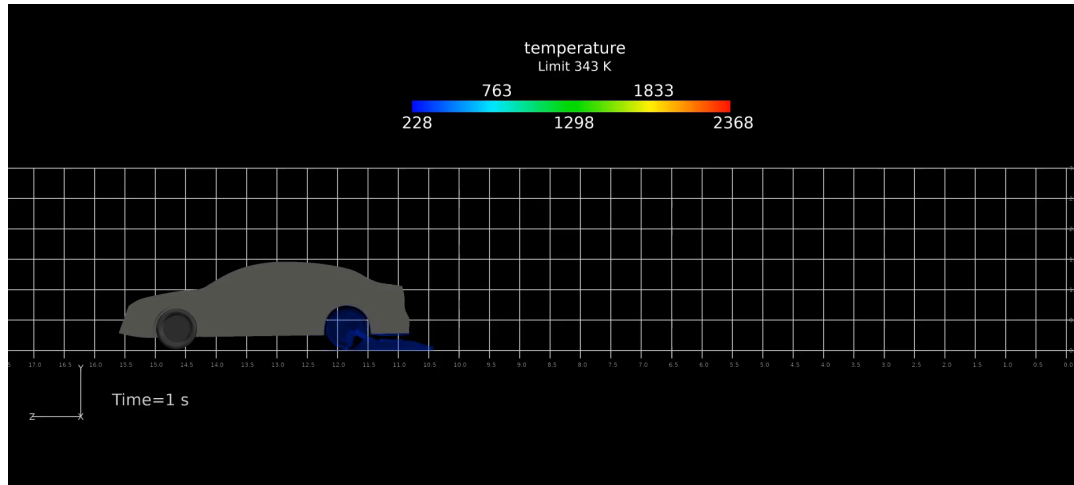
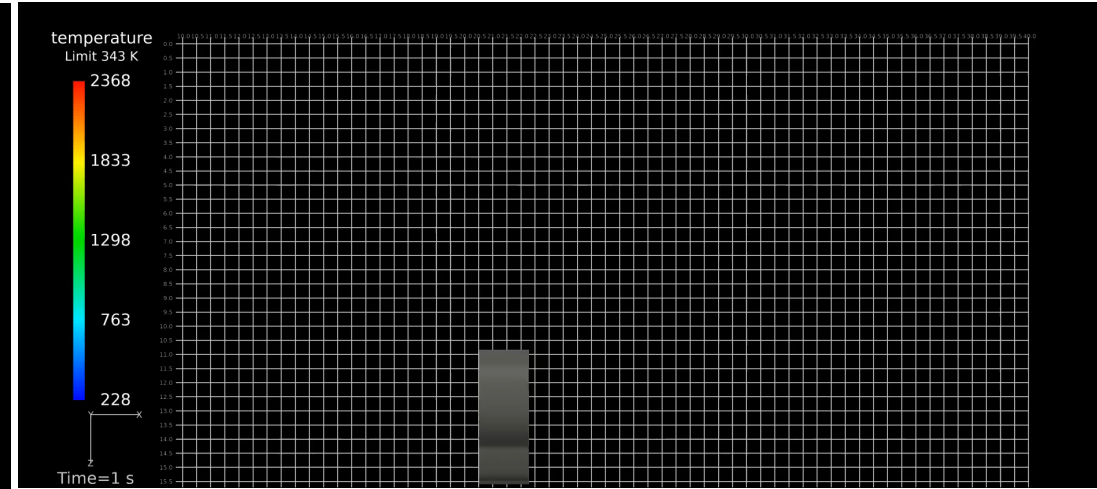
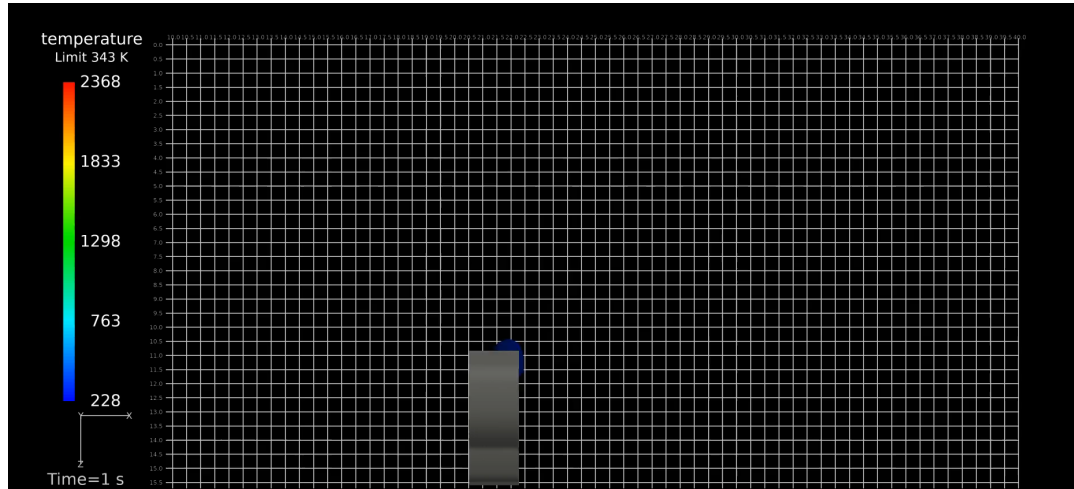




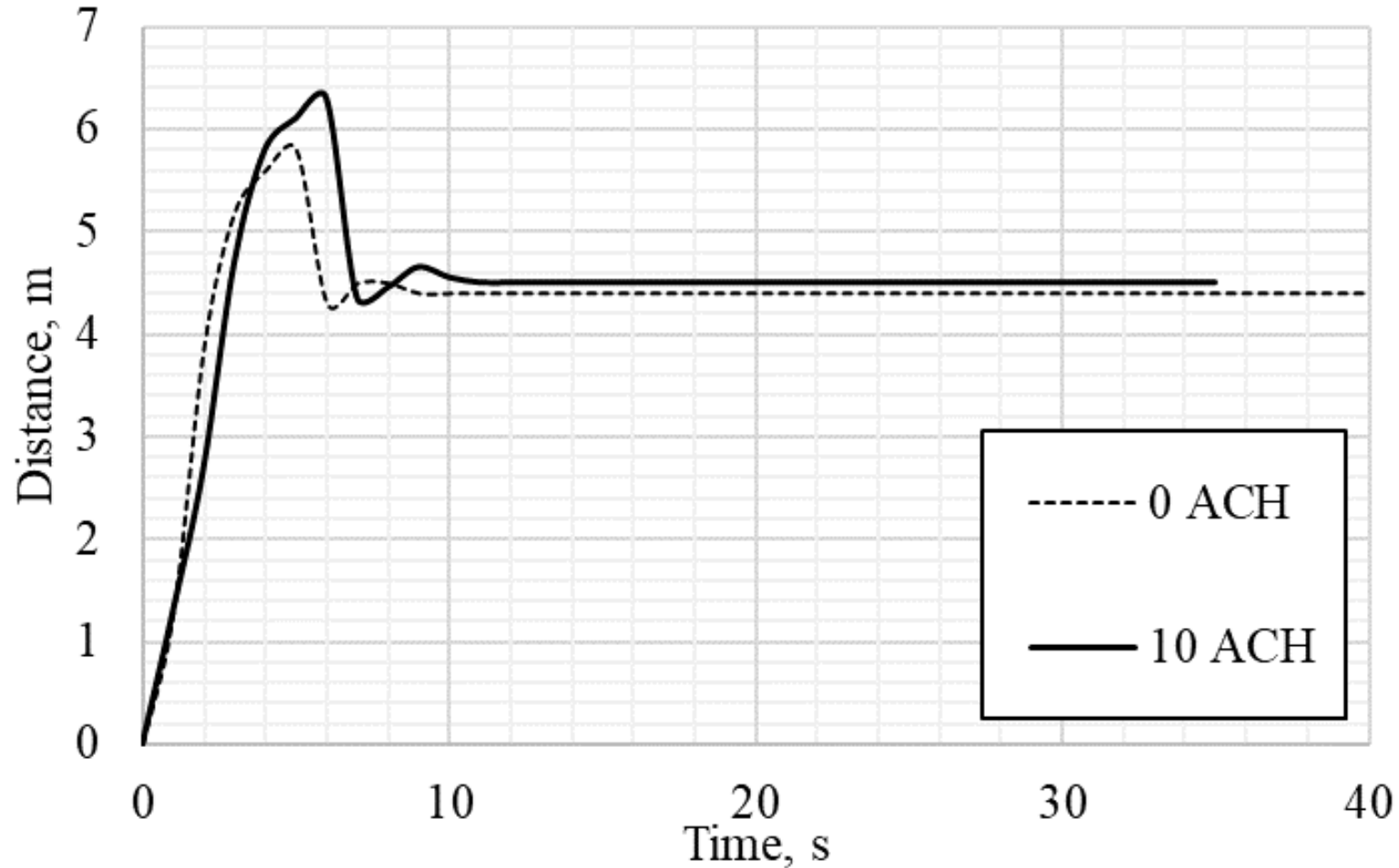
# TPRD 0.5mm, 45° - Harm to people (70°C)

## 0 ACH

## 10 ACH



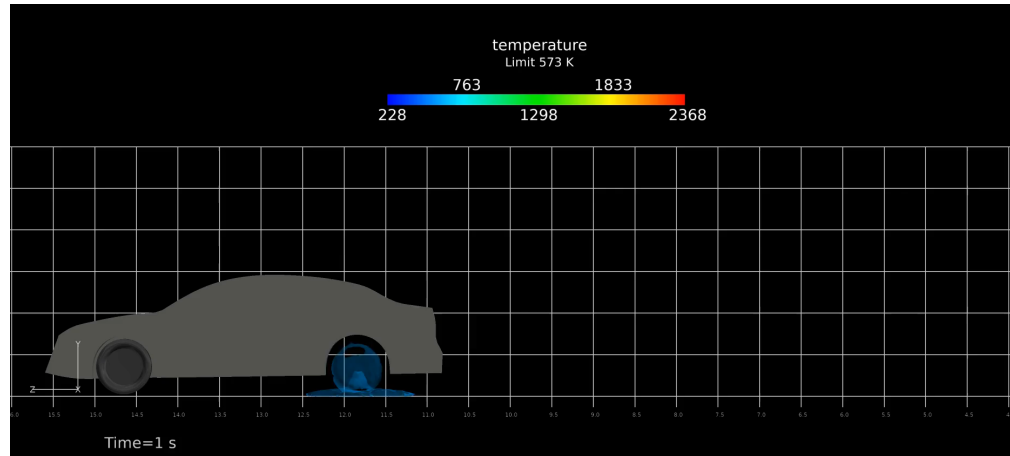
# TPRD 0.5mm, 45° - Harm to people



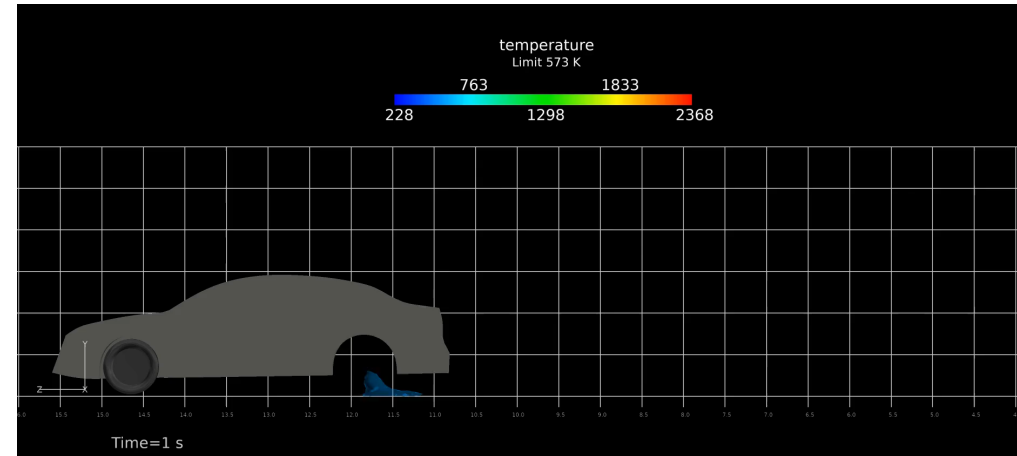
Maximum horizontal distance from the rear of a vehicle for a height within 0-2 m for the hot combustion products cloud with  $T \geq 70^\circ\text{C}$ .

# D=0.5mm, 10 ACH - Damage to ventilation system

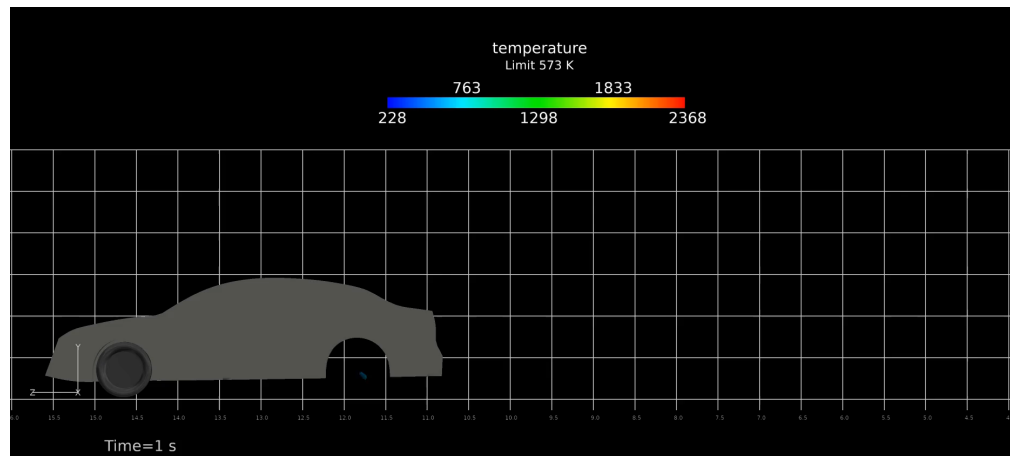
0° angle



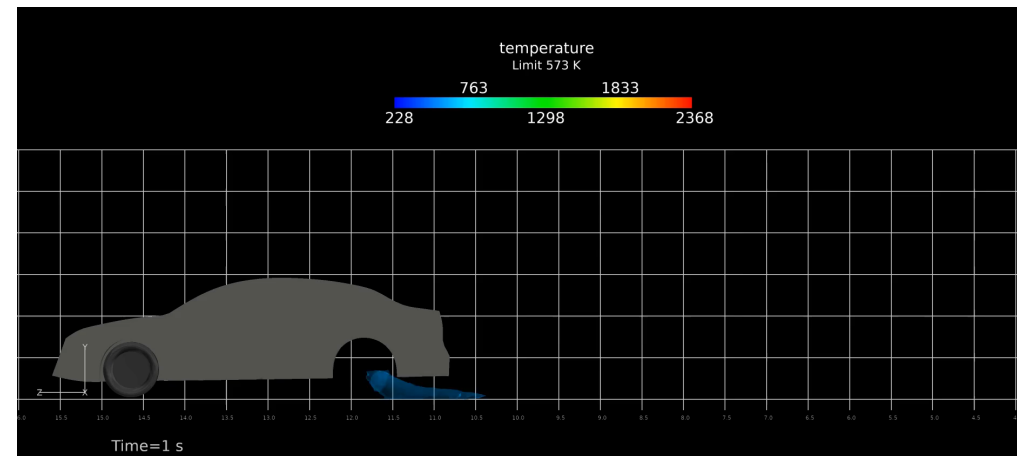
30° angle



45° angle

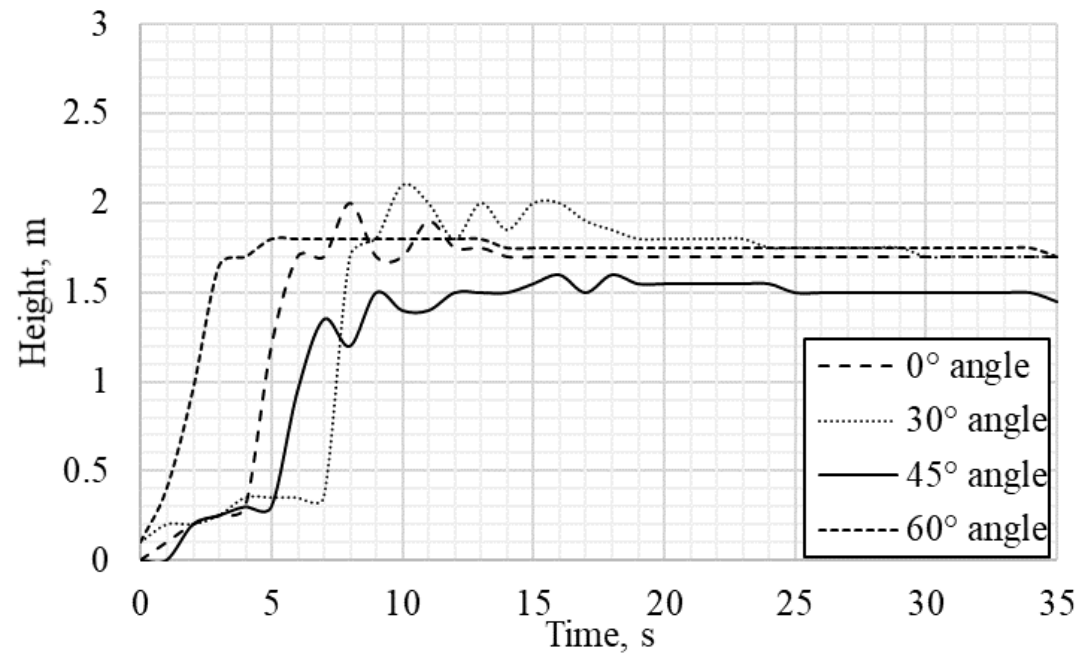
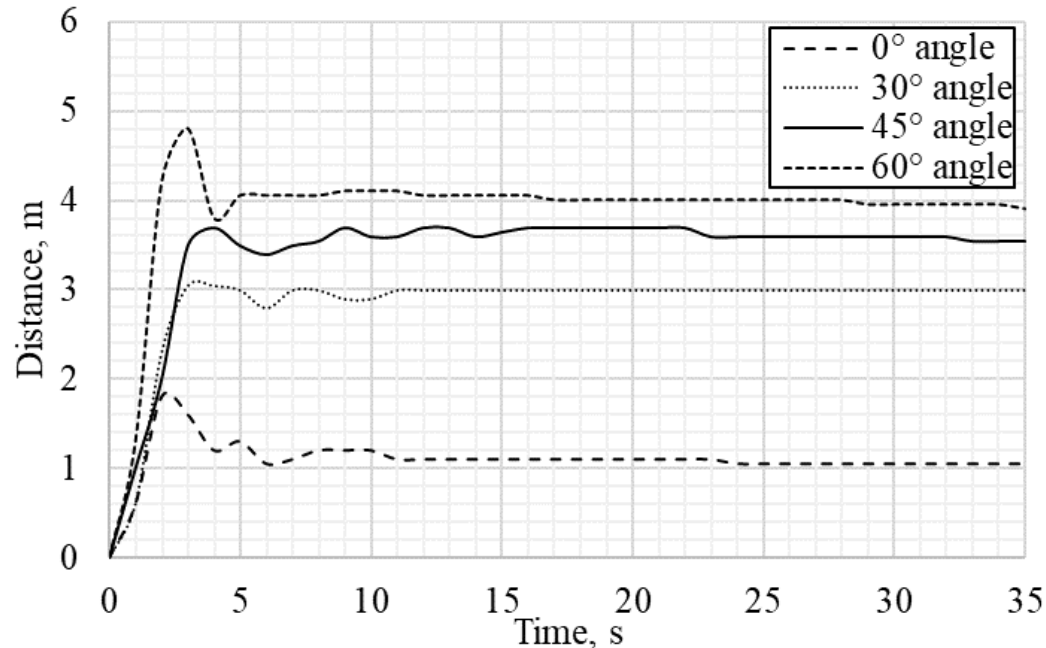


60° angle



# D=0.5mm, 10 ACH - Damage to ventilation system

Maximum horizontal distance from the rear of a vehicle and maximum height reached by cloud with  $T \geq 300^\circ\text{C}$ .

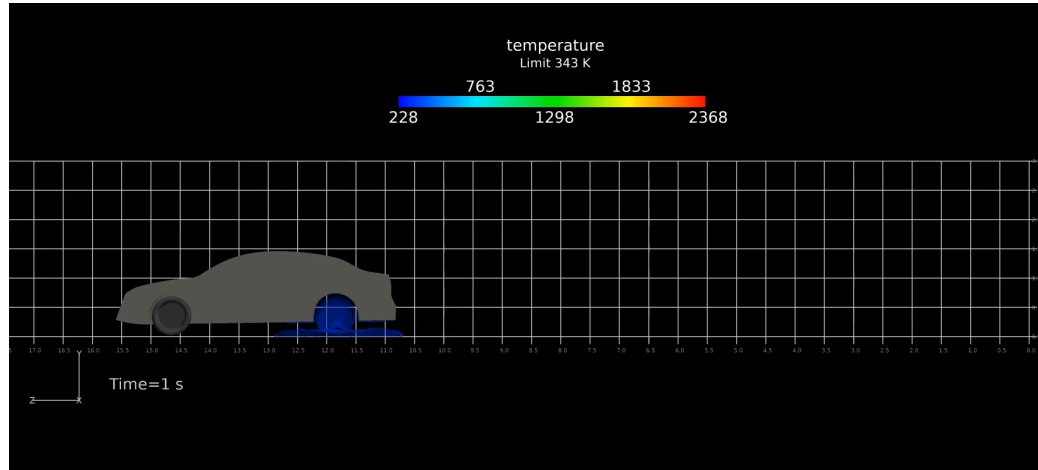


Effect of TPRD inclination: in all cases the damage level is not reached at the ceiling of 3 m.

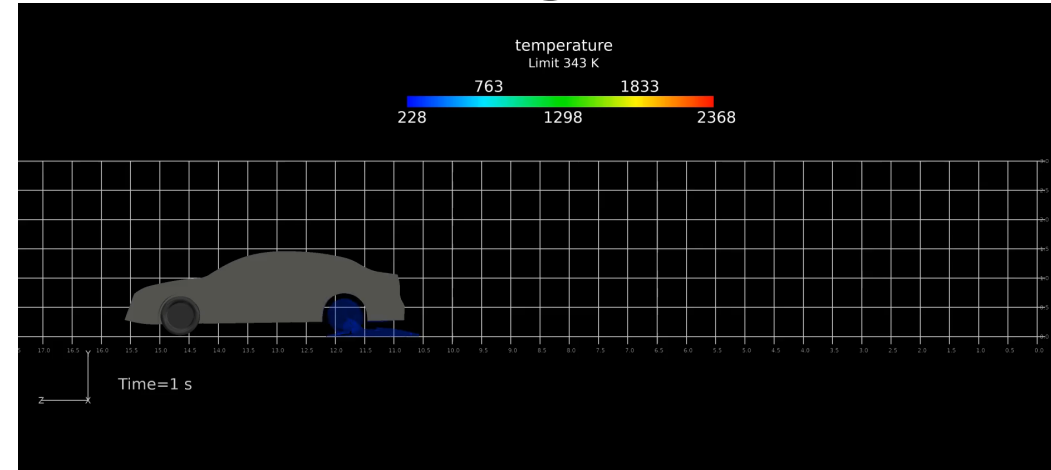
- 0° angle: damage level is reached at a max height of 2 m, even if for a short time. However, the hot combustion products with temperature corresponding to fatality harm criteria envelop the vehicle and may prevent escape of the occupants.
- 30° angle: damage level is reached at a max height of 2.1 m, even if for a short time.
- 45° and 60° angle: damage level is reached at heights < 2 m.

# D=0.5mm, 10 ACH – Harm to people

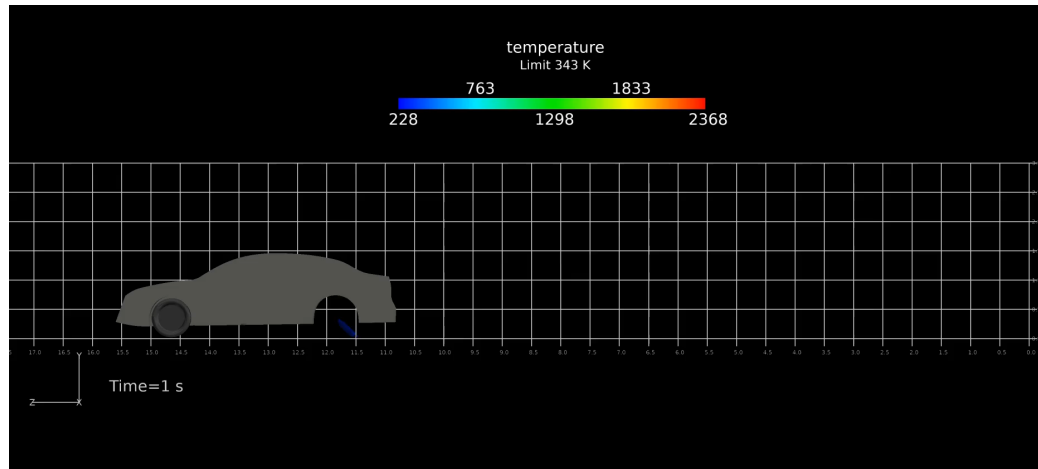
0° angle



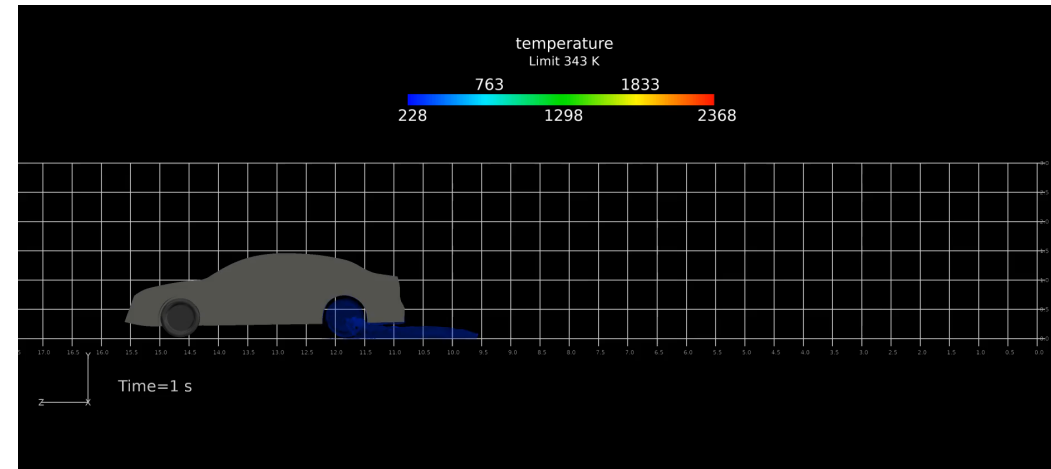
30° angle



45° angle



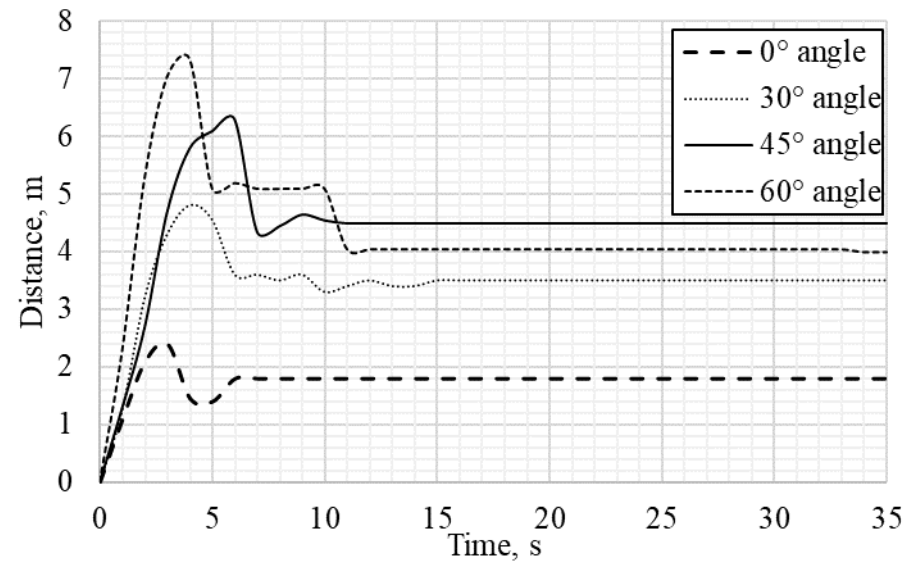
60° angle





# D=0.5mm, 10 ACH – Harm to people

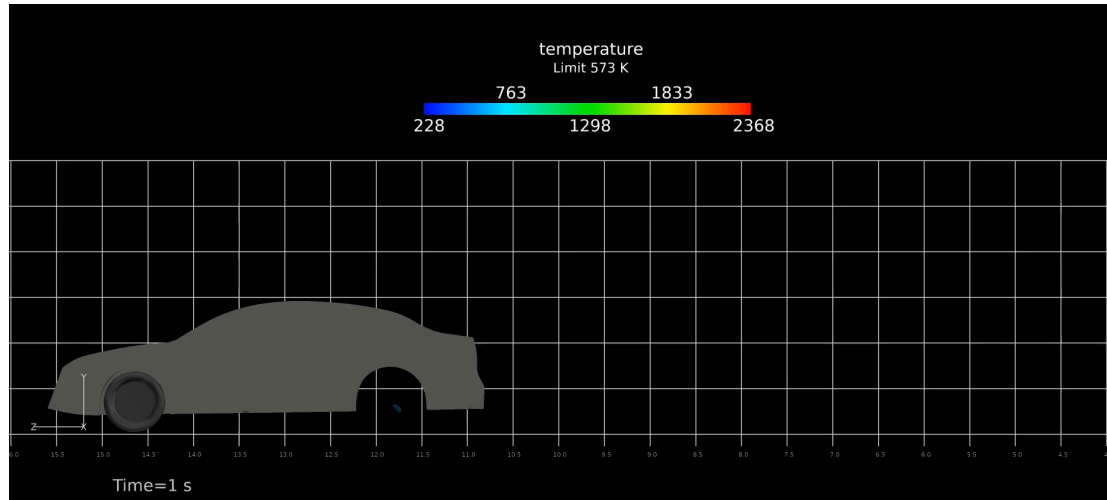
Maximum horizontal distance from the rear of a vehicle for a height within 0-2 m for the hot combustion products cloud with  $T \geq 70^\circ\text{C}$ .



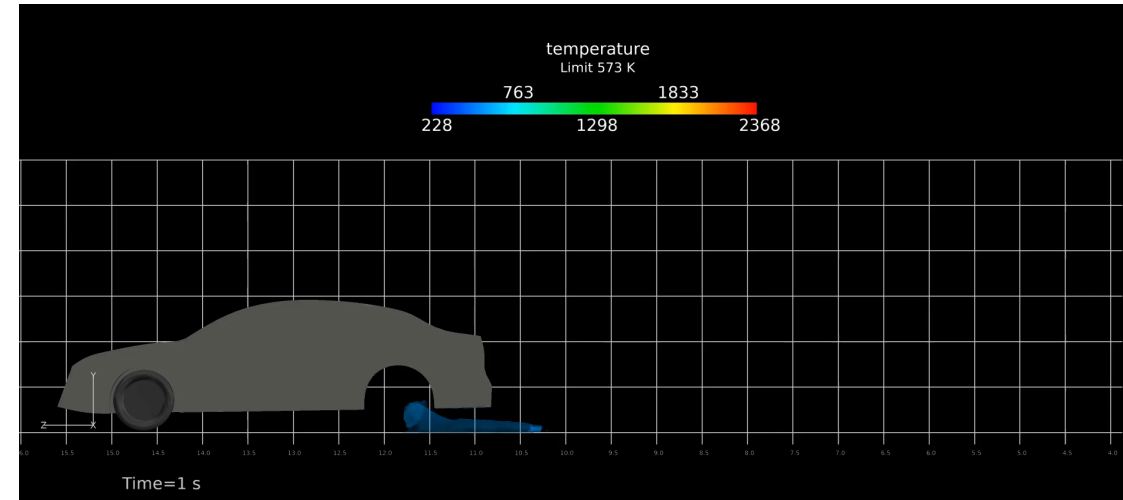
- 0° angle: No-harm distance is the lowest. However, the hot combustion products surround the vehicle, reaching the fatality harm level too, and may prevent escape of the occupants.
- 30° angle: No-harm distance is lower than 5 m.
- 45° angle presents no-harm distance of 6.2 m, which is lower than distance for 60° angle.
- Combining the conclusions reached for damage and harm criteria, 45° angle represents the best choice.

# 45° angle, 10 ACH - Damage to ventilation system

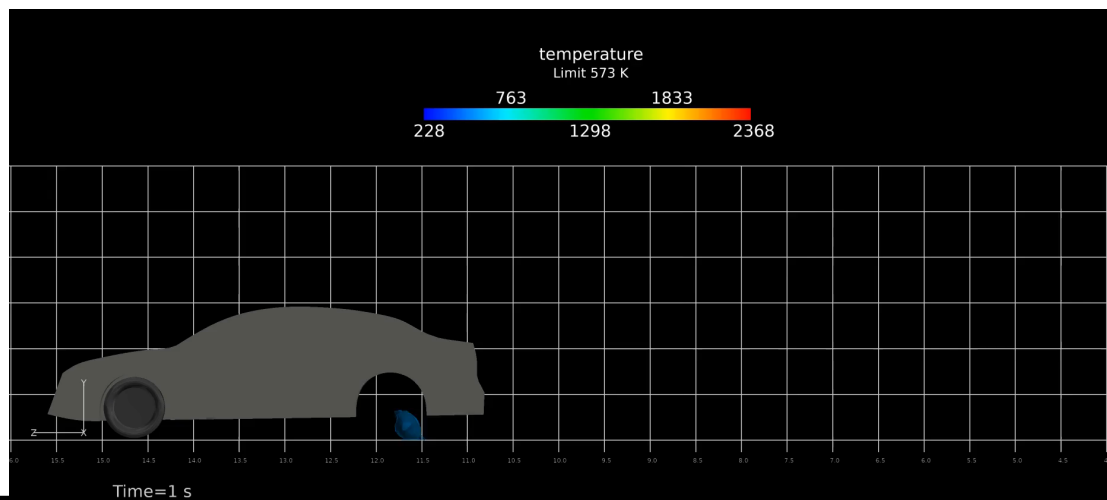
**0.5 mm**



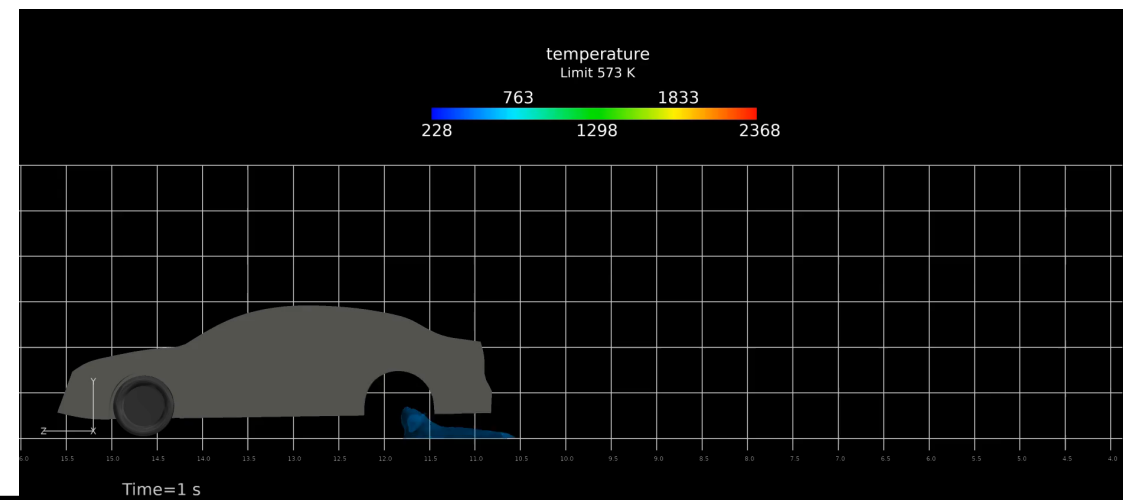
**0.6 mm**



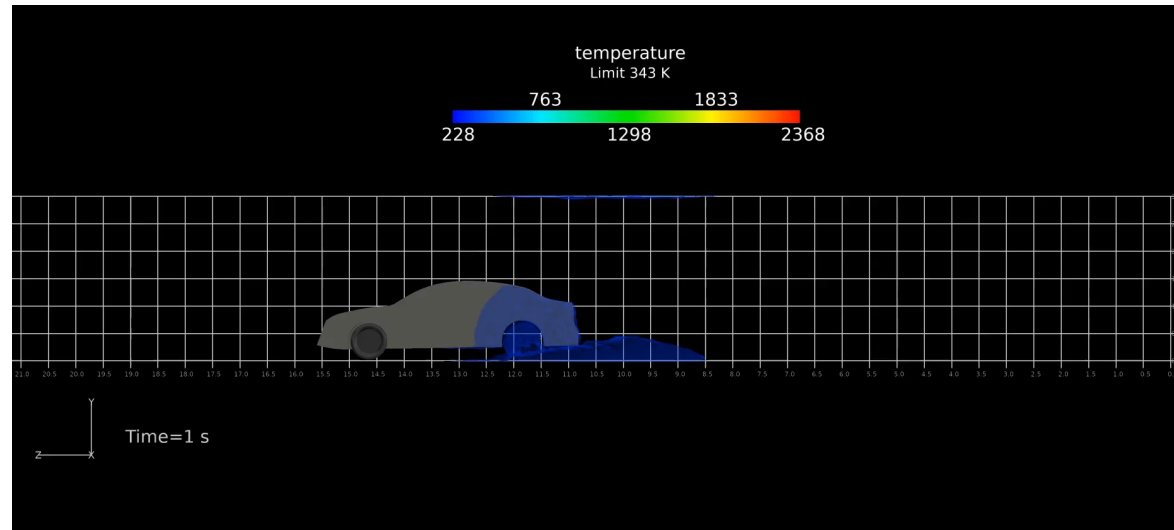
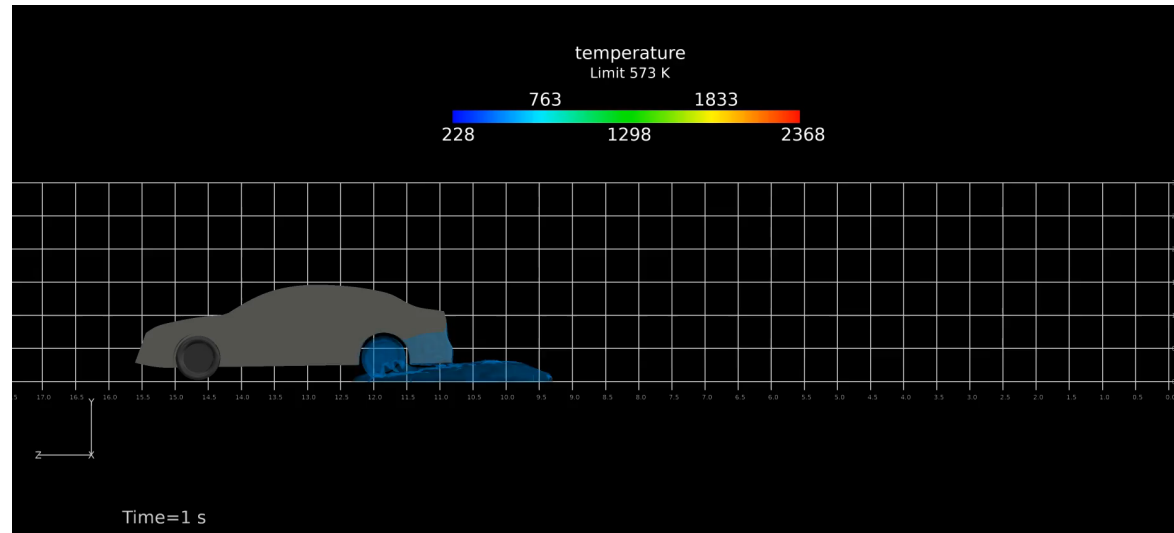
**0.75 mm**



**1 mm**

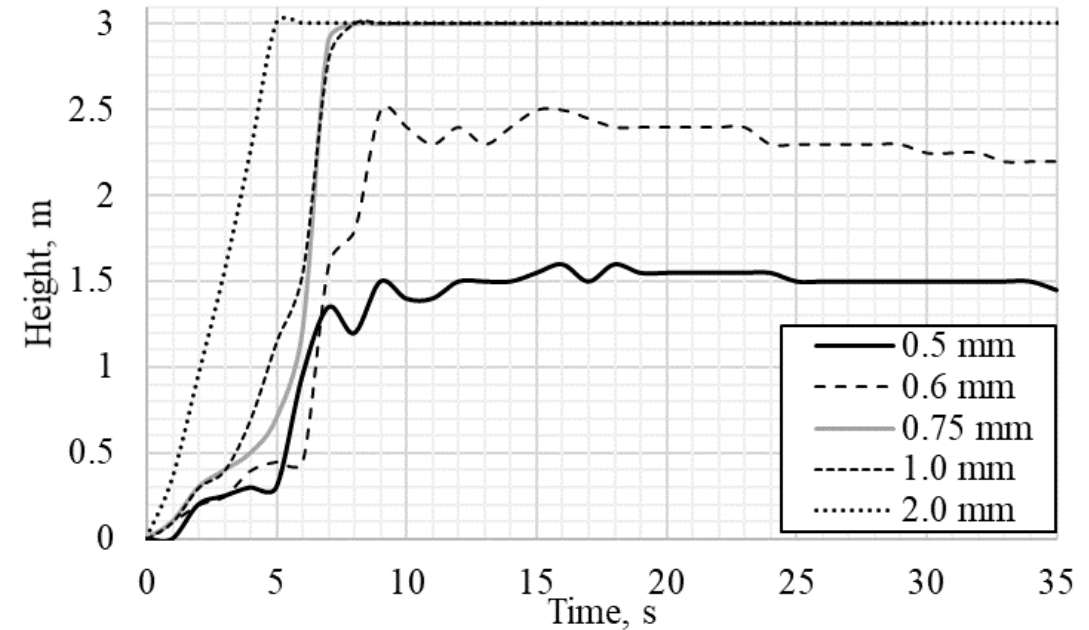
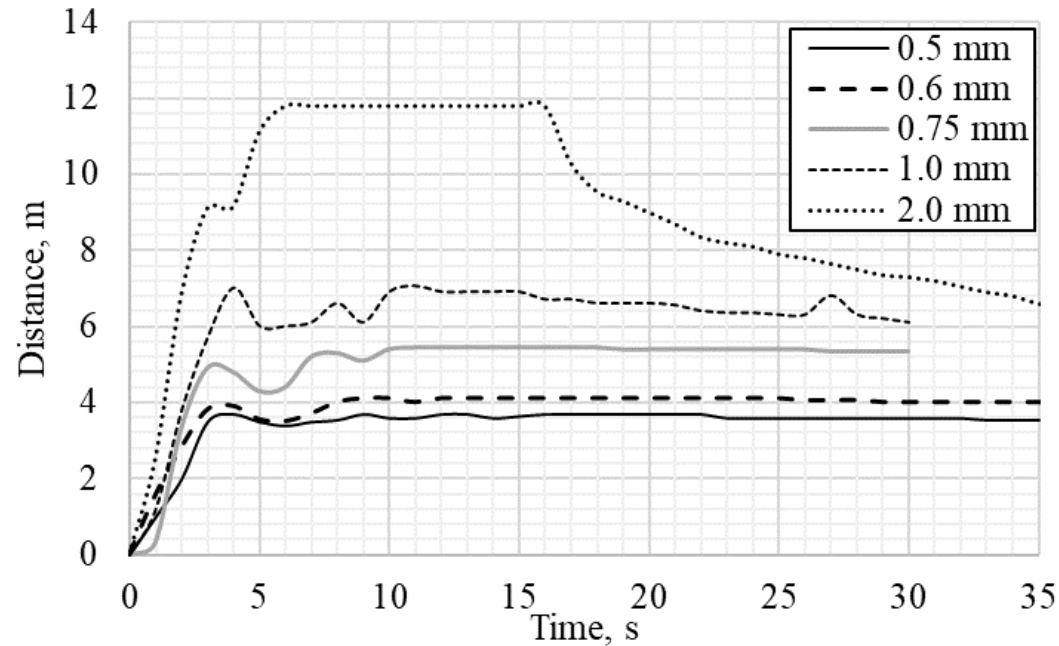


# D=2 mm, 45° angle, 10 ACH



# 45° angle, 10 ACH - Damage to ventilation system

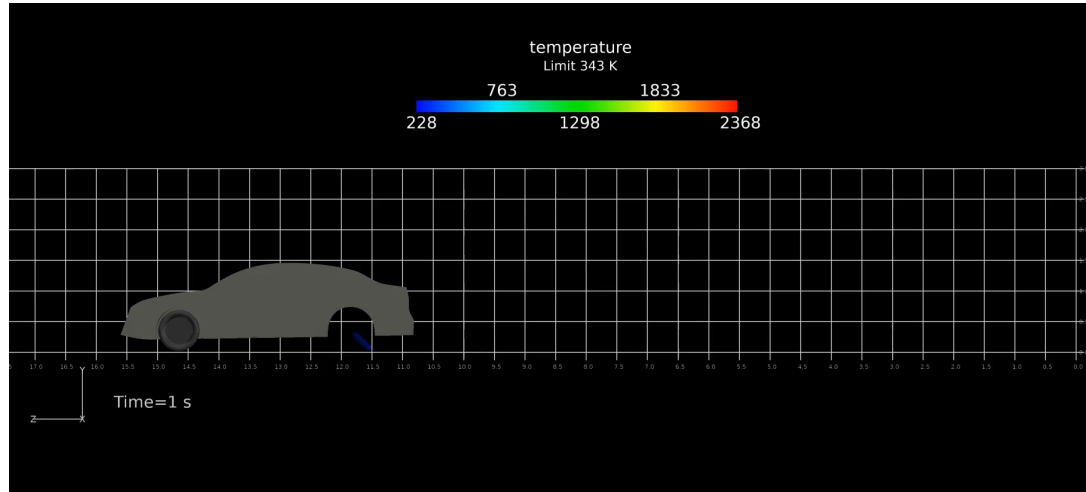
Maximum horizontal distance from the rear of a vehicle and maximum height reached by cloud with  $T \geq 300^\circ\text{C}$ .



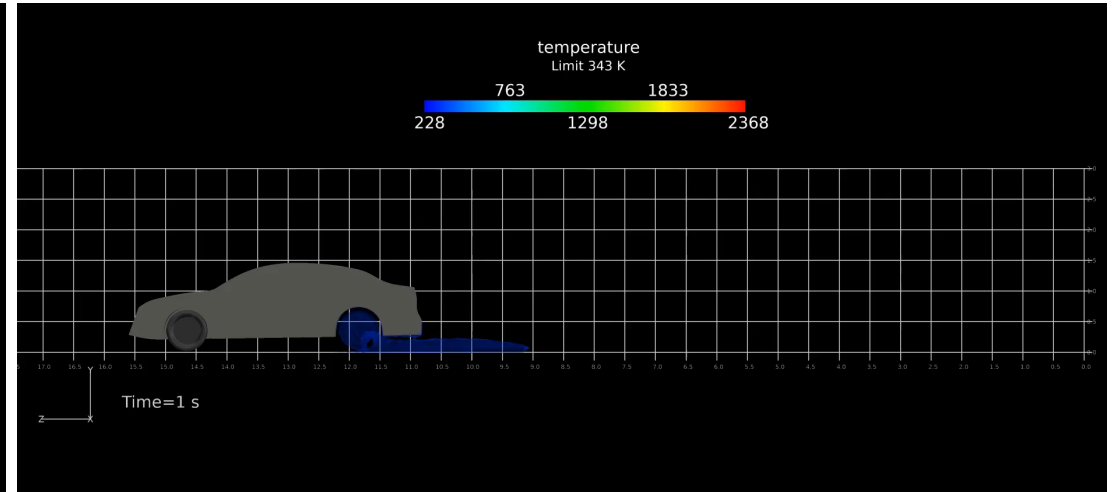
- TPRD  $\varnothing 0.5$  mm: damage level is not reached under the ceiling.  $T=300^\circ\text{C}$  is reached at max 1.6 m height.
- TPRD  $\varnothing 0.6$  mm: damage level is not reached under the ceiling for a car park height of 3 m. However,  $T=300^\circ\text{C}$  is reached at 2.5 m height, which could undermine safety for car parks with height 2.1 m..
- TPRD  $\varnothing 0.75$ -1.0 mm: damage level under the ceiling is reached within 8 s.

# 45° angle, 10 ACH – Harm to people

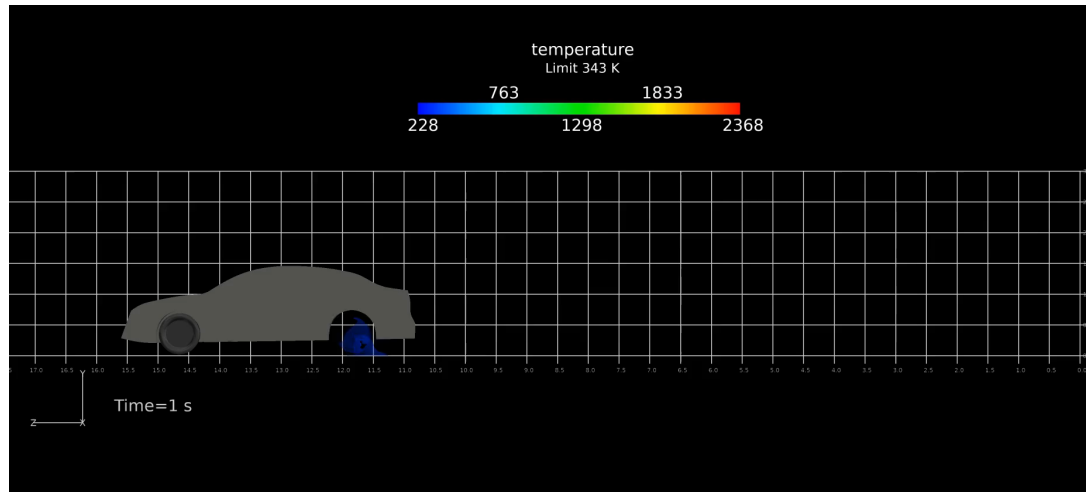
**0.5 mm**



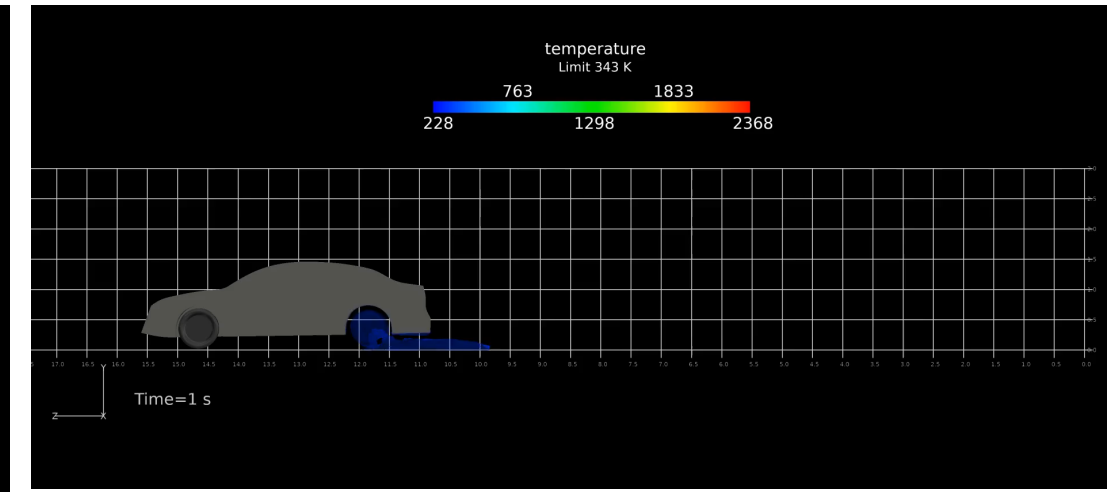
**0.6 mm**



**0.75 mm**



**1 mm**





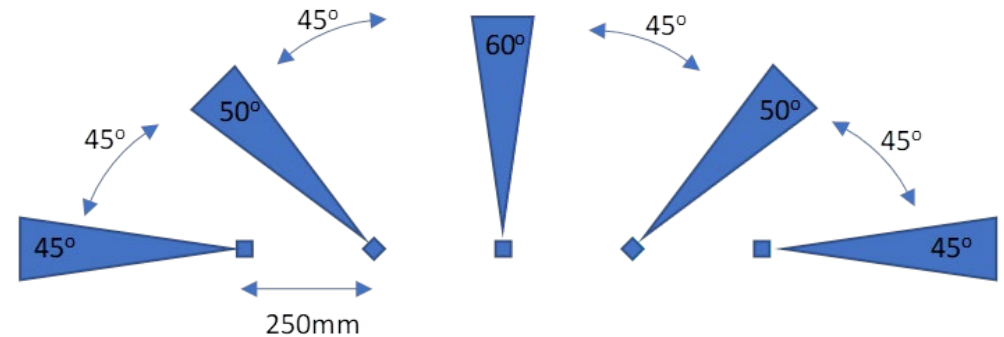
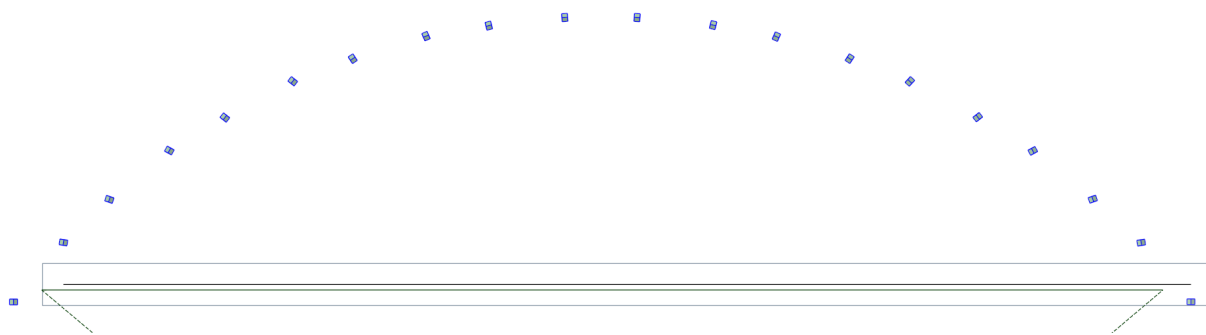
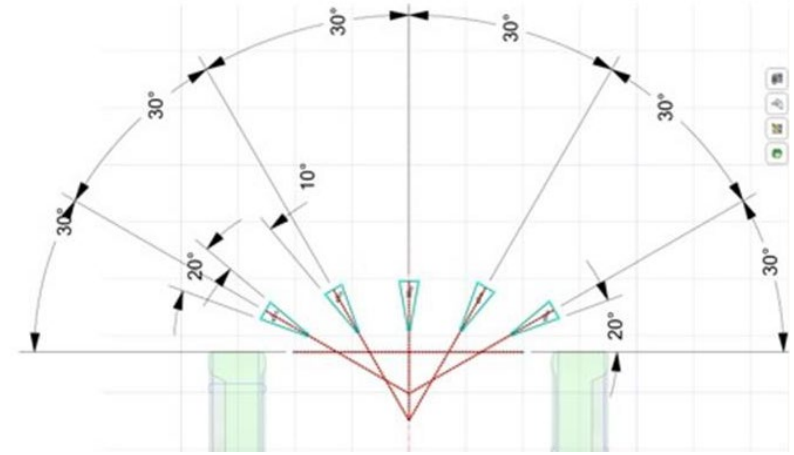
- Ventilation has minimal effect on hot combustion products distribution and hazard distances for TPRD 0.5 mm, aligning with unignited jet studies.
- TPRD release at a 45° angle is the best safety solution, minimizing hazards around the vehicle. A 0° angle poses risks, with temperatures above 70°C near the vehicle.
- For A=0° and A=30°, temperatures  $\geq 300^{\circ}\text{C}$  reach 2 meters in height, posing risks in low-ceiling car parks. A 45° angle offers a lower no-harm distance (6.2 m) than a 60° angle.
- TPRD 0.5 mm: No harm under ceilings; 300°C is reached at 1.6 m height. No-harm distance is below 6.5 m.
- TPRD 0.6 mm: 300°C is reached at 2.5 m height in car parks 3 m high; risk for 2.1 m height car parks.
- TPRD 0.75-1.0 mm: Damage occurs under the ceiling within 8 s.
- TPRD dimensions for jet fires are stricter than unignited releases.
- The damage criteria are conservative; jet fires are shorter in duration compared to car fires.

# Multiple unignited releases

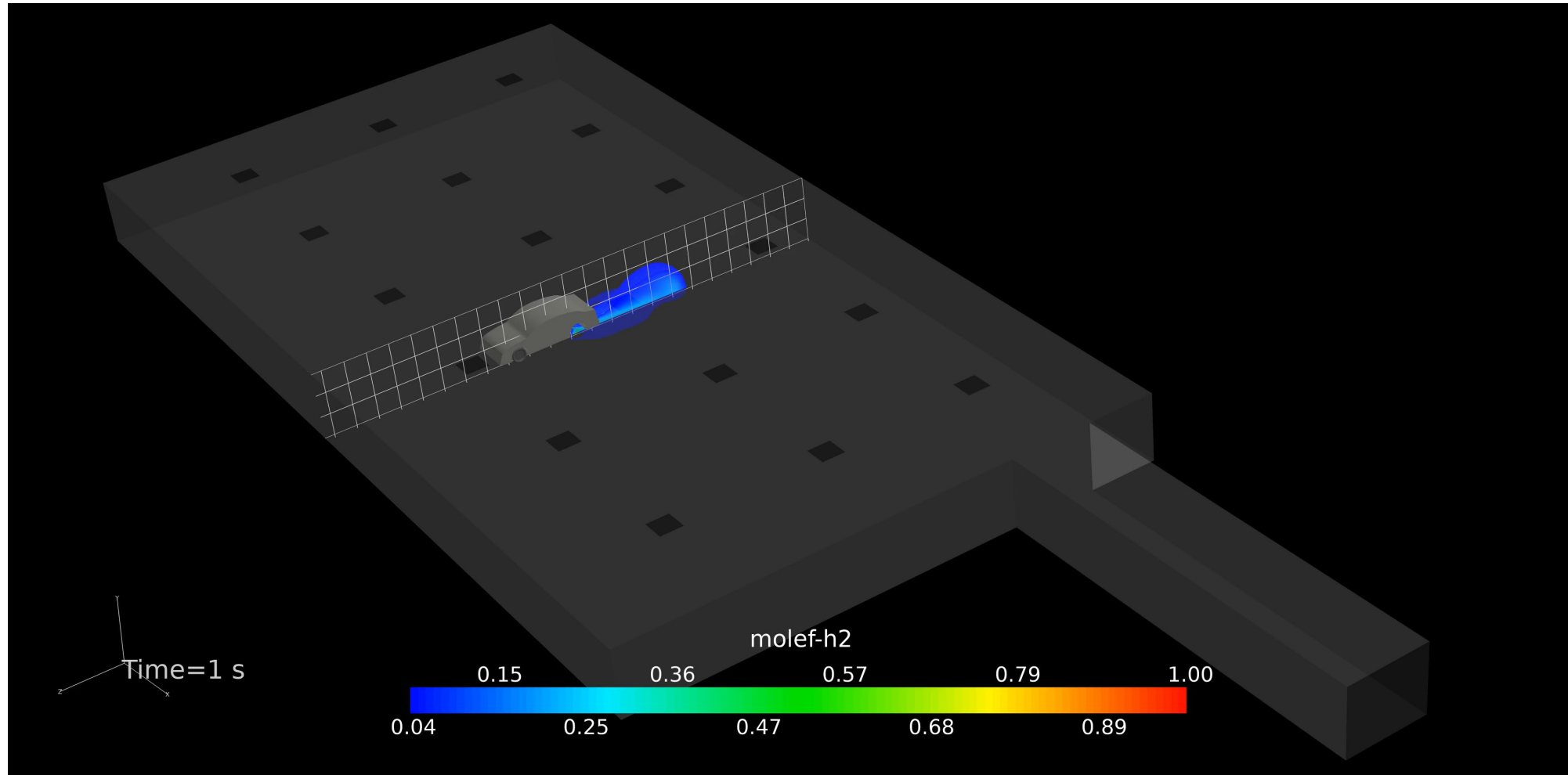
# Multiple release problem formulation

## Cases considered in this study

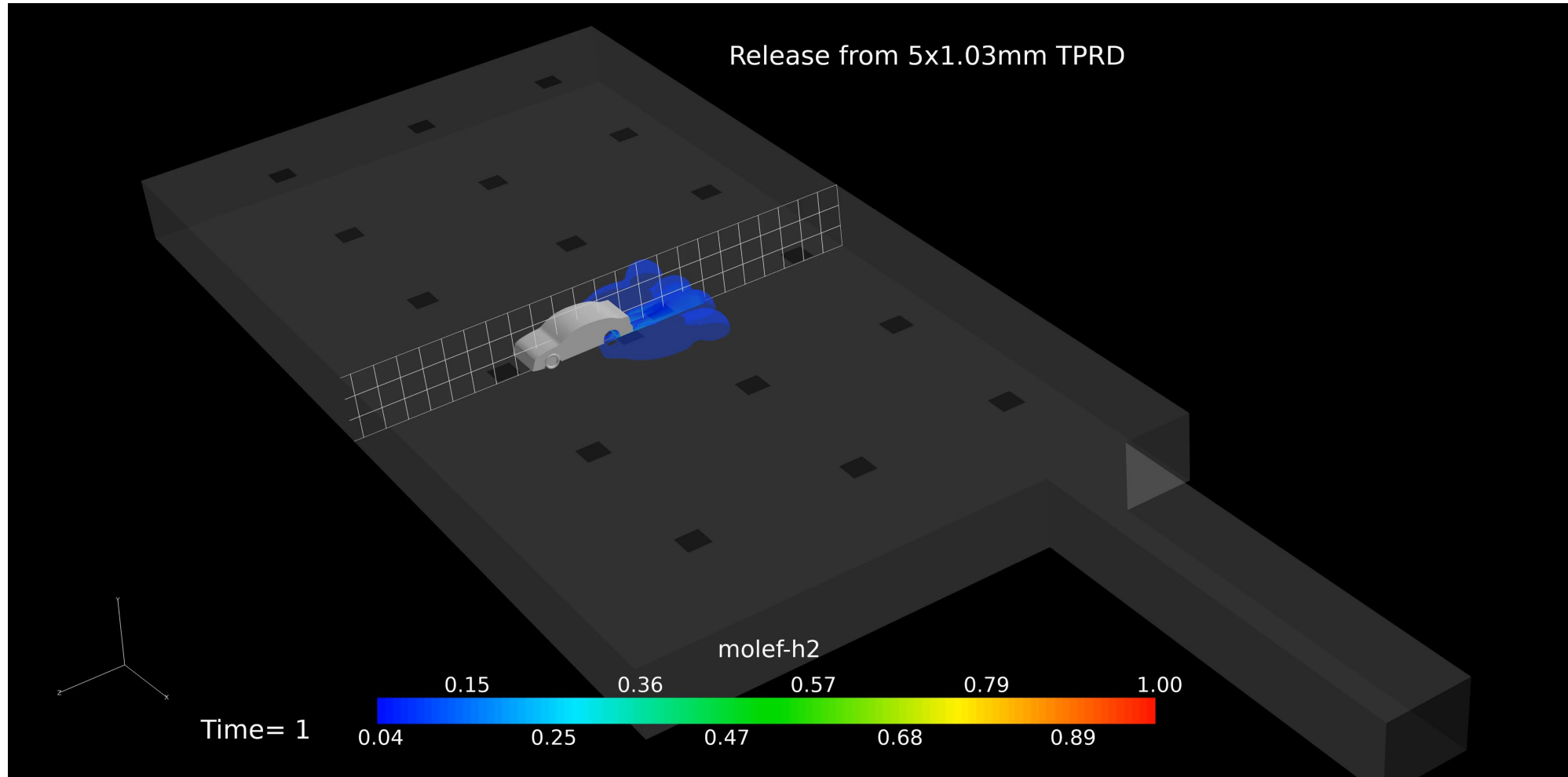
1. 10 nozzles of 0.7 mm at 45 degrees backward
2. 5 nozzles of 1.03 mm every 30° between and inclined at 45-40-35-40-45°
3. 5 nozzles of 1.03 mm every 45° between and inclined at 45-50-60-50-45°
4. 10 nozzles of 0.7 mm 20° between at 45°
5. 20 nozzles of 0.5 mm 9.5° between at 45°
6. 1 nozzles of 2.3 mm at 45°



# 10x0.7 mm at 45 degrees backward (4%)



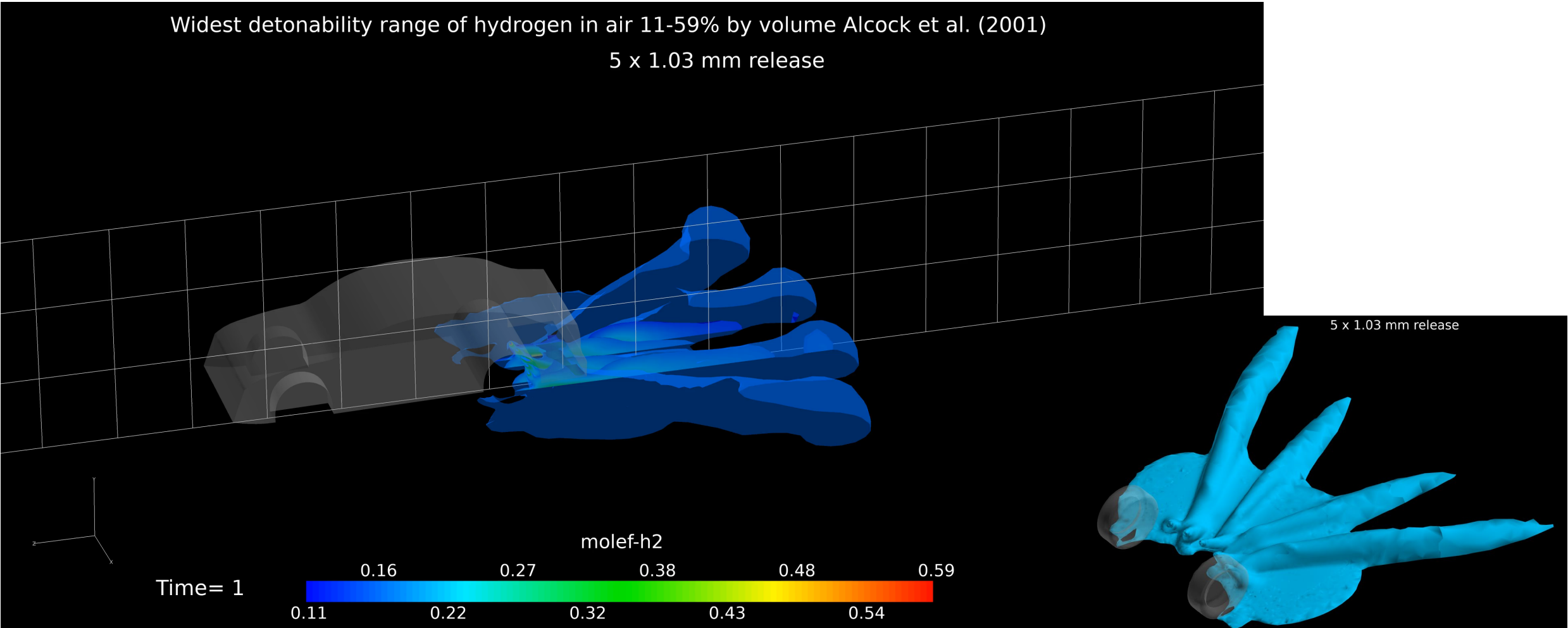
# 5x1.03 mm every 30° at 45-40-35-40-45° (4%)



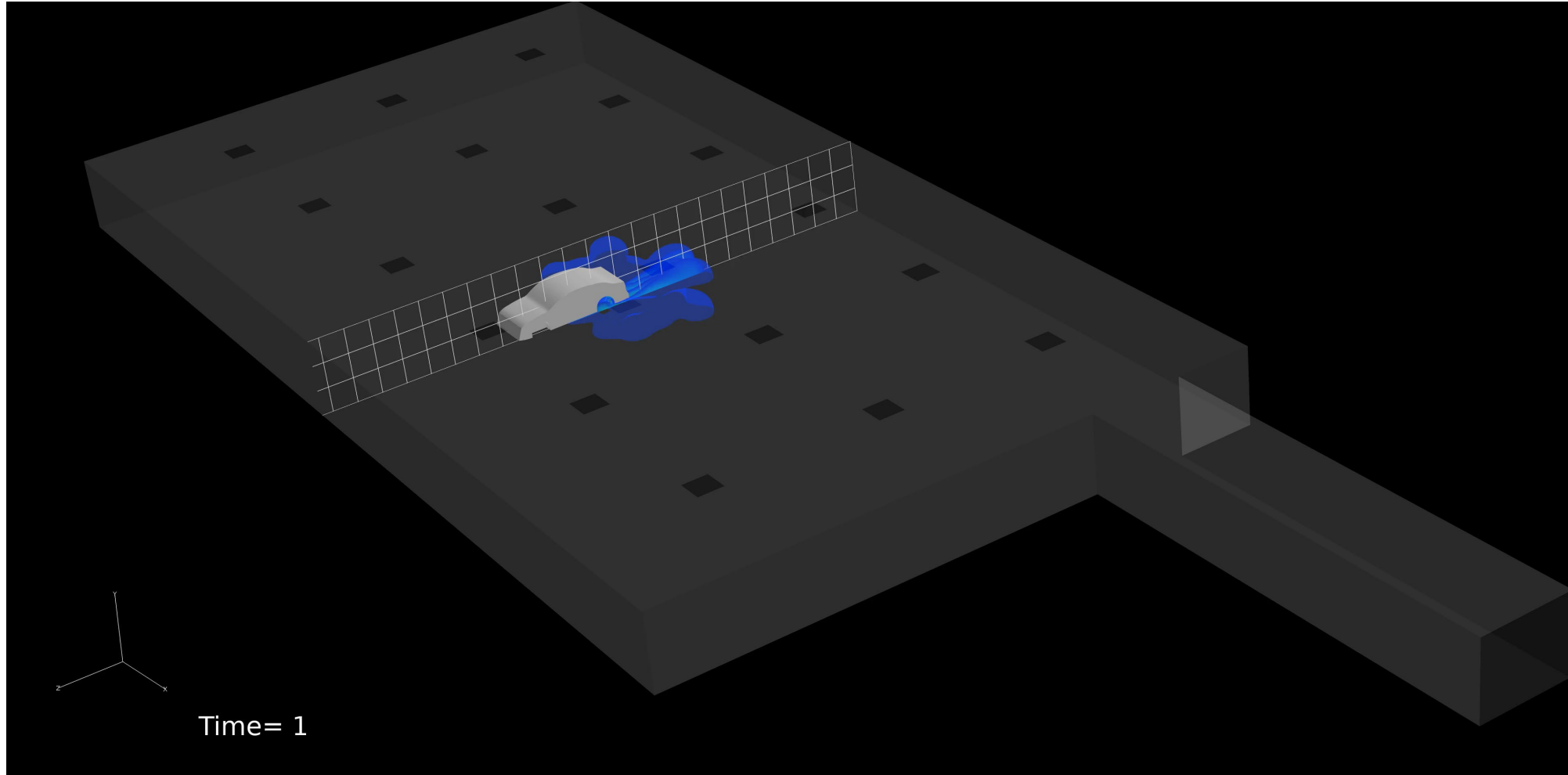


# 5x1.03 mm every 30° at 45-40-35-40-45° (11-59%)

Widest detonability range of hydrogen in air 11-59% by volume Alcock et al. (2001)  
5 x 1.03 mm release

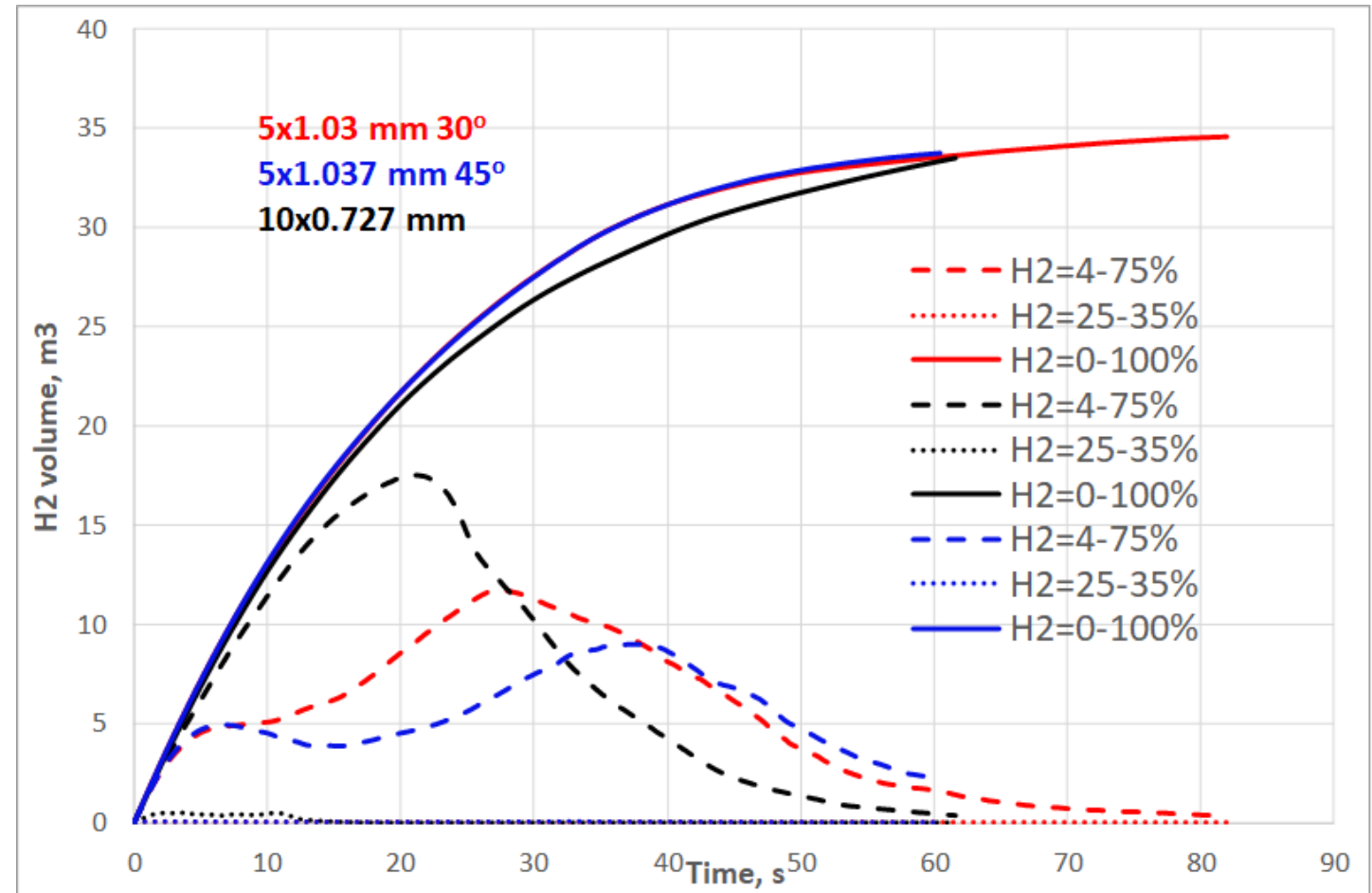


5x1.03 mm every 30° at 45-50-60-50-45°(4%)

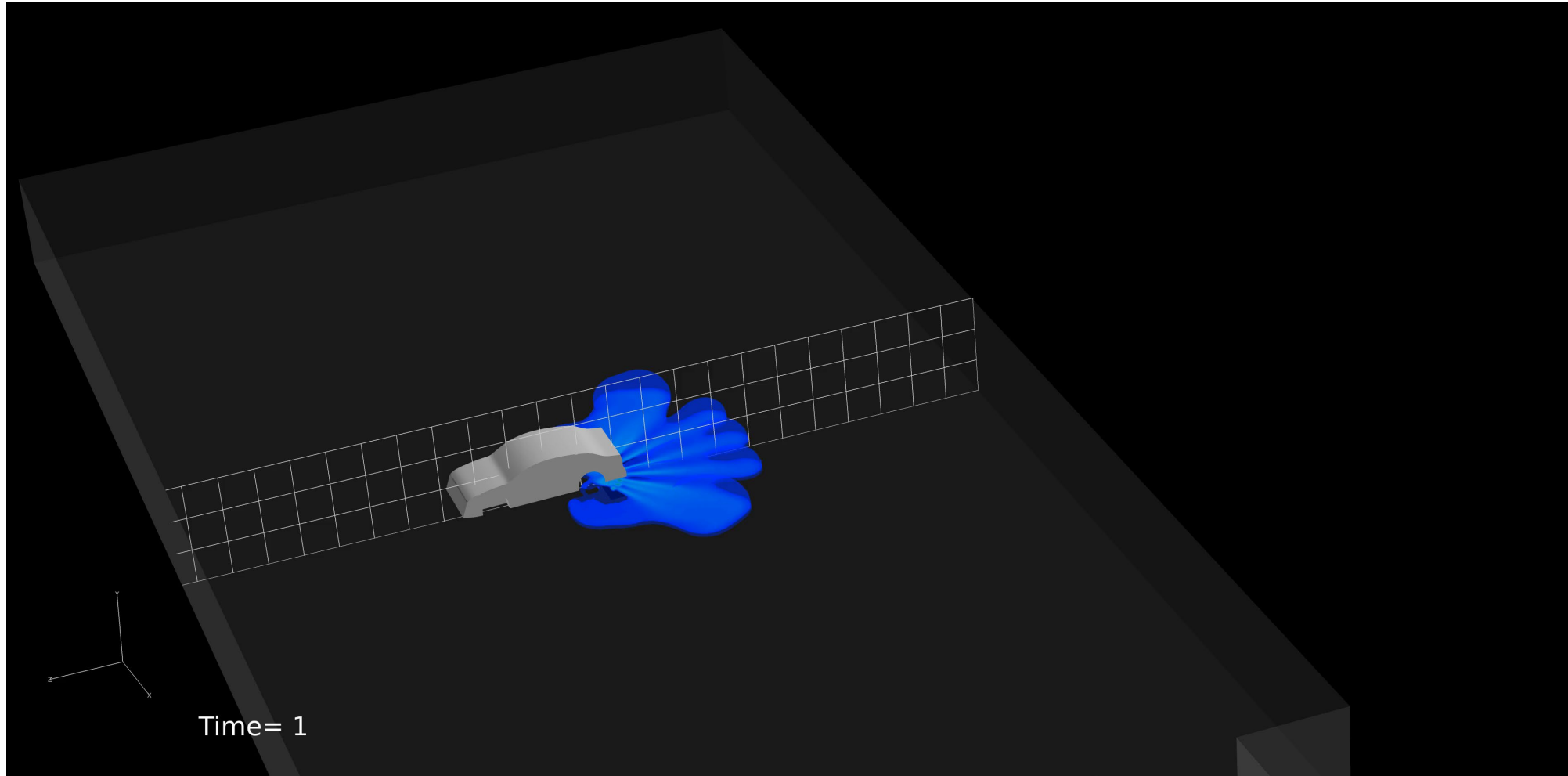


# Concentration comparison

- Total amount is the same
- Flammable concentration reduces with an increase of the angle between nozzles
- Concentration 25-35% does not differ much compared to various cases



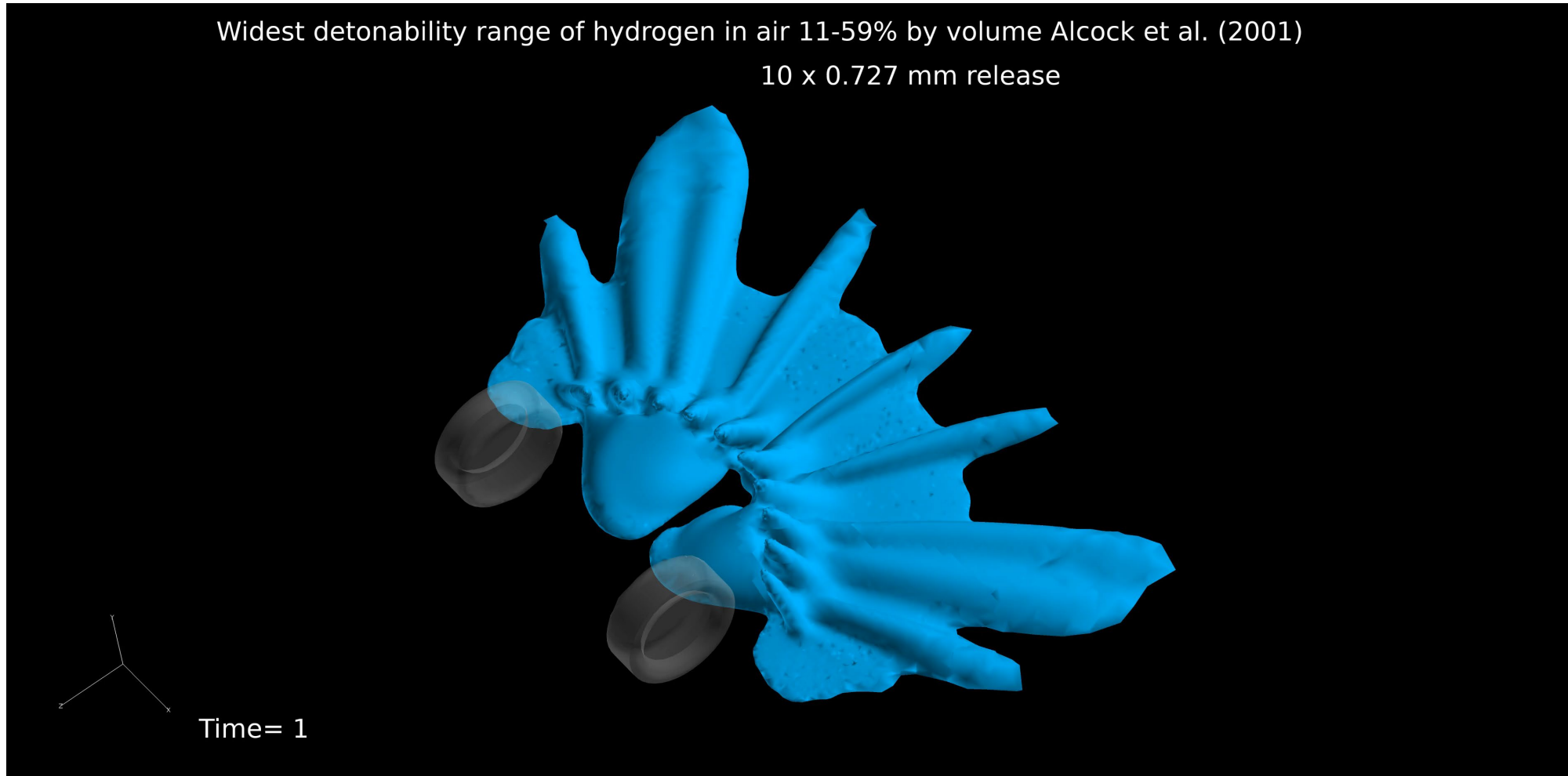
# 10x0.7 mm at 45° every 20° (4%)



# 10x0.7 mm at 45° every 20° (11%)

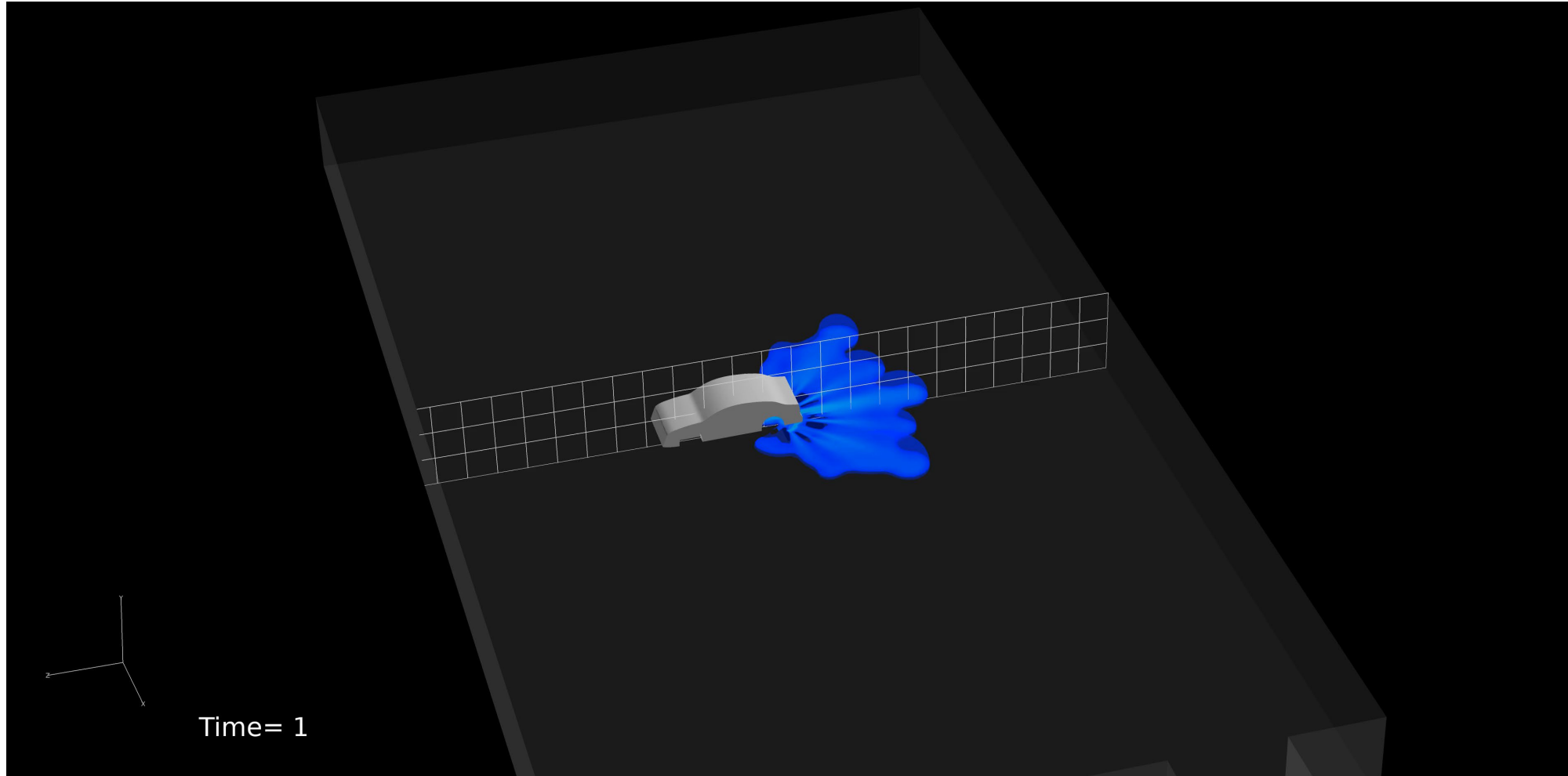
Widest detonability range of hydrogen in air 11-59% by volume Alcock et al. (2001)

10 x 0.727 mm release





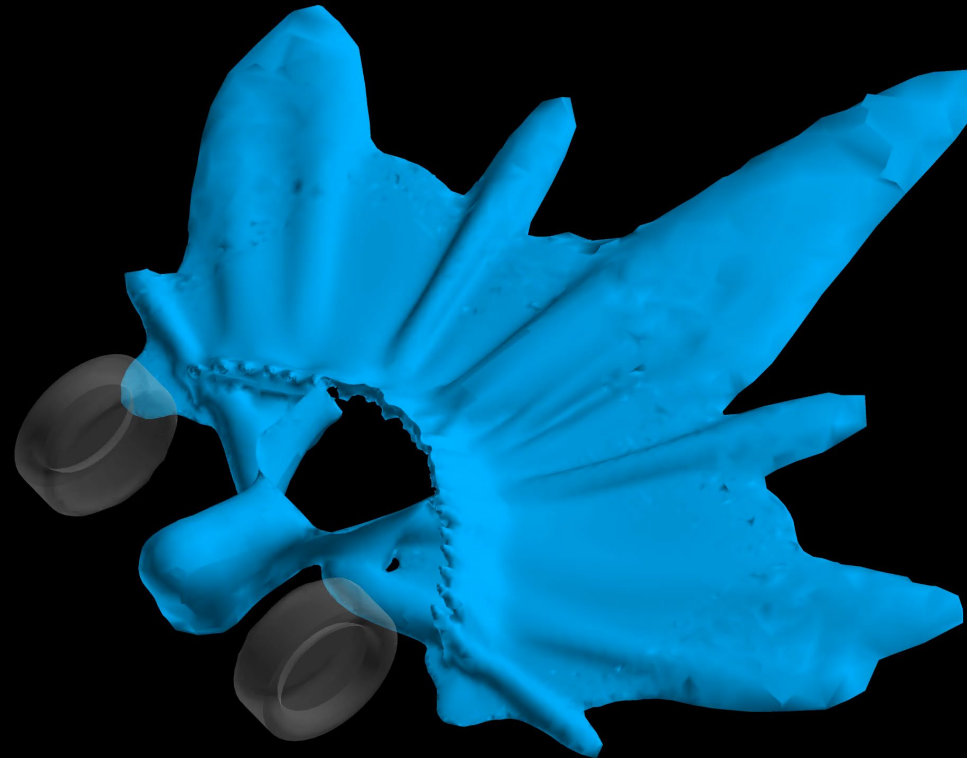
# 20x0.5 mm at 45° every 20° (4%)



# 20x0.5 mm at 45° every 20° (11%)

Widest detonability range of hydrogen in air 11-59% by volume Alcock et al. (2001)

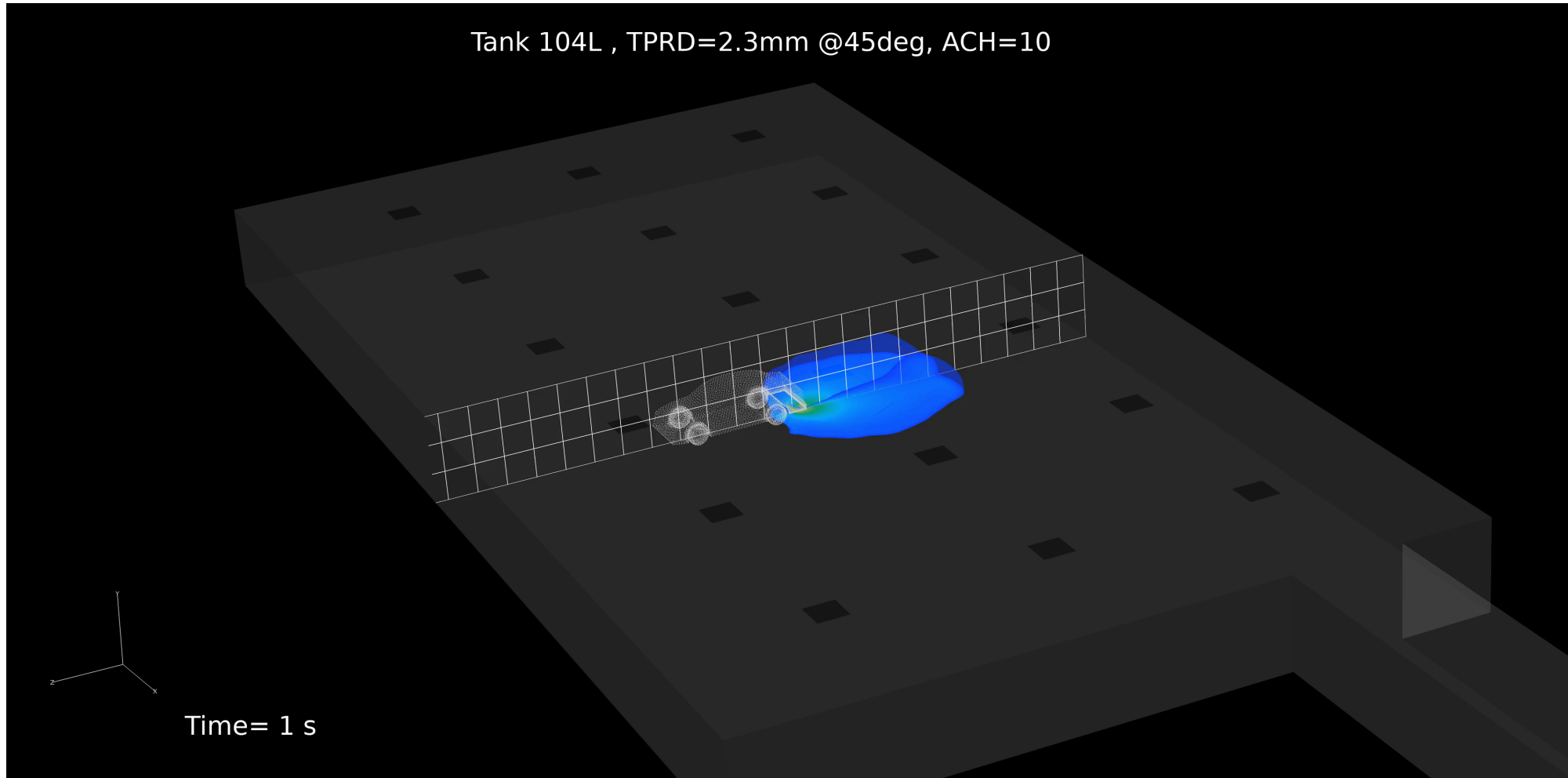
20 x 0.51 mm release



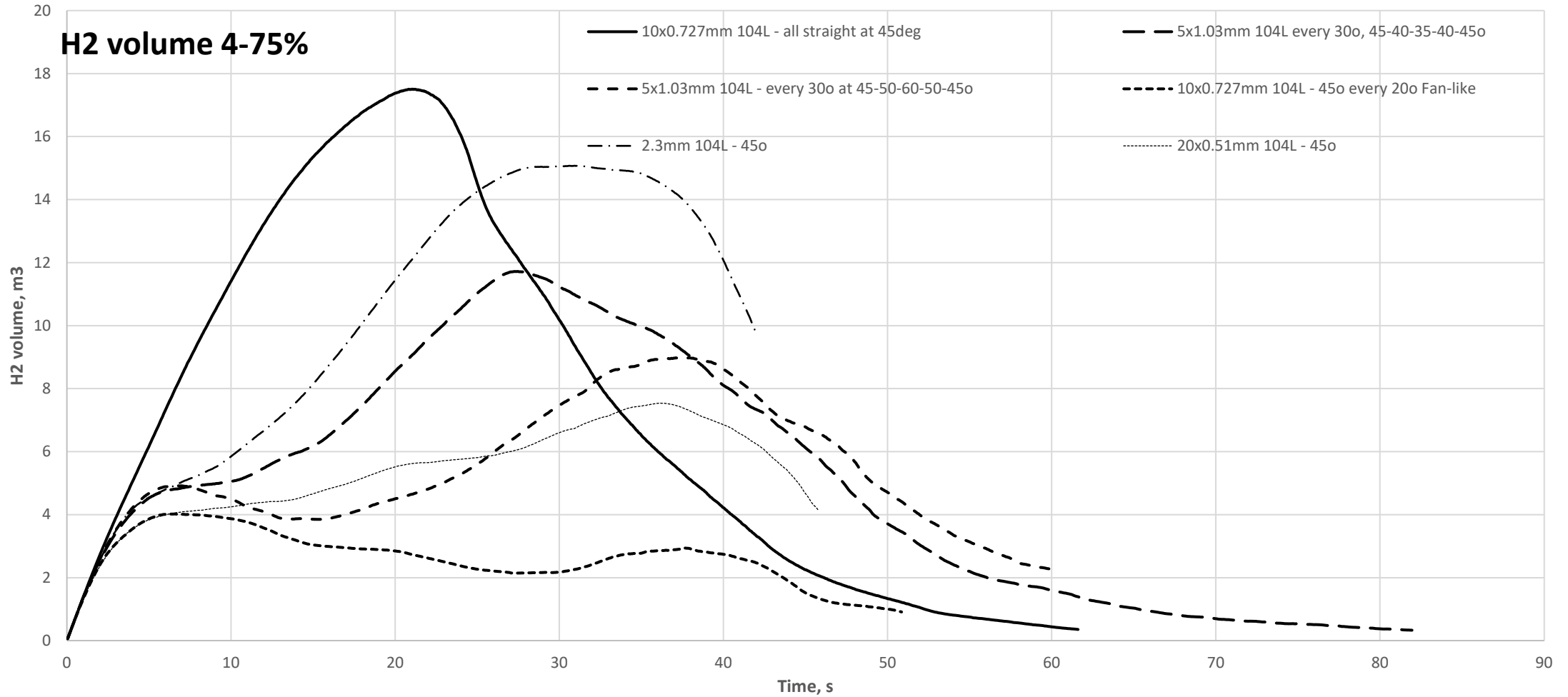
Time= 1

# 1x2.3 mm at 45° (4%)

Tank 104L , TPRD=2.3mm @45deg, ACH=10



# Combustible volume of H<sub>2</sub> in range of 4-75%



- Parallel release from multiple nozzles does not work due to re-entrainment of each other and attachment of jets
- Wider angles and further location of nozzles reduce the concentration
- Attached jets are formed by the neighbouring interaction
- 45° angle gives the best dispersion and shortest time of 4% concentration contact with the ceiling
- 10-point release at 45° gives the overall best depression amongst all cases in terms of the momentum volume of accumulated hydrogen in the space



# Thank you

PgCPD and PgCERT in Hydrogen Safety:

<https://www.ulster.ac.uk/research/topic/built-environment/hydrogen-safety-engineering/study>



This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.



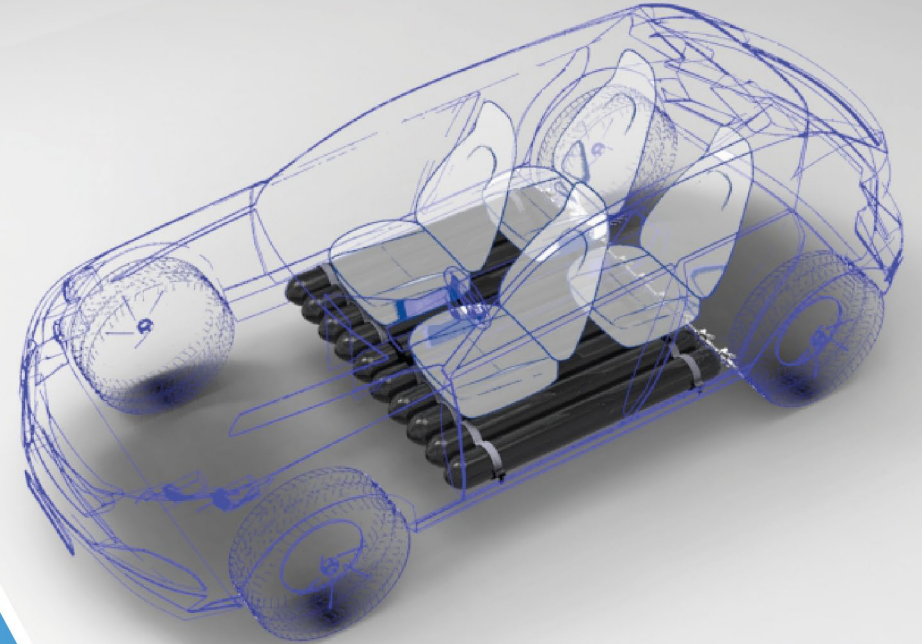
Storage of Hydrogen  
Alternative Pressure Enclosure Development



# Thermal behaviour of tanks during fast fuelling

Stakeholder's workshop of SH2APED project  
26-27 September 2024

H Xie, V Shentsov, S Kashkarov, V Molkov (UU)



[www.sh2aped.eu](http://www.sh2aped.eu)

- Introduction to thermal behaviour of fuelling
- Analytical model and CFD model
- Results of simulations
- Conclusions

# Thermal behaviour of fuelling

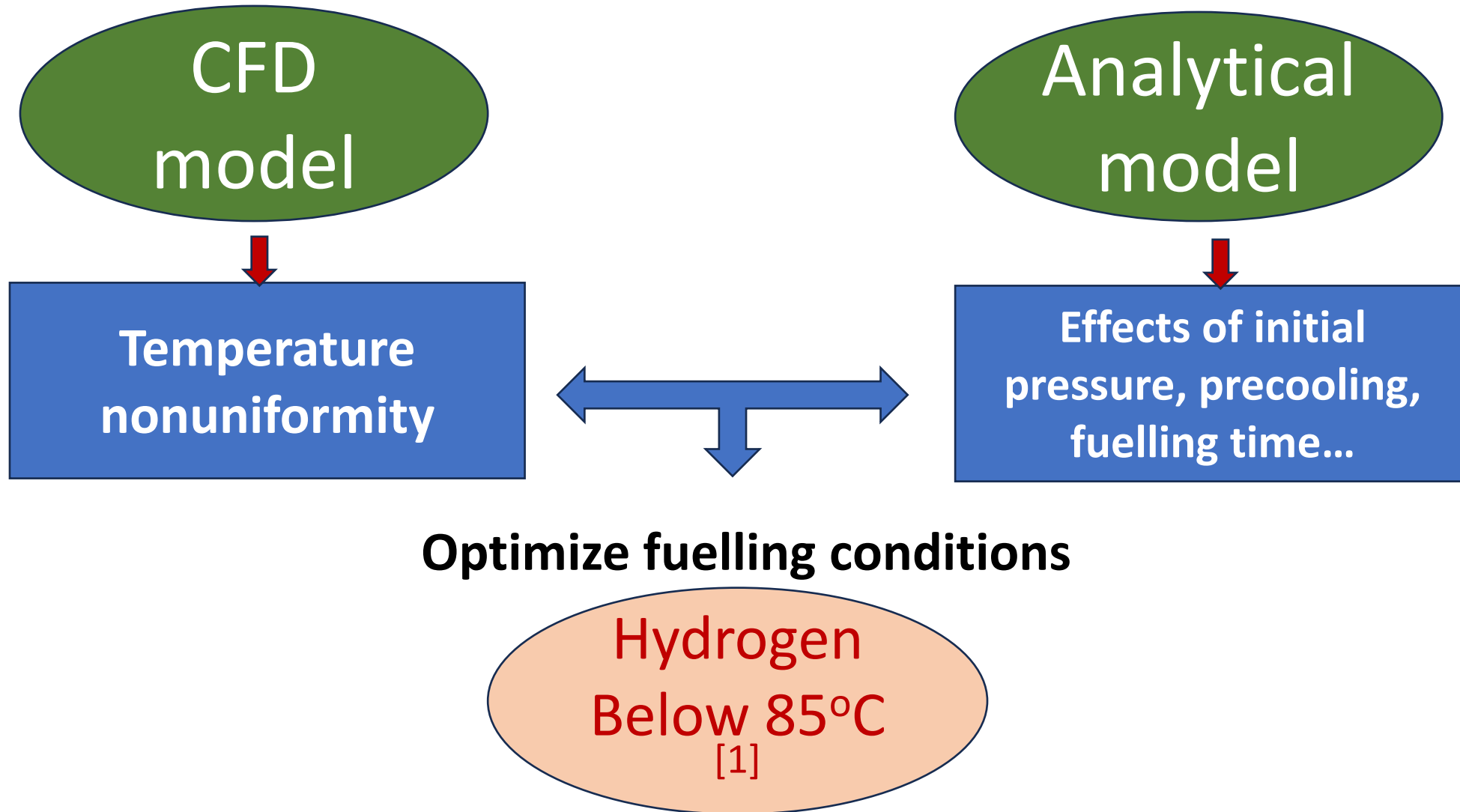
Four main reasons for the temperature change of the hydrogen inside the tank:

- The compression of the gas inside the tank
- The kinetic energy of high velocity hydrogen transforms into internal energy
- The Joule-Thomson effect
- The convective heat transfer between the hydrogen and the inner wall, the heat conduction within the wall and convective heat transfer between exterior wall and air.

↑  
H<sub>2</sub> Temperature  
↓



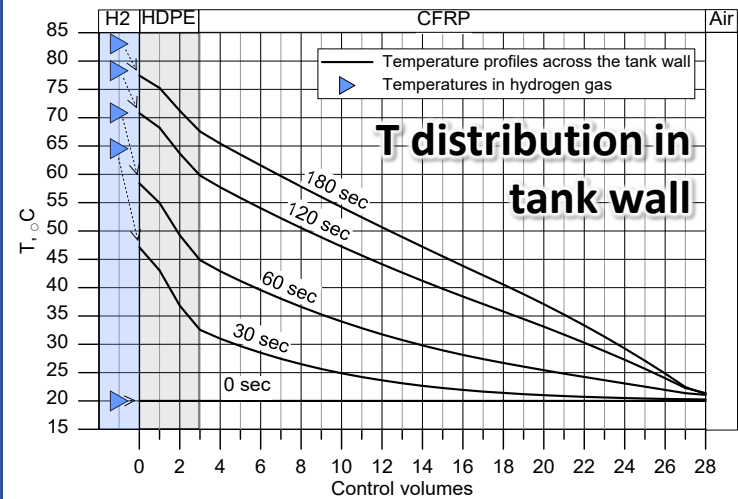
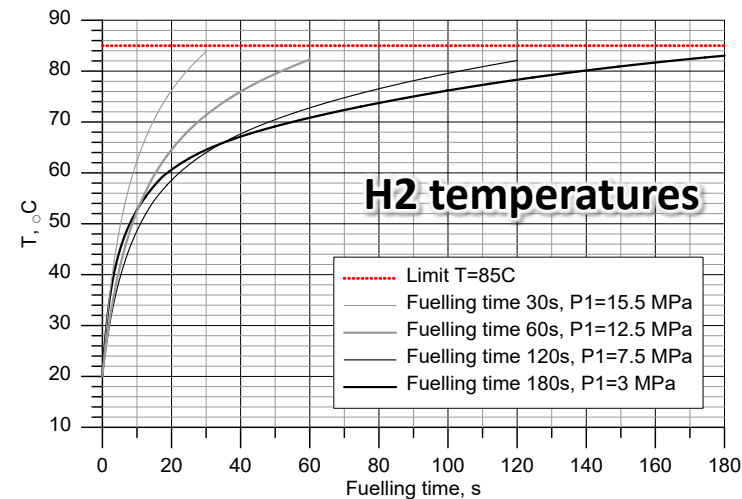
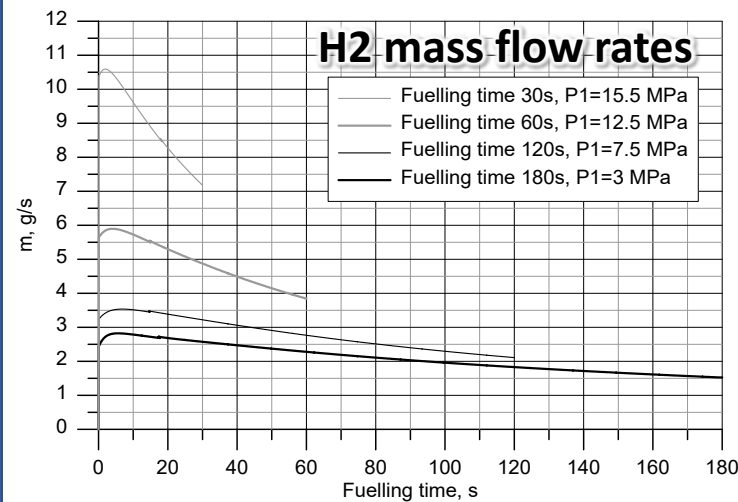
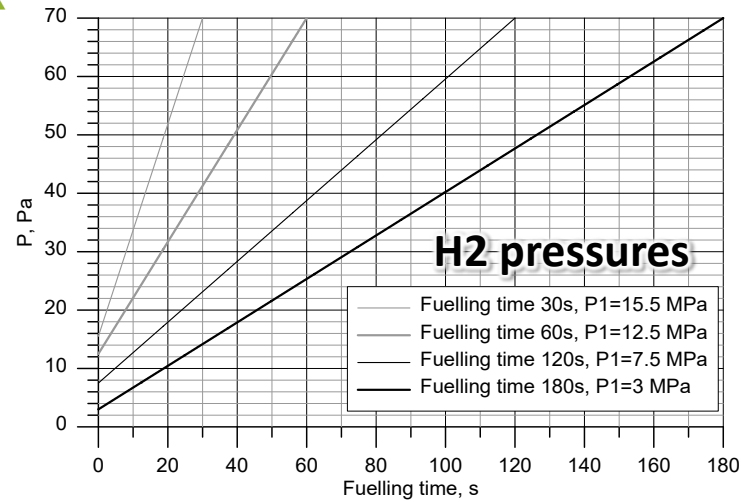
# Objectives



[1] United Nations Economic Commission for Europe. Global technical regulation on hydrogen and fuel cell vehicles. Addendum 13: Global technical regulation No. 13. Global Registry.



# Ulster analytical model



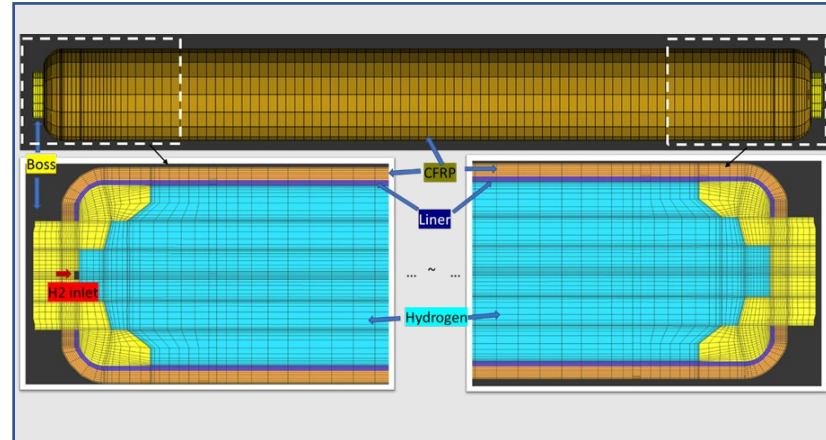
The Ulster analytical model is a one-dimensional model, which can predict efficiently any parameters of fuelling i.e. changing the initial pressure of the storage tank, initial temperate, fuelling time, and the temperature of pre-cooling to save energy.

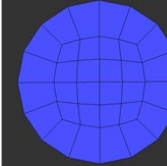
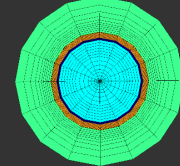
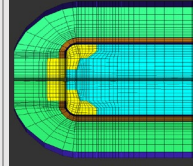
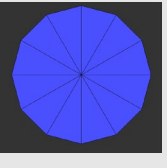
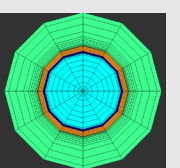
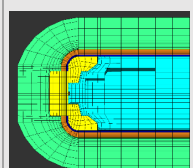
However, it is not capable to predict the temperature non-uniformity inside the tank.

# CFD models

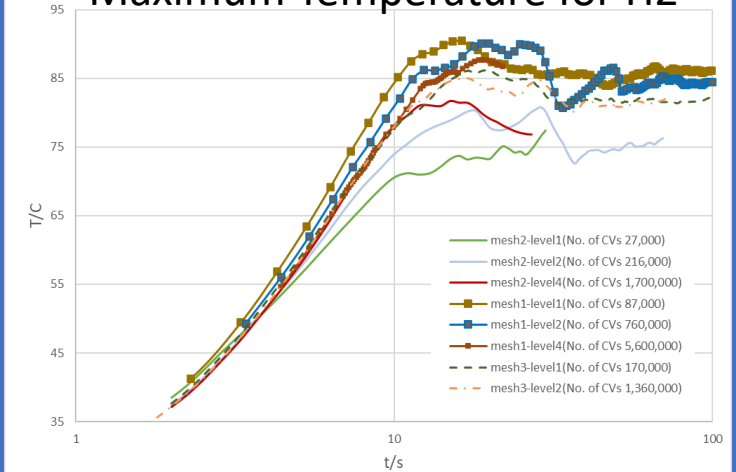
CFD model provides 3D prediction throughout the tank.

- Geometry model
- Numerical schemes
- Boundary conditions
- Grid strategy (Grid independence)

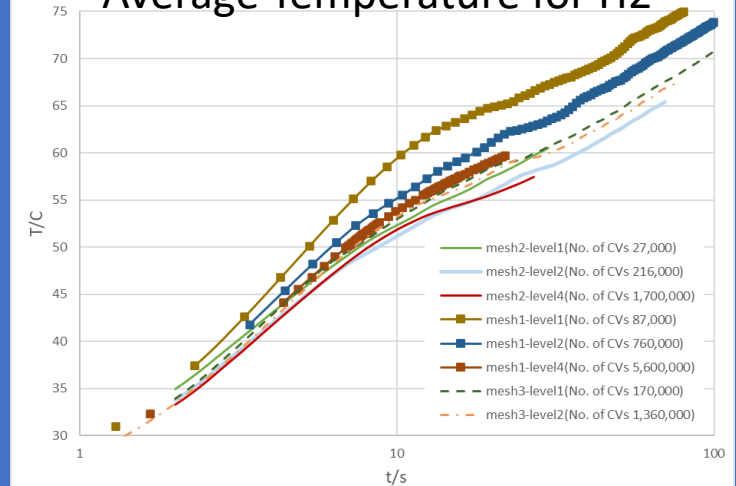


| Name   | Inlet                                                                                | XZ-Plane                                                                              | XY-Plane                                                                              | No. of Control Volumes |
|--------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|------------------------|
| Mesh 1 |   |   |   | 87,000                 |
| Mesh 2 |  |  |  | 27,000                 |

## Maximum Temperature for H2

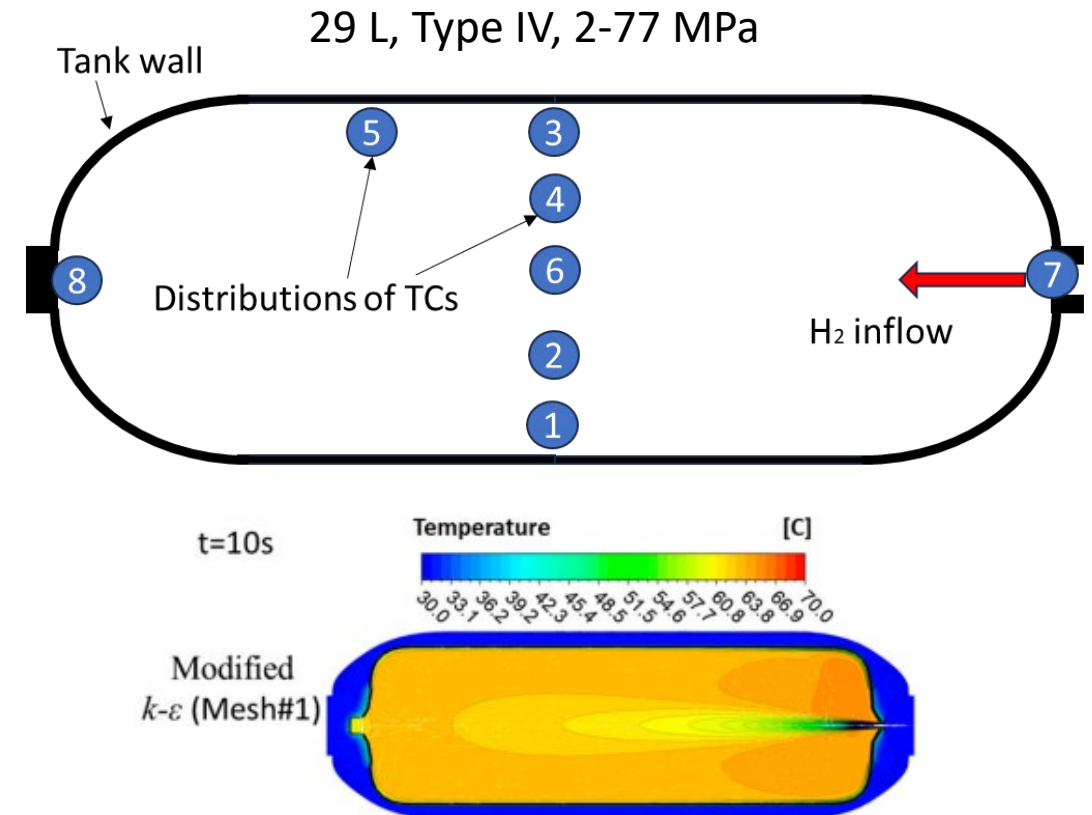
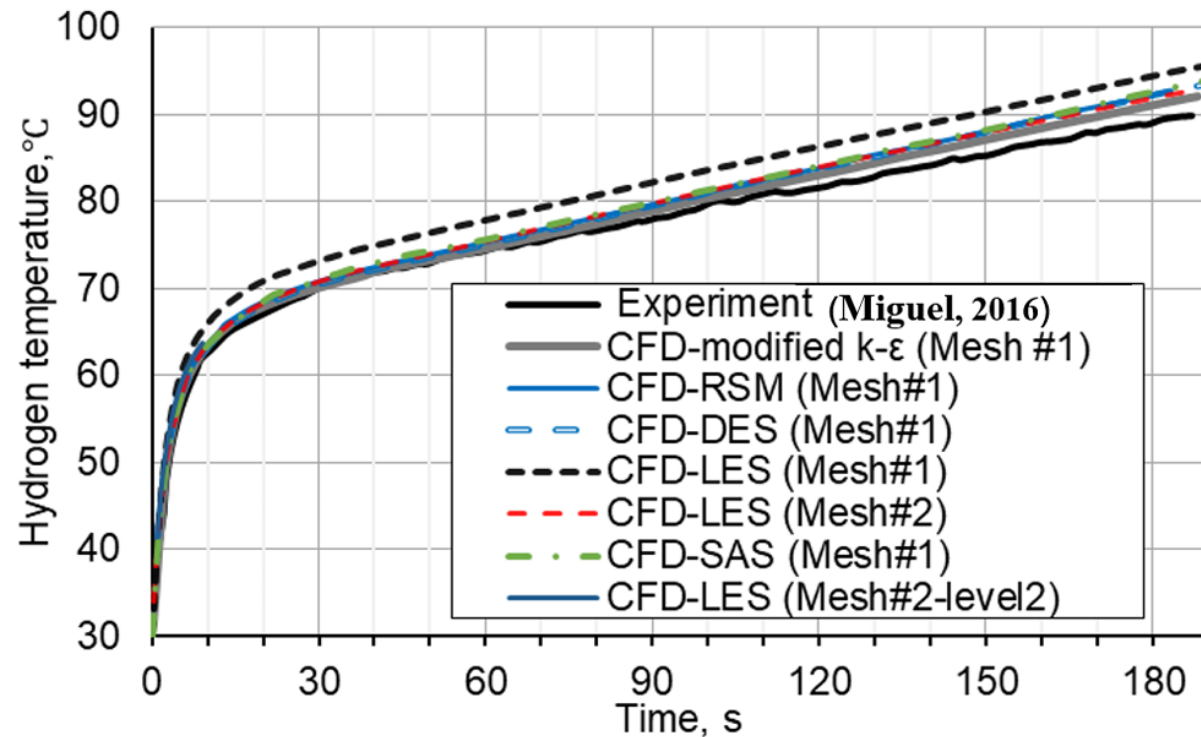


## Average Temperature for H2



# Verification and Validation of CFD model

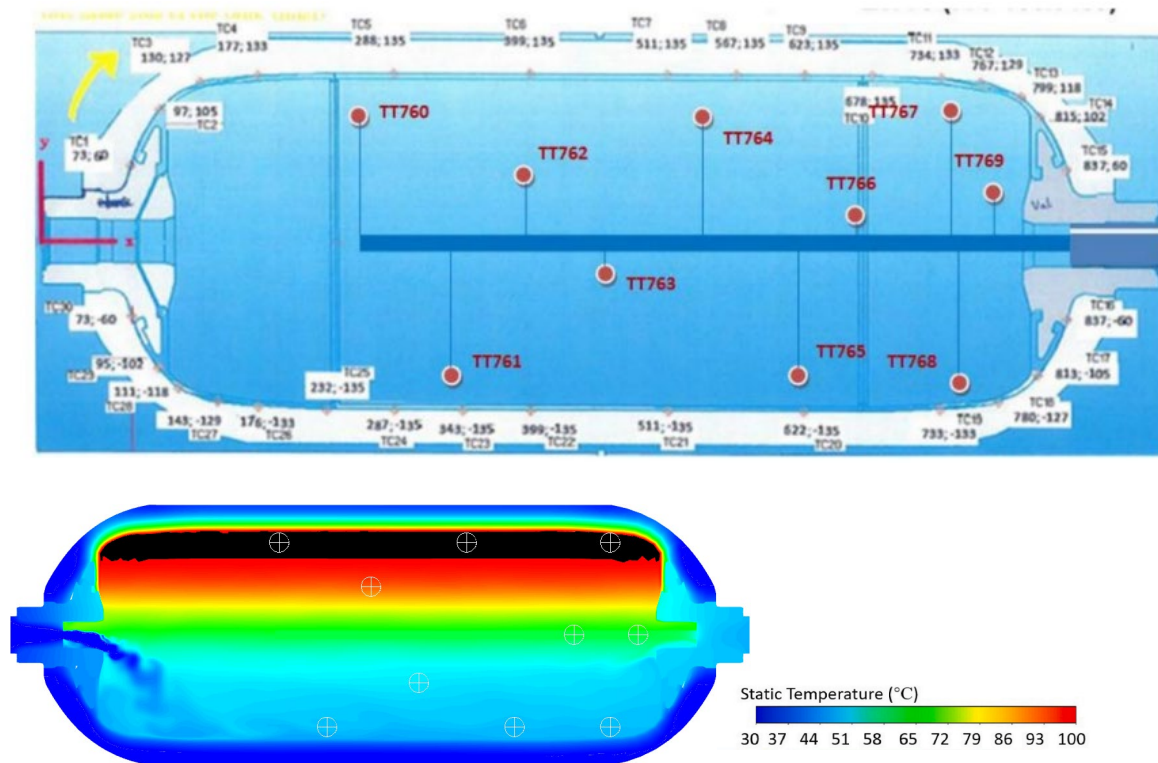
The accuracy of CFD models have been validated against two experiments from reference.



Xie H, Makarov D, Kashkarov S, Molkov V. CFD Simulations of Hydrogen Tank Fuelling: Sensitivity to Turbulence Model and Grid Resolution. Hydrogen. 2023;4:1001-21.

# Verification and Validation of CFD model

The accuracy of CFD models have been validated against two experiments from reference.



## Overall tank characteristics

|                                      |      |
|--------------------------------------|------|
| Volume (L)                           | 36   |
| External length (mm)                 | 913  |
| External diameter (mm)               | 325  |
| Inlet diameter (mm)                  | 10   |
| Thickness of liner (mm)              | 3.8  |
| Thickness of composite overwrap (mm) | 27.8 |

## Polymer liner properties

|                                       |       |
|---------------------------------------|-------|
| Liner heat conductivity (W/m/K)       | 0.414 |
| Liner specific heat capacity (J/kg/K) | 1799  |
| Liner density (kg/m <sup>3</sup> )    | 914   |

## Carbon fibre reinforced polymer (CFRP) overwrap properties

|                                           |       |
|-------------------------------------------|-------|
| Composite heat conductivity (W/m/K)       | 0.616 |
| Composite specific heat capacity (J/kg/K) | 783   |
| Composite density (kg/m <sup>3</sup> )    | 1365  |

## Stainless Steel 316L Plug and pipe properties

|                                       |      |
|---------------------------------------|------|
| Metal heat conductivity (W/m/K)       | 16.2 |
| Metal specific heat capacity (J/kg/K) | 500  |
| Metal density (kg/m <sup>3</sup> )    | 7990 |

## Aluminium 6601 Boss properties

|                                       |      |
|---------------------------------------|------|
| Metal heat conductivity (W/m/K)       | 167  |
| Metal specific heat capacity (J/kg/K) | 896  |
| Metal density (kg/m <sup>3</sup> )    | 2700 |

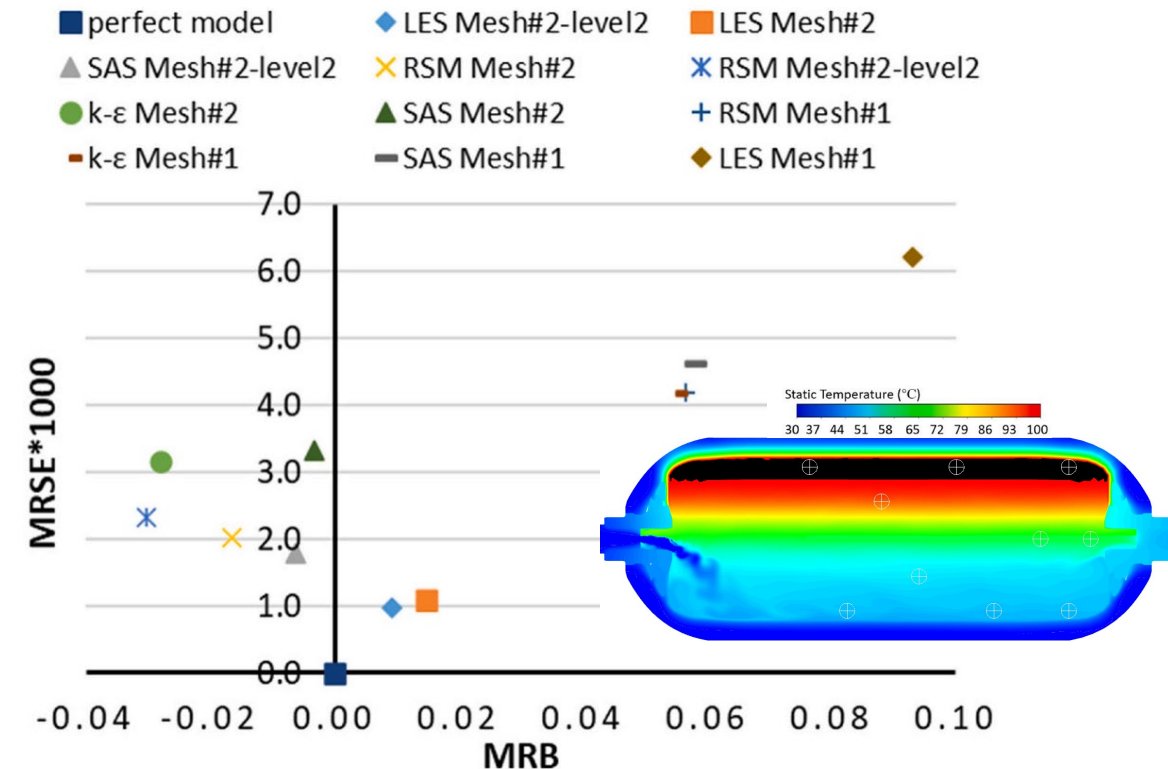
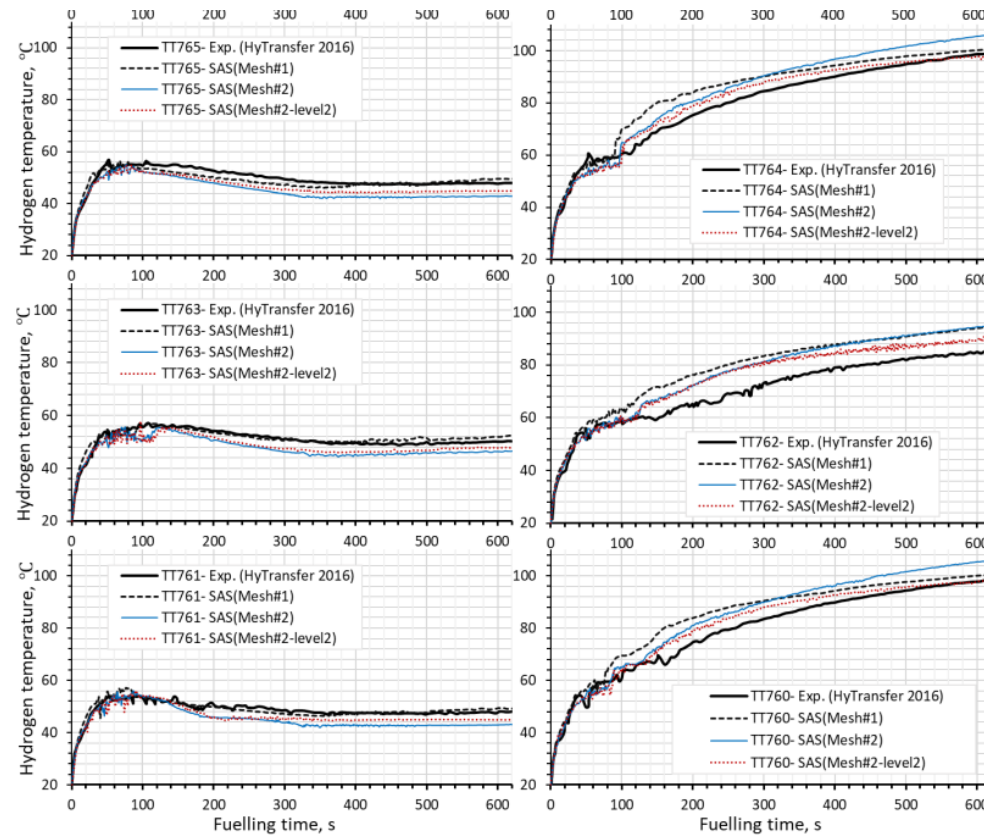
Xie H, Makarov D, Kashkarov S, Molkov V. Comparative analysis of CFD models to simulate temperature non-uniformity during hydrogen tank refuelling. International Journal of Hydrogen Energy. 2024;70:715-28.

Ravinel B, Acosta B, De Migue N, Moretto P, Rafael O-C, Goran J, et al. HyTransfer project D4.1 report on the experimental filling test campaign. 2017.



# Verification and Validation of CFD model

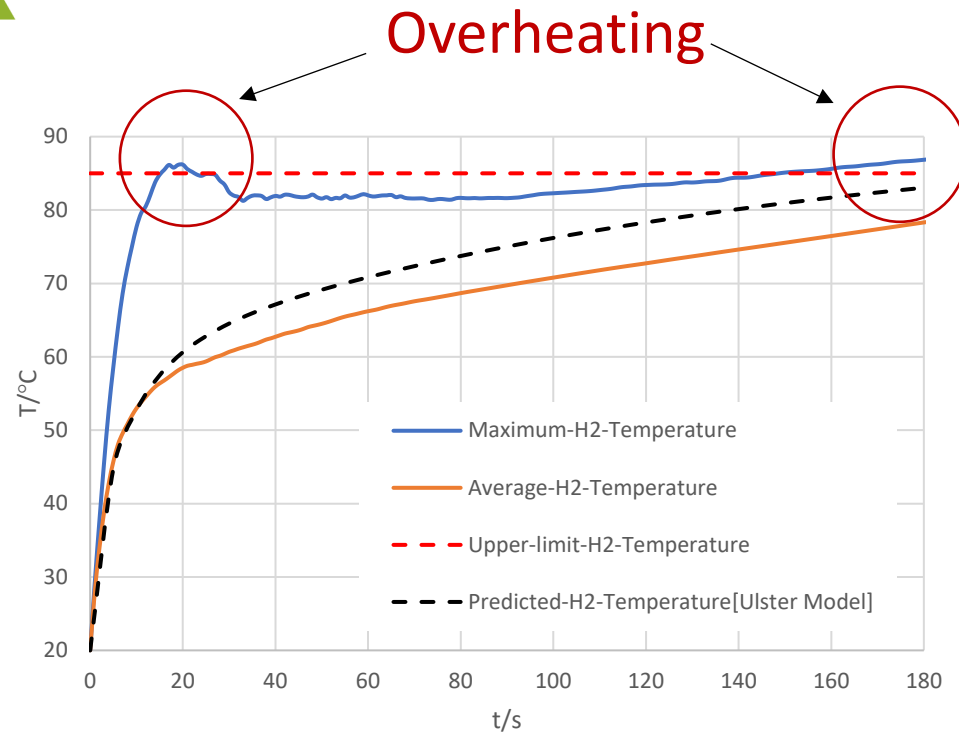
The accuracy of CFD models have been validated against two experiments from reference.



Xie H, Makarov D, Kashkarov S, Molkov V. Comparative analysis of CFD models to simulate temperature non-uniformity during hydrogen tank refuelling. International Journal of Hydrogen Energy. 2024;70:715-28.

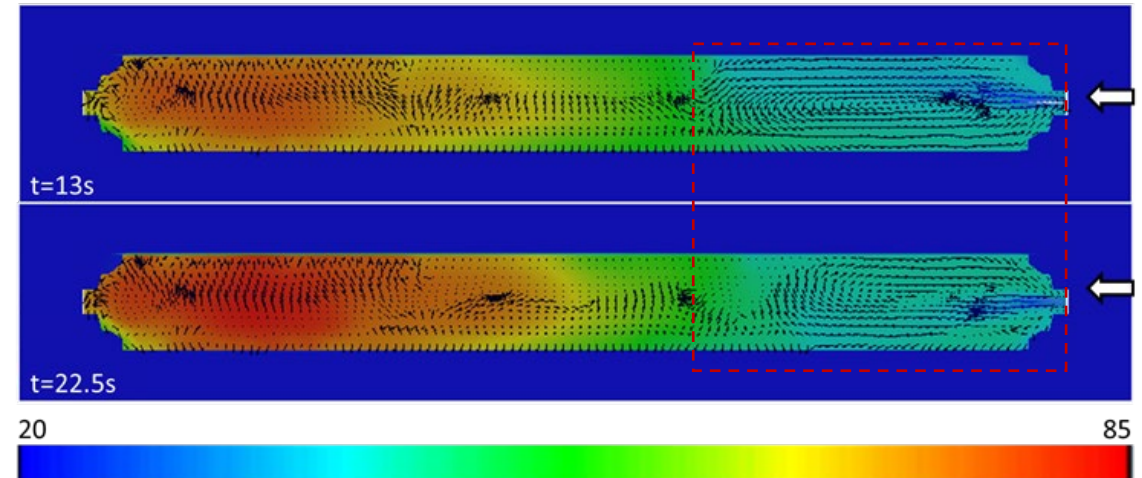


# CFD results for temperature nonuniformity



Linear pressure ramp, 3-70 MPa in 180 s

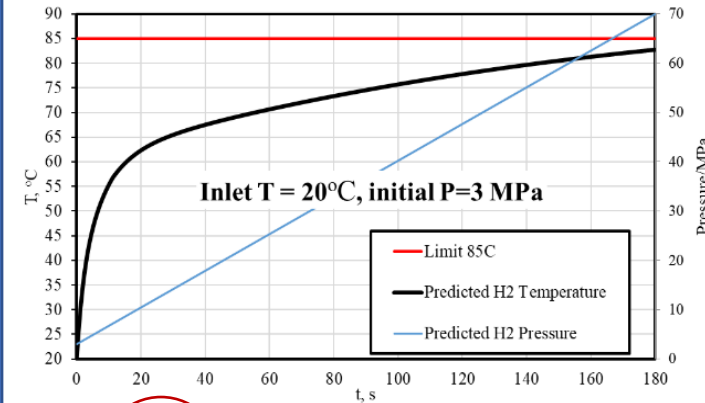
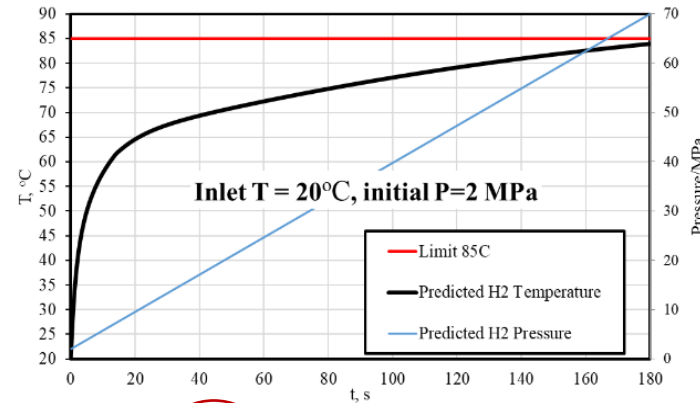
Temperature,  $^{\circ}\text{C}$



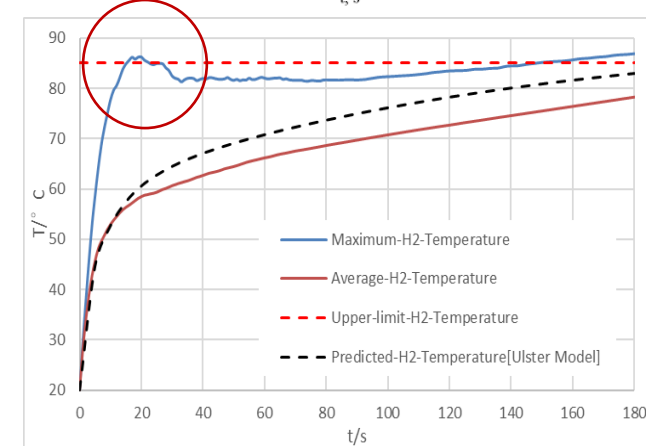
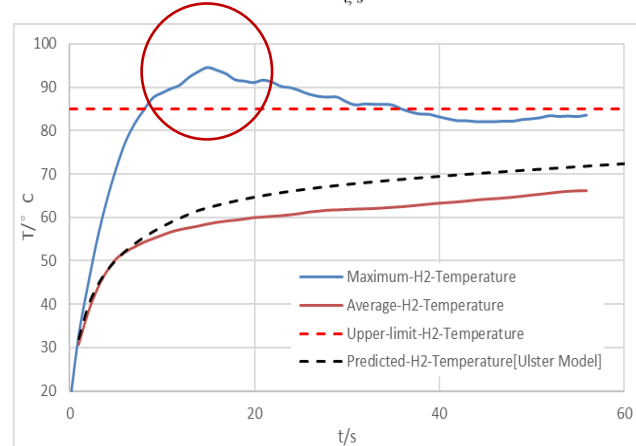
- CFD results show that overheating of hydrogen can occur at the beginning and end of fuelling.
- A temperature nonuniformity around  $28^{\circ}\text{C}$  is found at  $t=16\text{s}$  and it decreases to  $8^{\circ}\text{C}$  at  $t=180\text{s}$ .
- Ulster analytical model is able to evaluate the final average temperature at the end of fuelling.

# Effect of initial pressure

analytical model

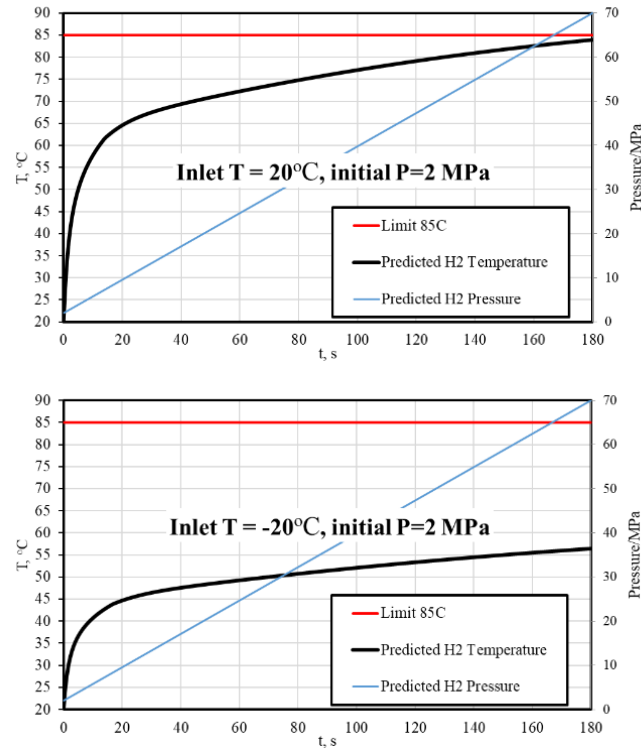


CFD model vs UU analytical (black dashed)

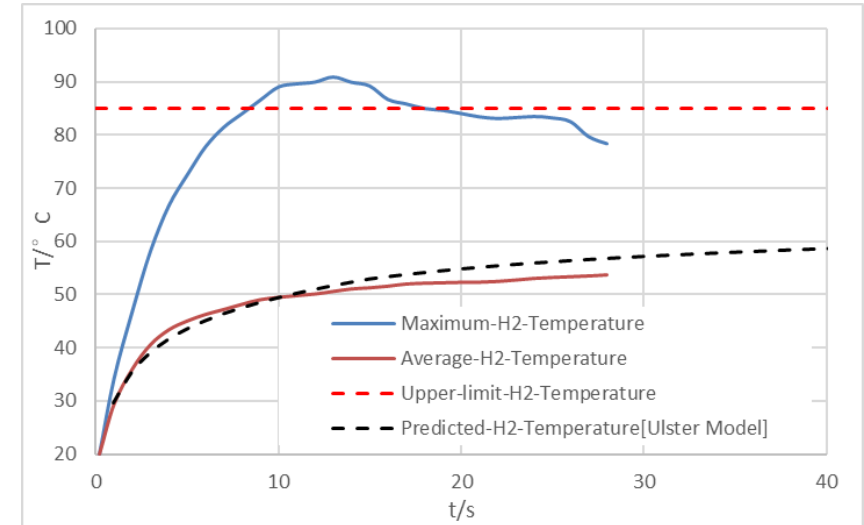
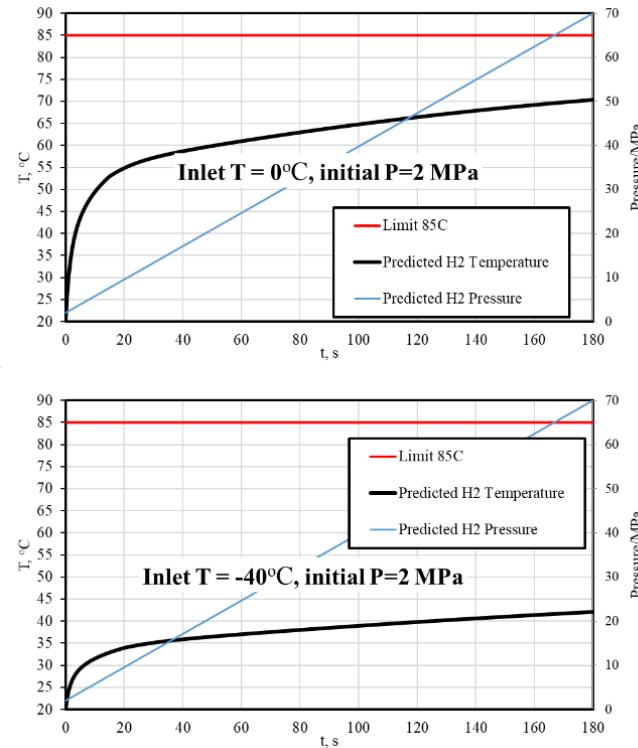


- Fuelling starting with an initial pressure of 2 and 3 MPa in 180s risks overheating.
- CFD models show overheating caused mainly by temperature nonuniformity in the first 20s.
- Fuelling regimes/protocols will be developed for conformable tanks to satisfy RCS requirements.

# Effect of precooling

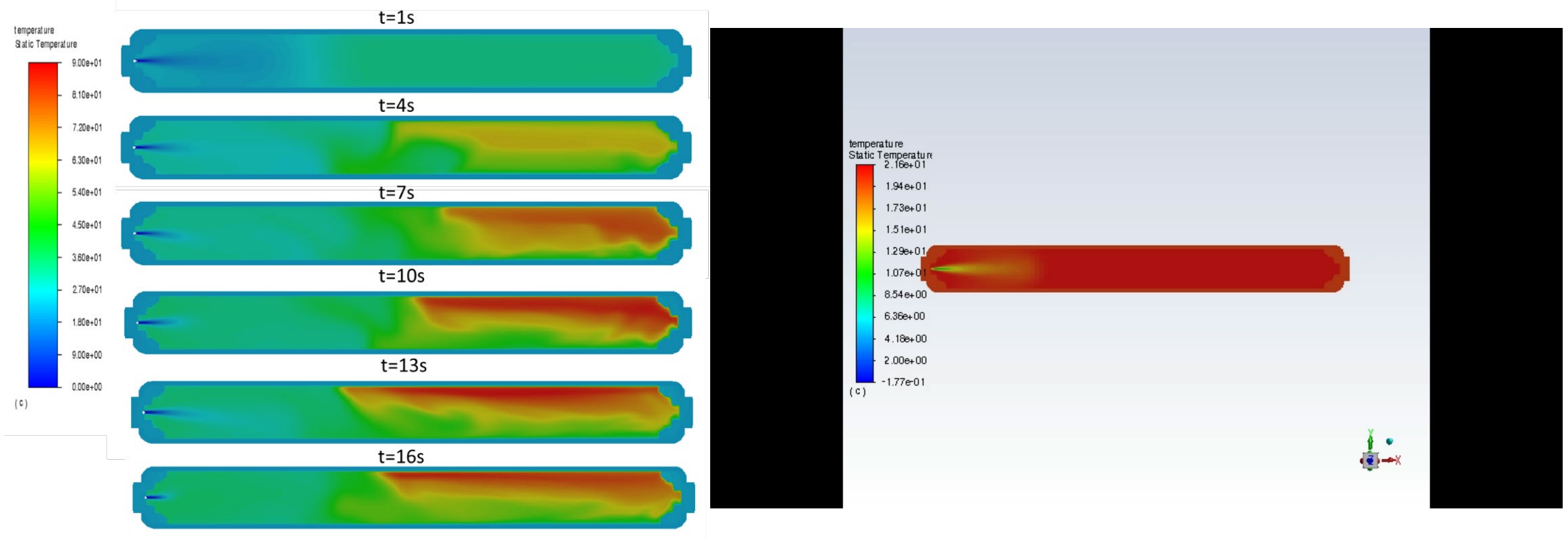


analytical model



CFD model (inlet T = 0°C)

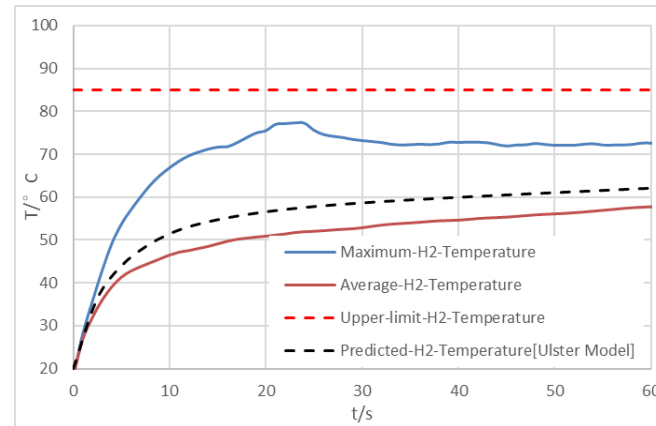
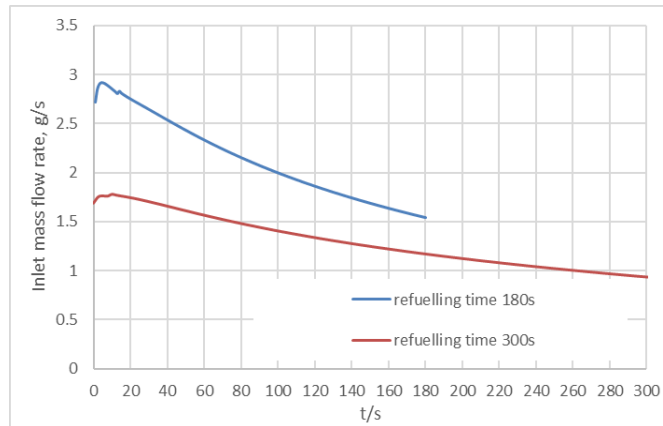
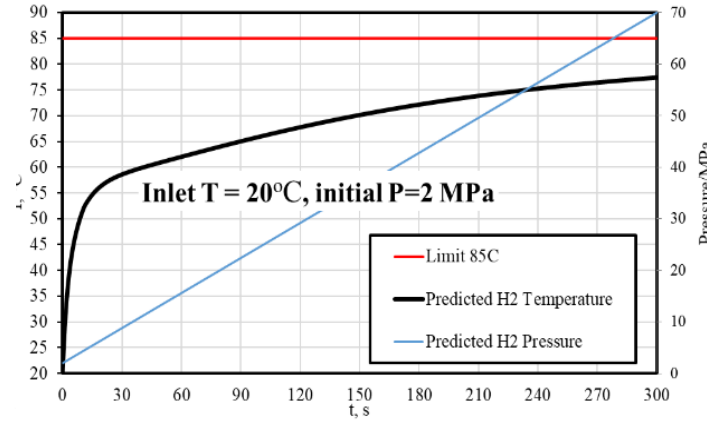
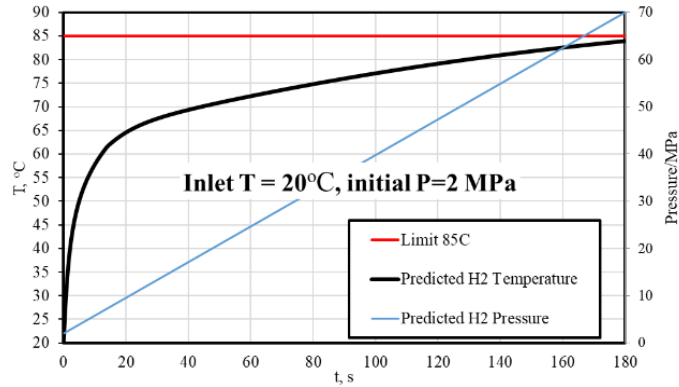
- Precooling can significantly decrease the average hydrogen temperature in the tank.
- To avoid overheating at the beginning the increase of precooling or fuelling time is required!
- 3 min fuelling is required but not “must”, can be extended to 5 min see slide below.



The low-temperature H<sub>2</sub> was not able to be mixed with high-temperature H<sub>2</sub> due to gas stratification.

# Effect of extending fuelling time

Analytical  
model



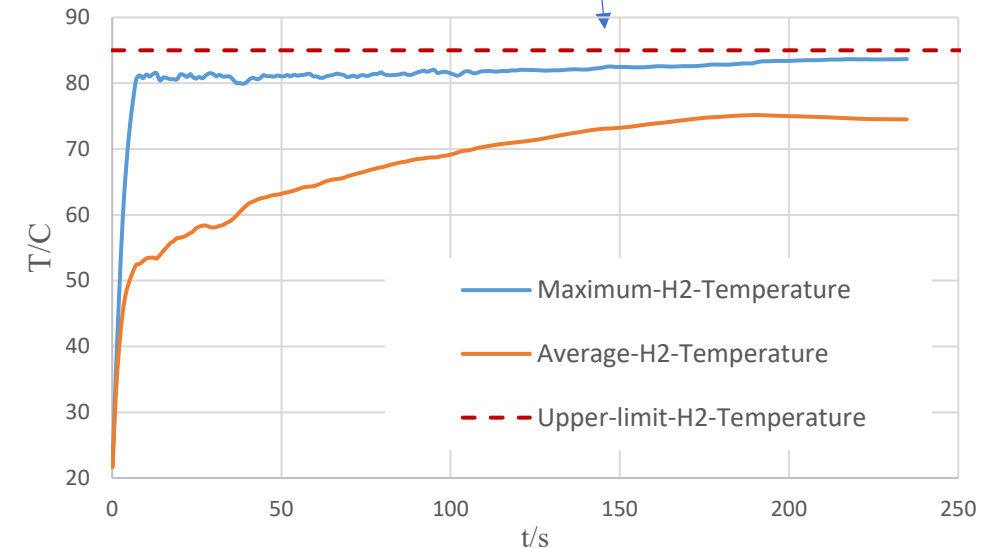
CFD model vs UU  
analytical (black  
dashed)

The hydrogen temperature will not exceed 85°C, if fuelling time is extended from the 180s to 300s **without pre-cooling**.

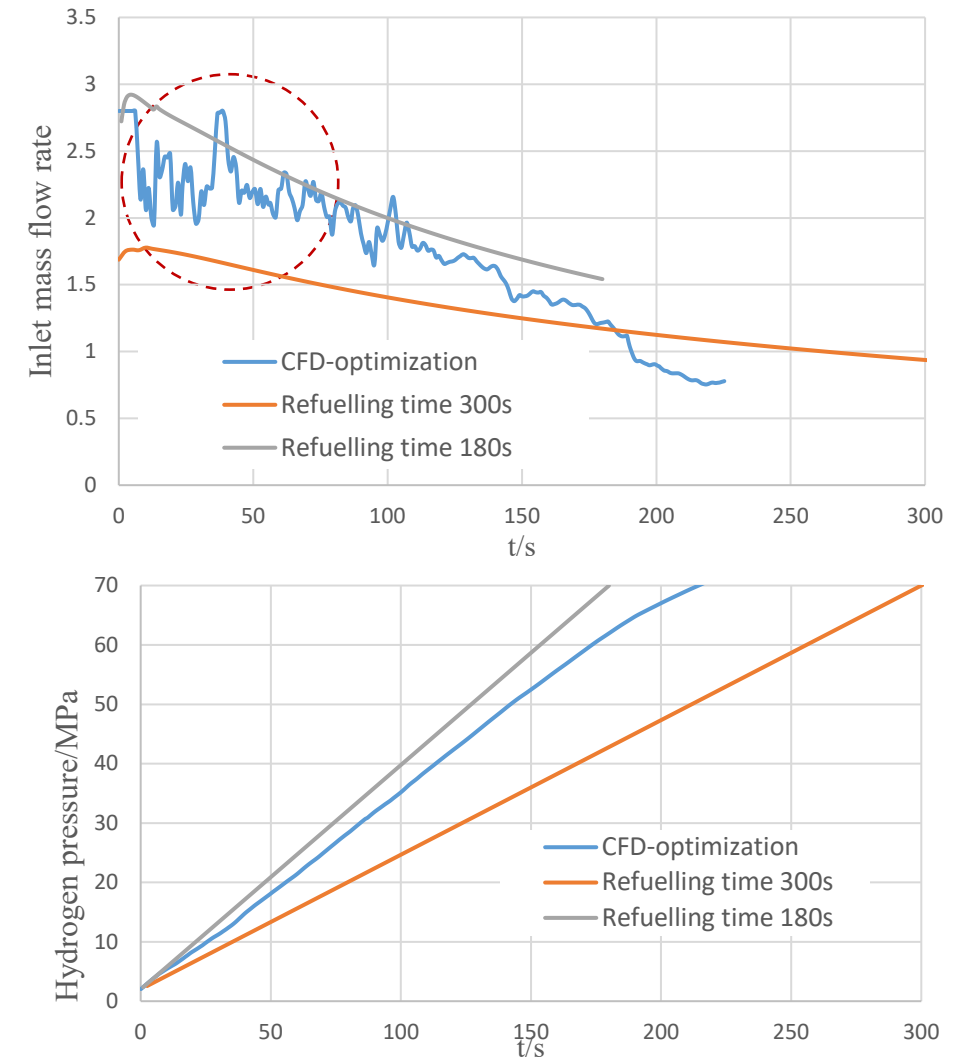


- Fuelling within 300 s, too long?
- Can we do it faster? without precooling?
- CFD allows us to monitor and modify all the parameters during the real-time fuelling process and as a result to be used for the development of the fuelling protocol.
- A method is developed to automatically control the maximum temperature during the fuelling process in CFD formulation which allows to use it for the development of the fuelling protocol.

## Perfect control of maximum temperature



- A non-linear pressure ramp is produced during CFD simulations to prevent the maximum temperature from exceeding 85°C.
- Using a non-linear pressure ramp and starting with fuelling from 2MPa without precooling can be completed in about 210s, not in 300s in case of linear pressure ramp.



- The efficient CFD model was built at Ulster to simulate the fuelling process. The model has been further validated by successfully repeating the experimental results from two references.
- The phenomenon of temperature nonuniformity (28°C) is investigated, discovering the tendency of overheating at the beginning of the fuelling process.
- The effects of initial pressure, precooling and fuelling time are investigated with combined CFD and analytical models.
- Current investigations on non-linear pressure ramp shows a promising way to optimize the fuelling process without exceeding the upper limit temperature of 85°C.

# Thank you

Questions, please



This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.



Storage of Hydrogen  
Alternative Pressure Enclosure Development

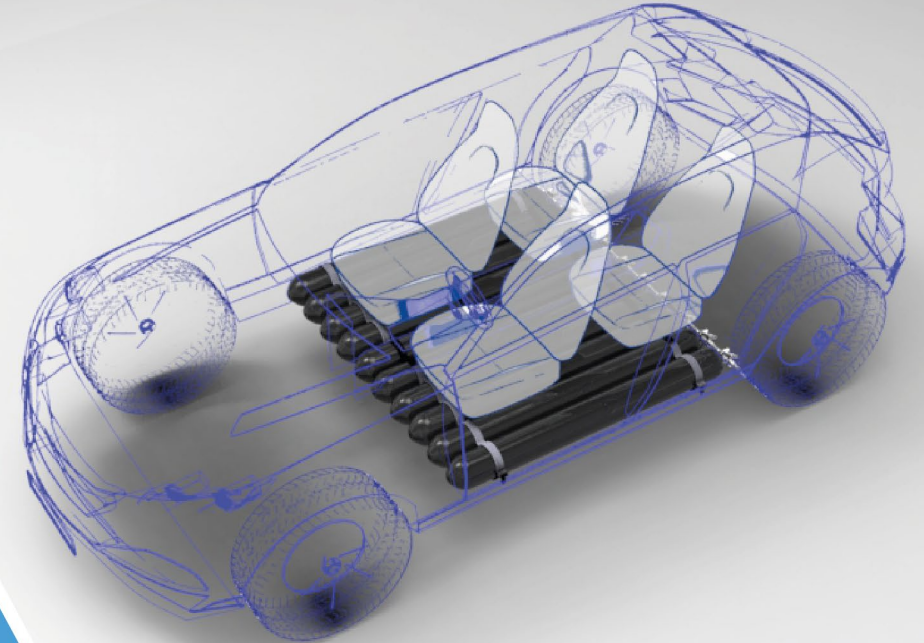


# TPRD performance during fuelling failure

Stakeholder's workshop of SH2APED project

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[www.sh2aped.eu](http://www.sh2aped.eu)

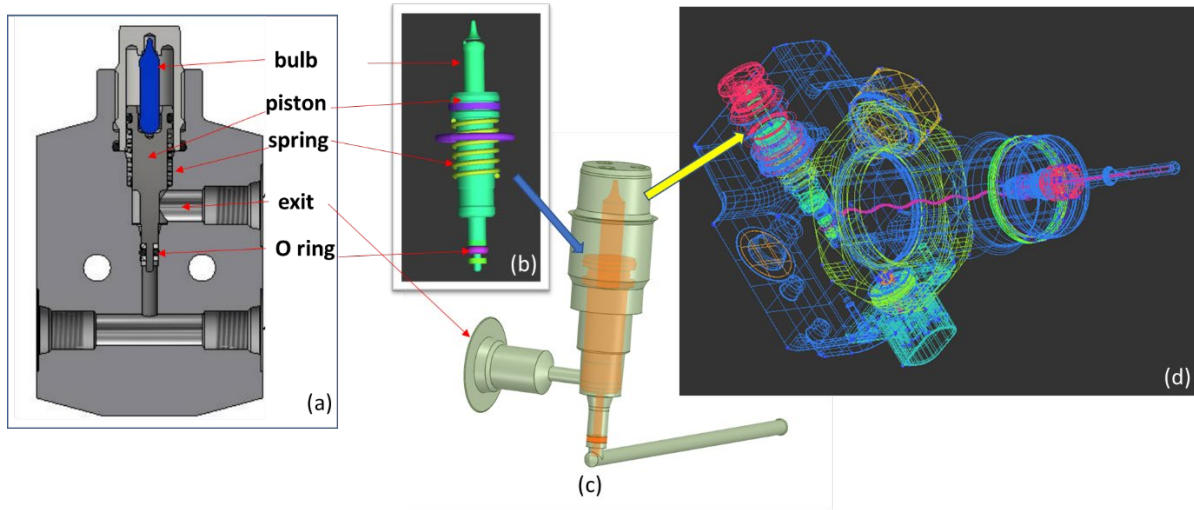


- Background
- Problem formulation
- Numerical method
- Simulation results and discussions
- Conclusions

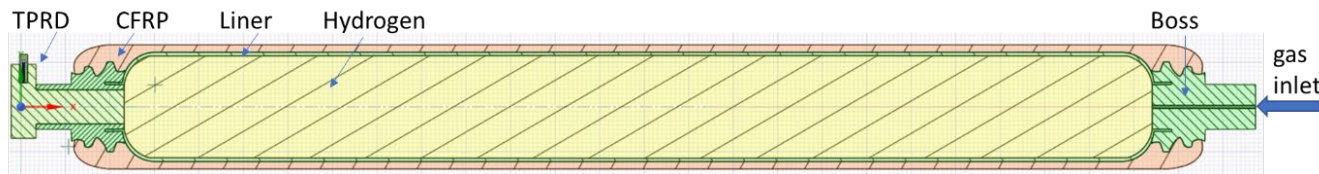
During a fast-fuelling process, high temperatures and temperature non-uniformity can be reached by the fast compression of gas. One glass-bulb type TPRD can be activated at **110 °C** or a slightly lower temperature [26]. A standard tank with a PA liner can allow temperature rise to the melting point of around 220 °C [27] before the gas leak happens. So, the TPRD could be activated before the PA liner melts.

The SAE J2601 suggests that hydrogen temperature in the tank should be limited between -40 °C and 85 °C [28]. However, the calculation based on adiabatic compression of hydrogen from 2 MPa to 70 MPa shows that the gas temperature can reach **hundreds of degrees**. This study will investigate the possibility of TPRD activation during an extremely fast fuelling process. An extreme situation like the complete failure of the pressure control valve and the temperature monitor during the fuelling process will be considered. In an investigation of fire accidents at the AC transit hydrogen fuelling station in Emeryville, Harris et al. [29] reported that the nozzle subassembly portion of the pressure relief valve failed, causing an immediate release of approximately **30 kg of hydrogen in the first minute**. In that case, the fuelling from 2 MPa to 70 MPa can be finished in a few seconds instead of 180 seconds.

# Problem formulation



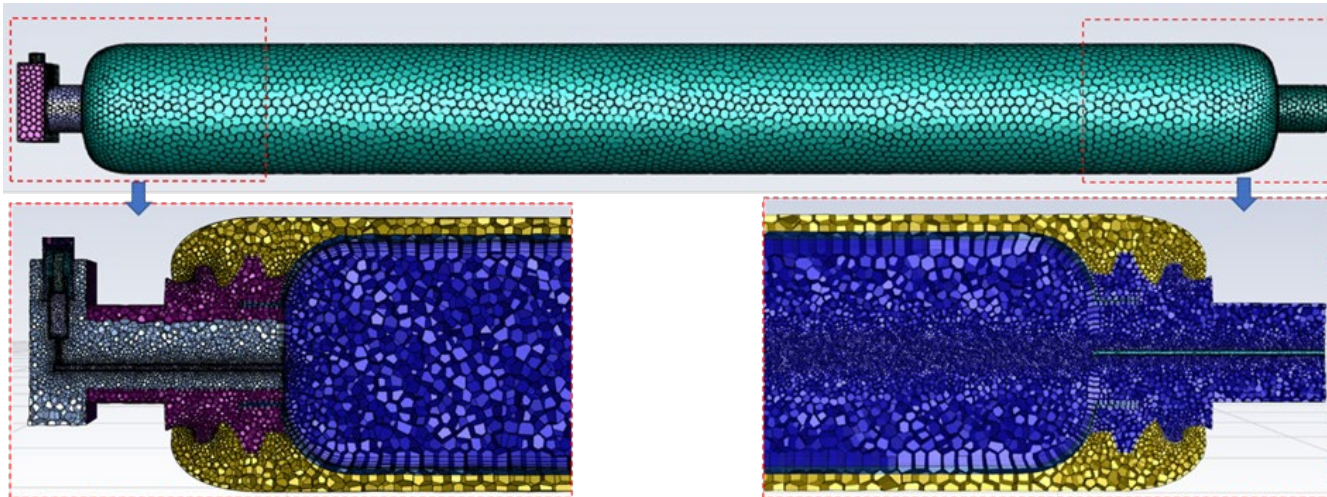
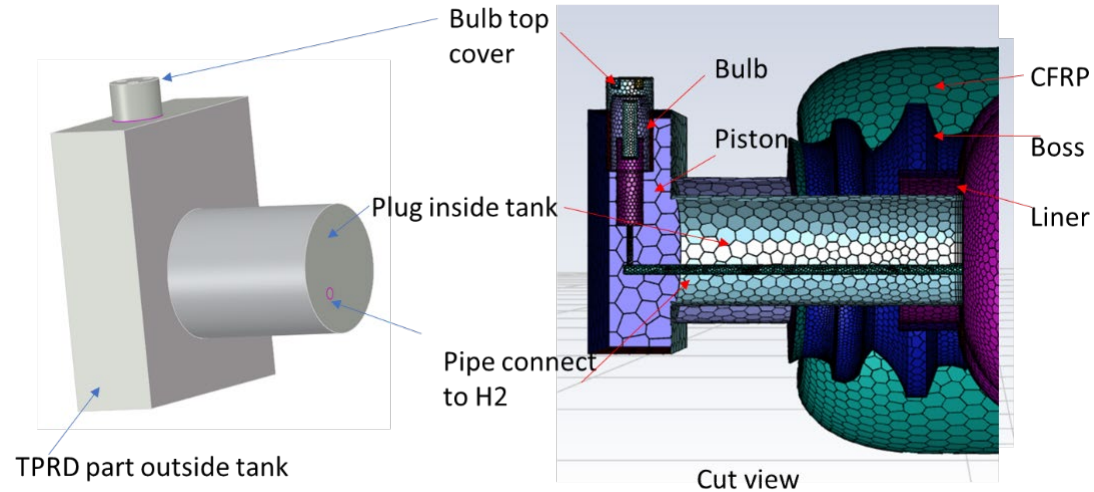
Structure of a TPRD: a) cut view of a similar TPRD from the reference [30]; b), c), d) show the structure of the piston, hydrogen release channel, and the complete structure of SH2APED TPRD.



For a glass bulb TPRD, the hollow glass will break when the temperature reaches around **110 °C**, which opens the O-ring seal and vents the gas through the exit.

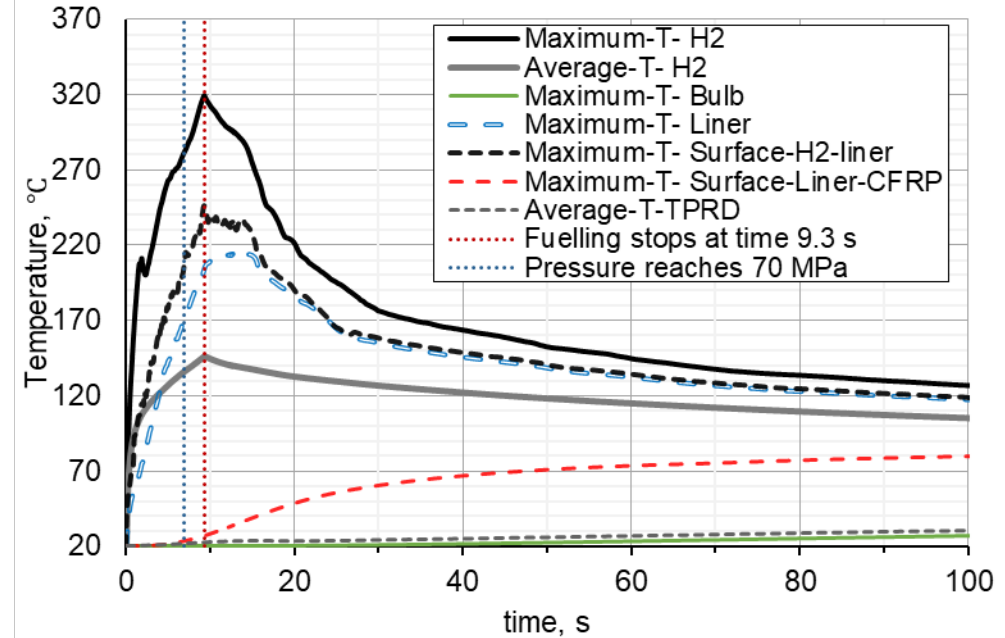
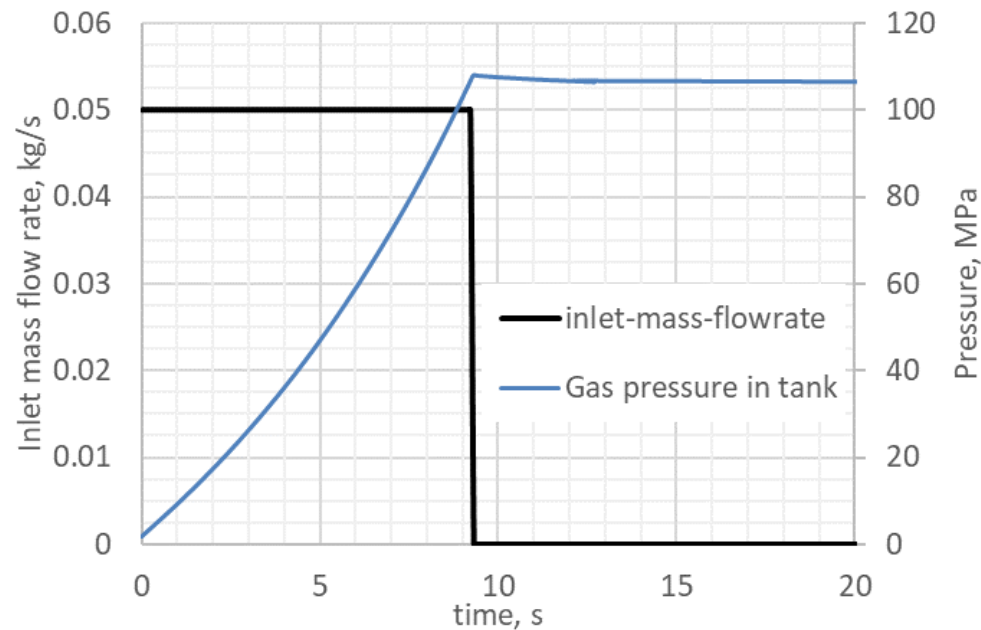
The previous simulations show that the gas temperature increases with increasing inlet mass flow rate. To investigate the possibility of TPRD activation during fast fuelling, we first assume an extreme situation of fuelling with **450g/s**, which is close to the accident at the AC transit hydrogen fuelling station in Emeryville. Numerical simulations will be carried out to analyse this process. Special attention will be given to the heat transfer process of the glass bulb and its temperature rise.

# Numerical mesh



A polyhedron mesh is built with 476 K cells and 2142 K nodes. Five boundary-layer meshes are added near the fluid/solid interface to accurately calculate the heat flux. The Scale adaptive simulation (SAS) model is chosen to include the turbulence effect.

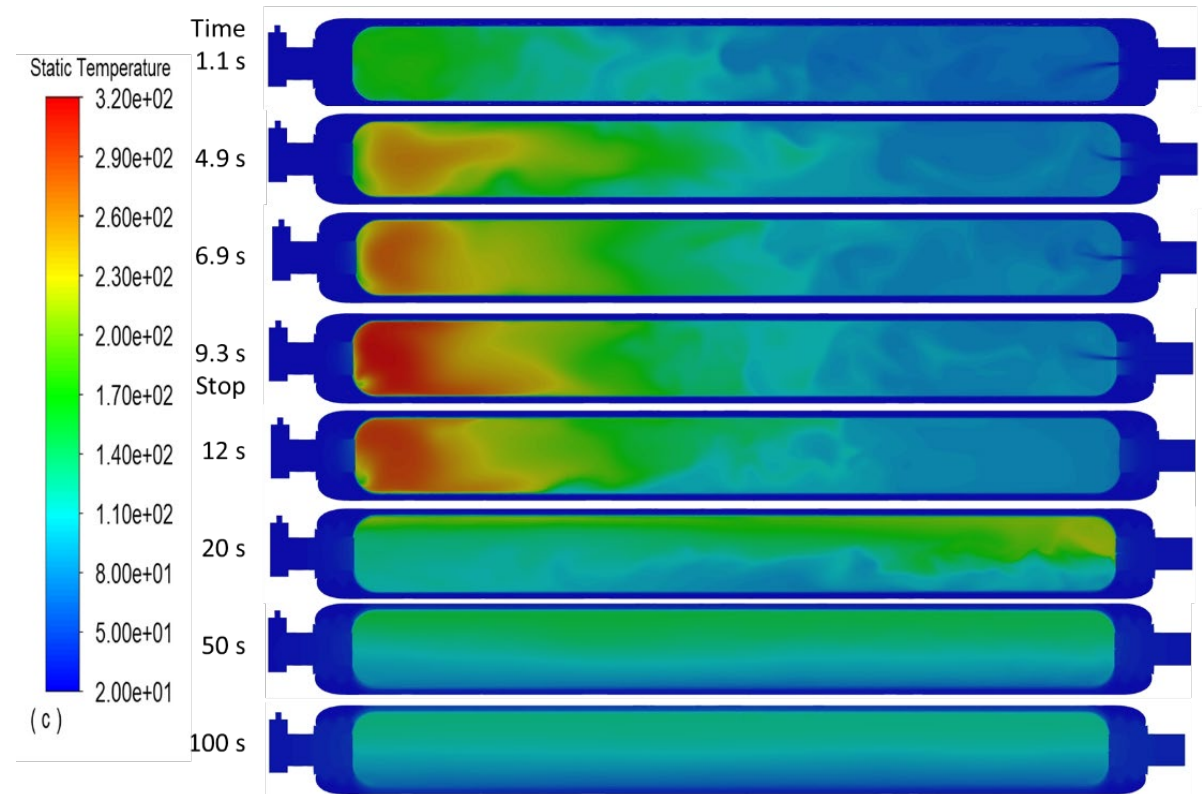
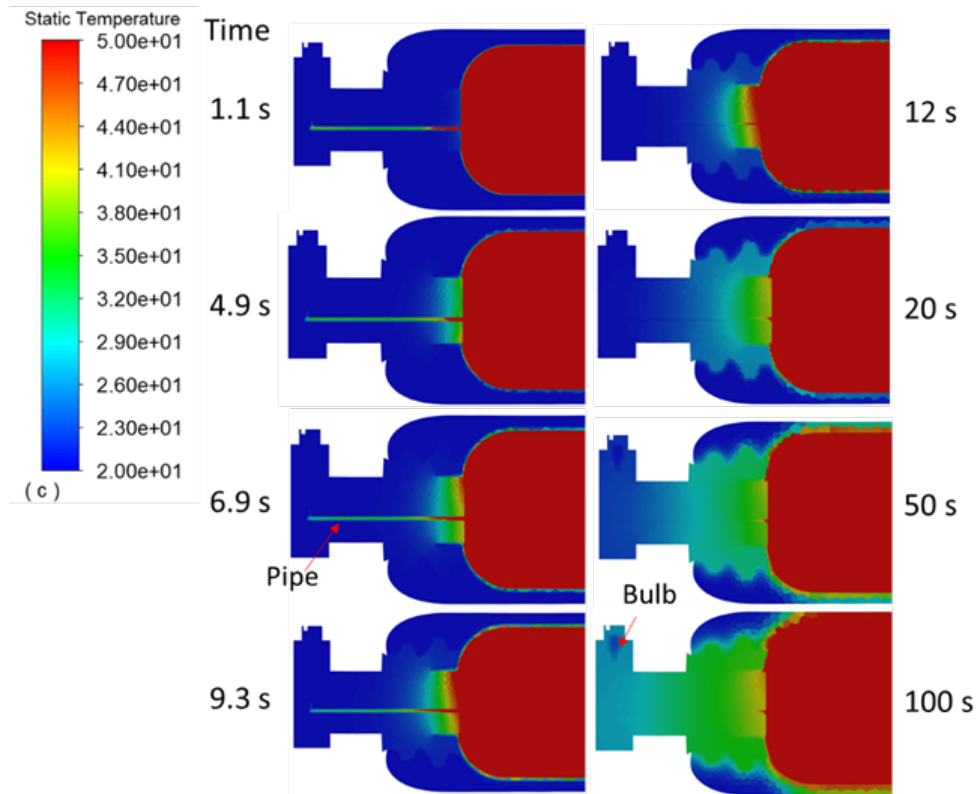
# Simulation results and discussions



The maximum hydrogen temperature reaches over 300 °C within 10 seconds while the pressure reaches over 100 MPa. However, the results show that the temperature rise in the bulb is a slow process (0.08 °C/s). This is because the heat transfer to the bulb needs to pass through the metal plug connected to the hydrogen.



# Simulation results and discussions



The simulation results prove that the bulb's temperature is always lower than the average temperature of the whole TPRD, which makes it unlikely to reach above 100 °C in a fast-fuelling process.

- This study investigates the possibility of TPRD activation during a failing fast-fuelling process (450g/s for 9 conformable SH2APED tanks).
- The results show that the TPRD will not be activated in such a failing fast-fuelling process.
- However, the maximum hydrogen temperature reaches over 300 °C while the liner's temperature may reach above 200 °C in such an accident condition.

# Thank you

Questions, please



This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.

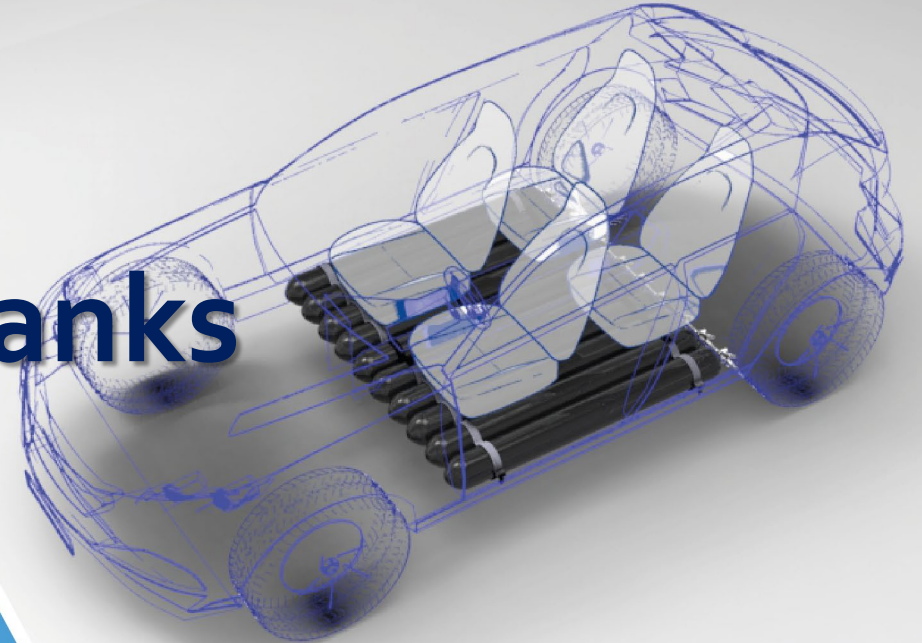


Storage of Hydrogen  
Alternative Pressure Enclosure Development



# Defuelling of conformable tanks

V Shentsov



Stakeholder's workshop 26-27 September 2024

[www.sh2aped.eu](http://www.sh2aped.eu)

## ■ Objectives:

- Maintain the temperature inside the hydrogen storage tank above -40°C during the defueling process at a maximum rate of 2 g/s.
- Check how sensitive the system is to changes in storage and ambient temperatures.
- Identify storage and ambient temperatures to maintain safe operating conditions

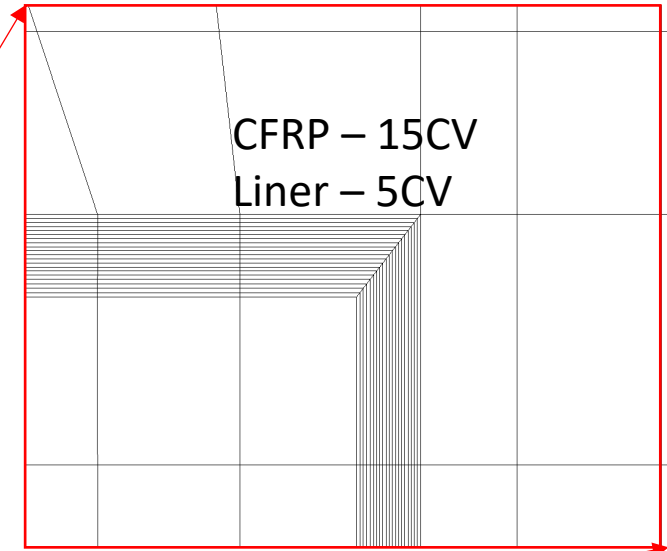
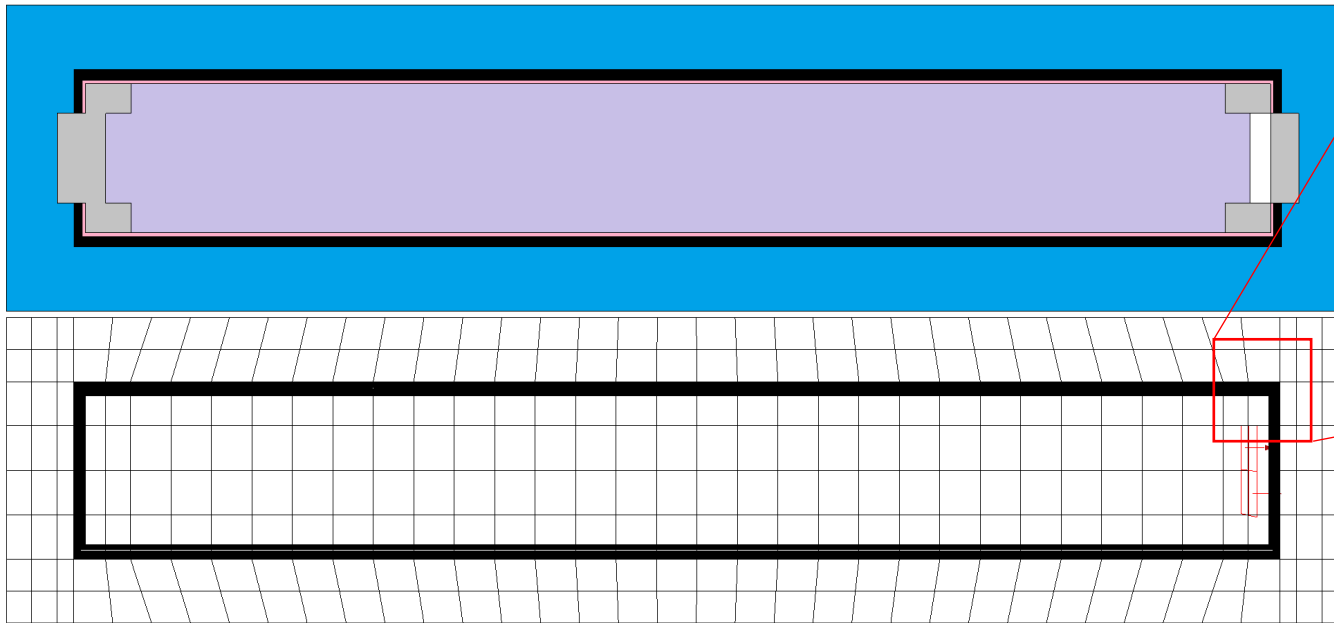
## ■ Initial and boundary conditions:

- Initial storage temperature and pressure 700 bar, -20°C, -40°C
- Ambient temperature
- Defueling rate (2 g/s)
- Material properties of CFRP and liner (HDPE) i.e. specific heat and thermal conductivity

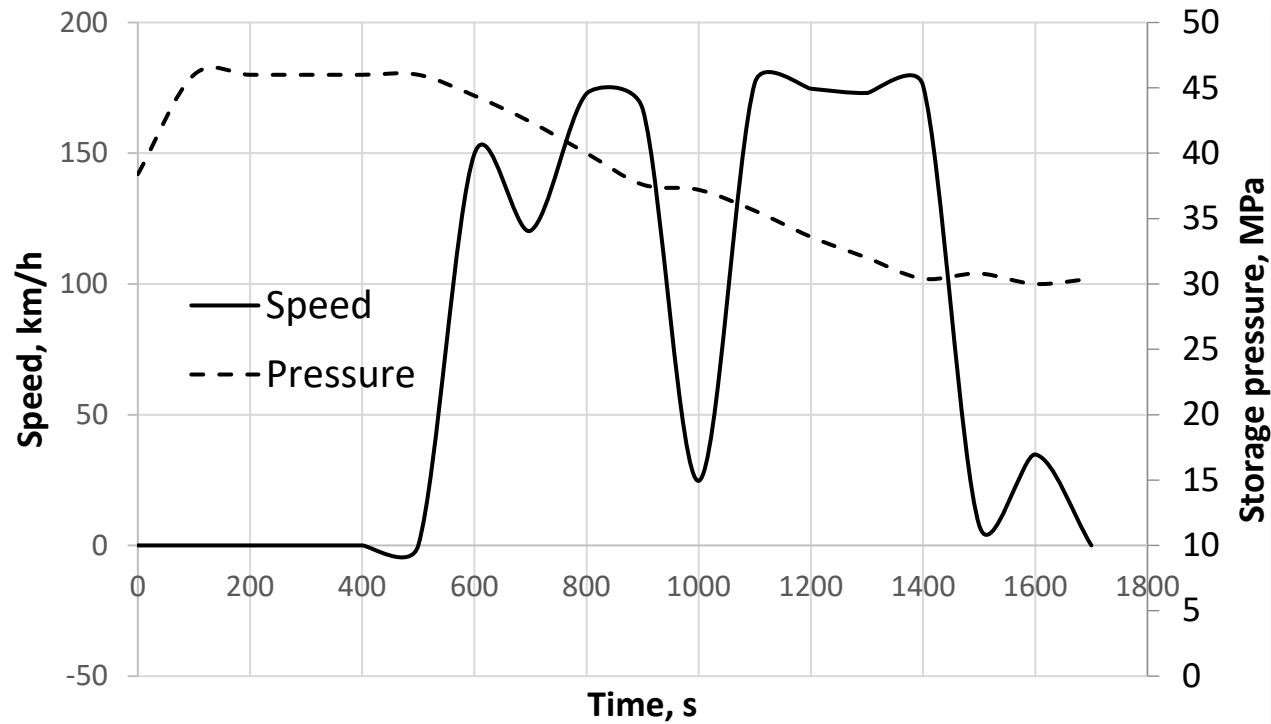


# Numerical geometry and grid

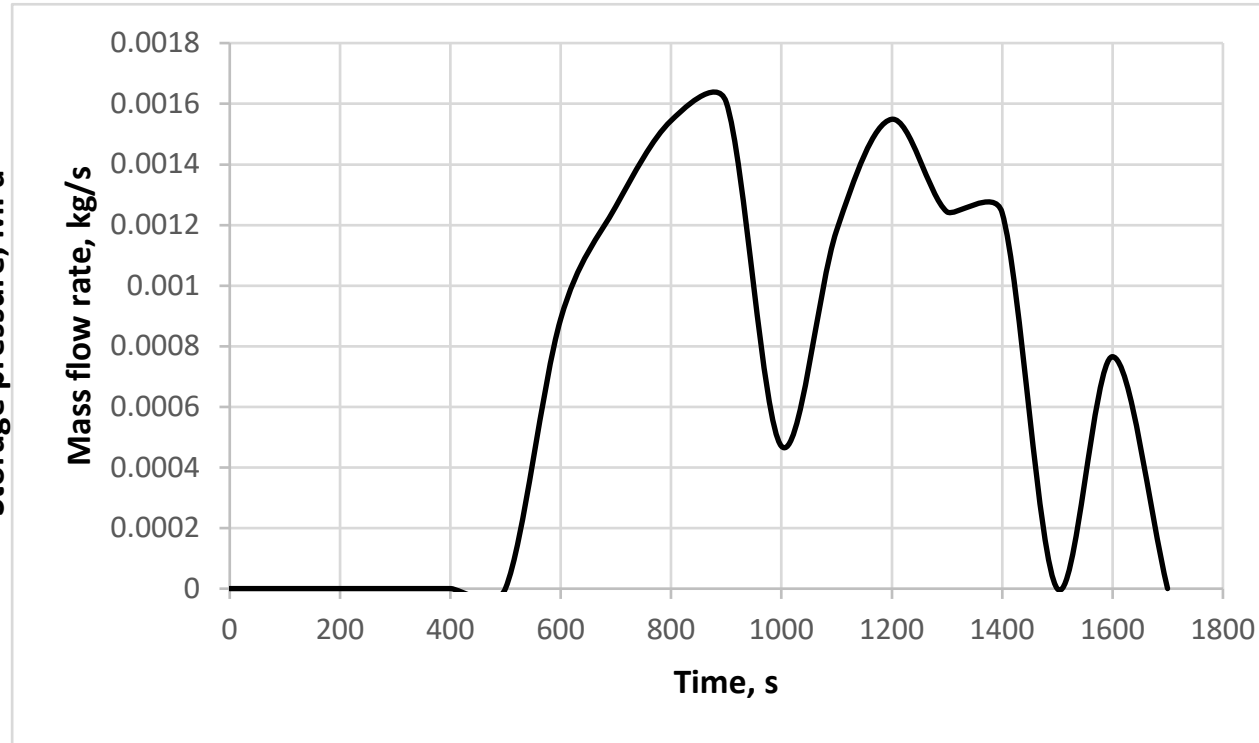
- Hexahedral structural coarse grid 12924 CVs
- Tank volume 11.7L
- Initial pressure 700bar



# Justification for 2 g/s defueling rate

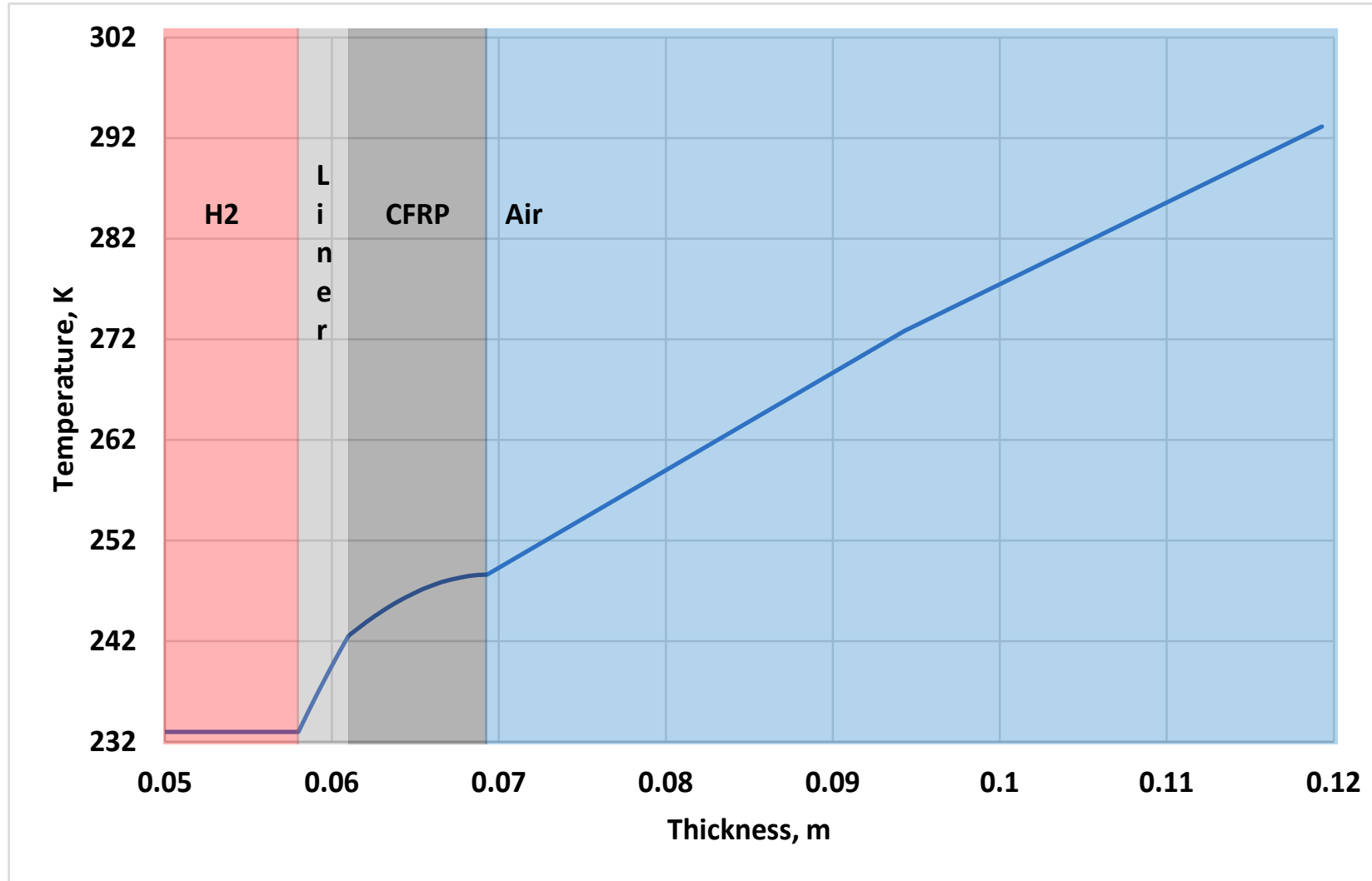


Speed and tank storage pressure of the HFCV



Mass flow rate dynamics

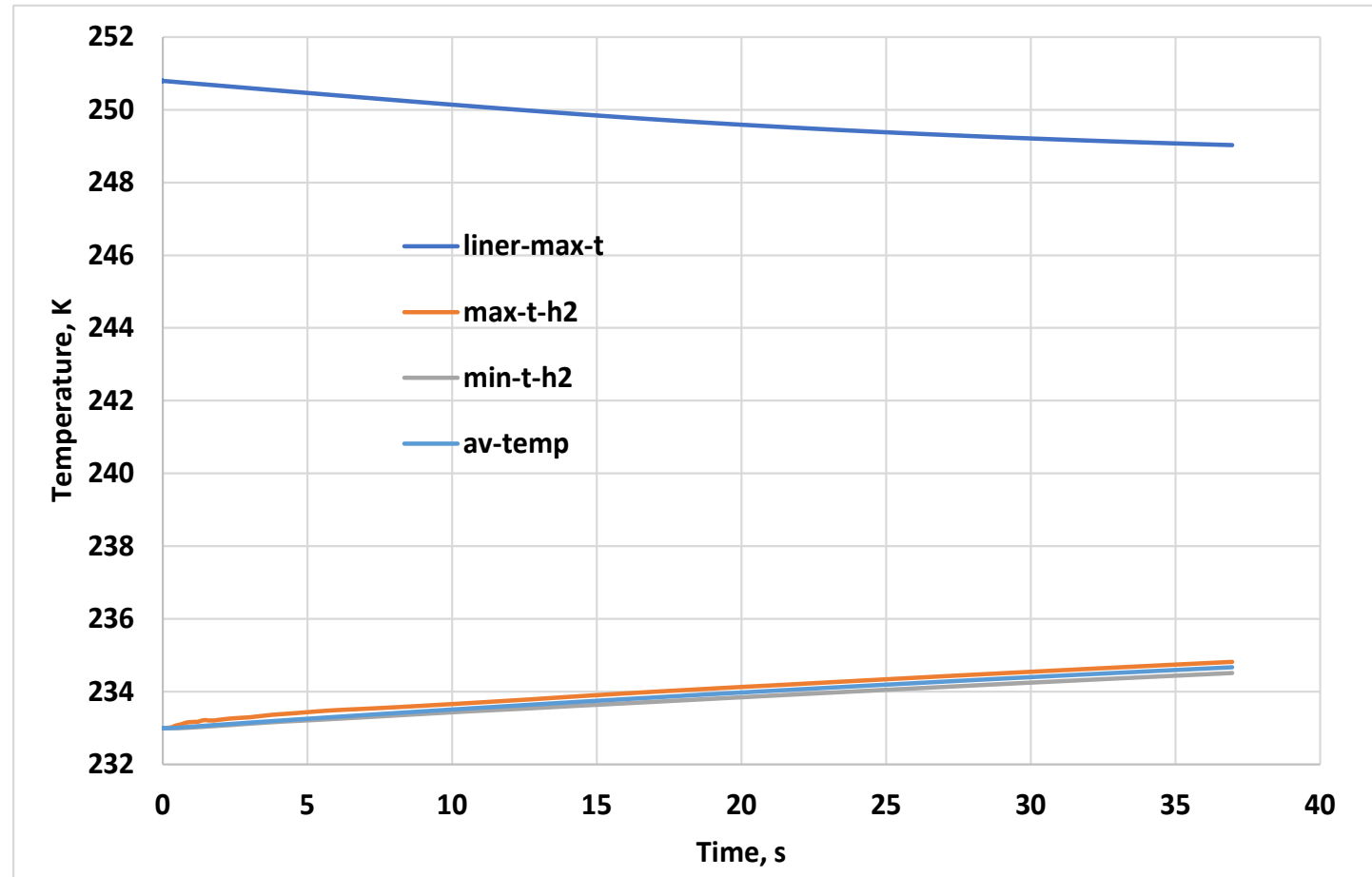
# Steady state distribution -40°C initial, 20°C amb



Initial condition of tank before defueling

# 1. Defueling: 2 g/s, -40°C initial, 20°C amb

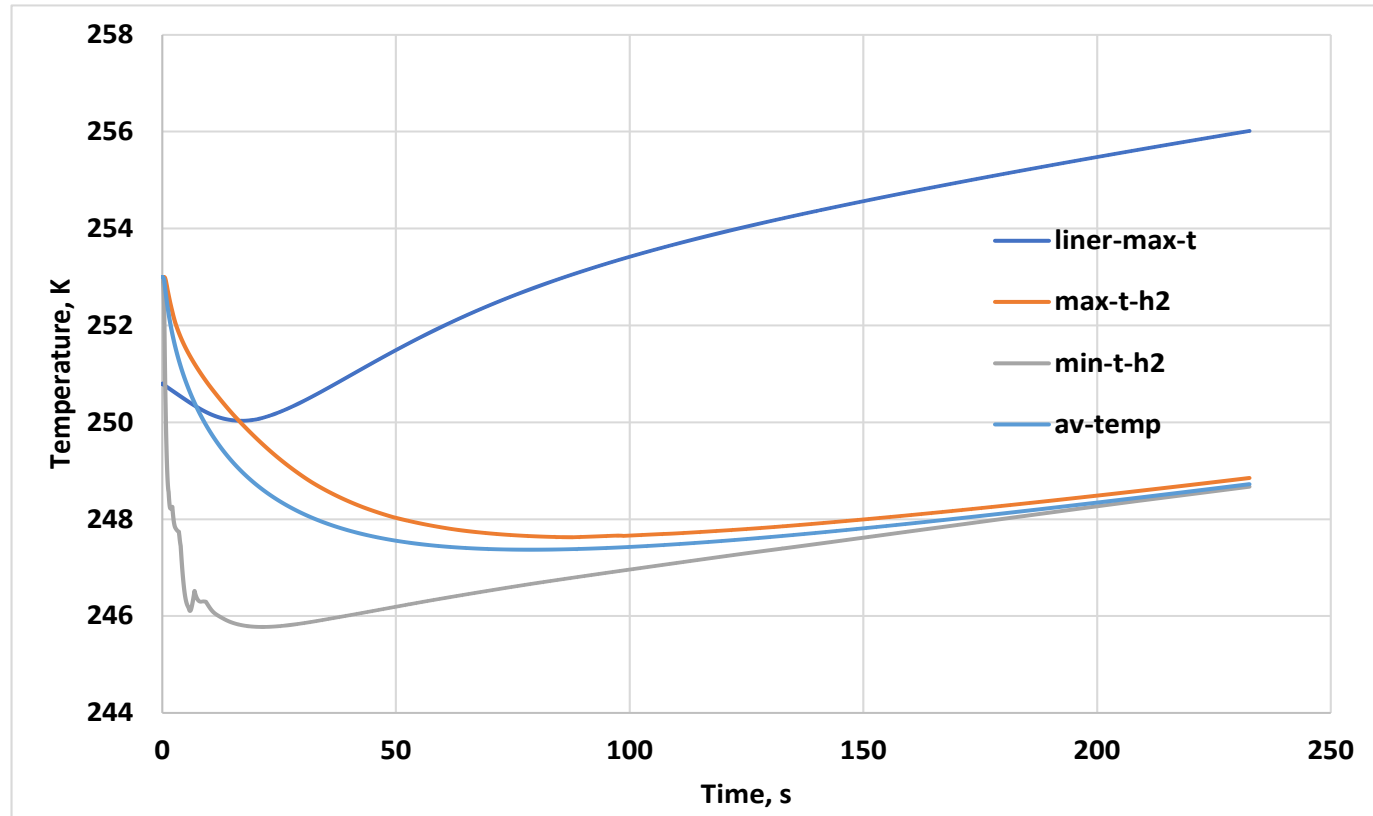
Defueling at initial temperature of -40°C shows increase of temperature!



Transient temperature inside the tank -40°C of hydrogen and 20°C ambient

## 2. Defueling: 2 g/s, -20°C initial, 20°C amb

Defueling at initial temperature of -20°C shows increase of temperature!



Transient defueling, temperature inside the tank, -20°C initial, 20°C ambient



# Concluding remarks

- Defueling process results in temperature increase over time, even with an initial tank temperature as low as -40°C (233K).
- No temperature drop below the initial -40°C is observed during defueling, suggesting effective thermal management.
- In the case of an initial temperature of -20°C, the temperature briefly decreases before recovering and rising.
- Heat transfer from the environment and exothermic nature of the process during defueling raise the hydrogen gas temperature inside the tank.
- Findings are significant for design and safety considerations in compressed hydrogen storage systems.

# Thank you

PgCPD and PgCERT in Hydrogen Safety:

<https://www.ulster.ac.uk/research/topic/built-environment/hydrogen-safety-engineering/study>



This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.

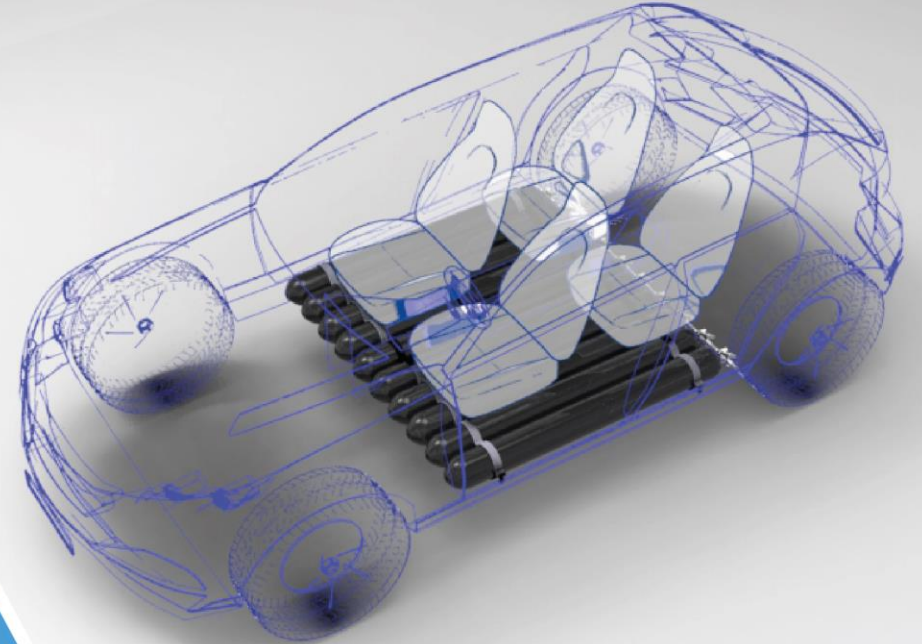


# Overview of experimental testing at BAM: Hydraulic pressure, drop and fire tests

Stakeholders' Meeting – September 26-27, 2024

BAM 3.5: Safety of Gas Storage Systems

N. Lengas, G. Mair, K. Müller, C. Sklorz, B. Wang, R. Natasya



[www.sh2aped.eu](http://www.sh2aped.eu)

# Sites & branches



Fabeckstraße  
branch



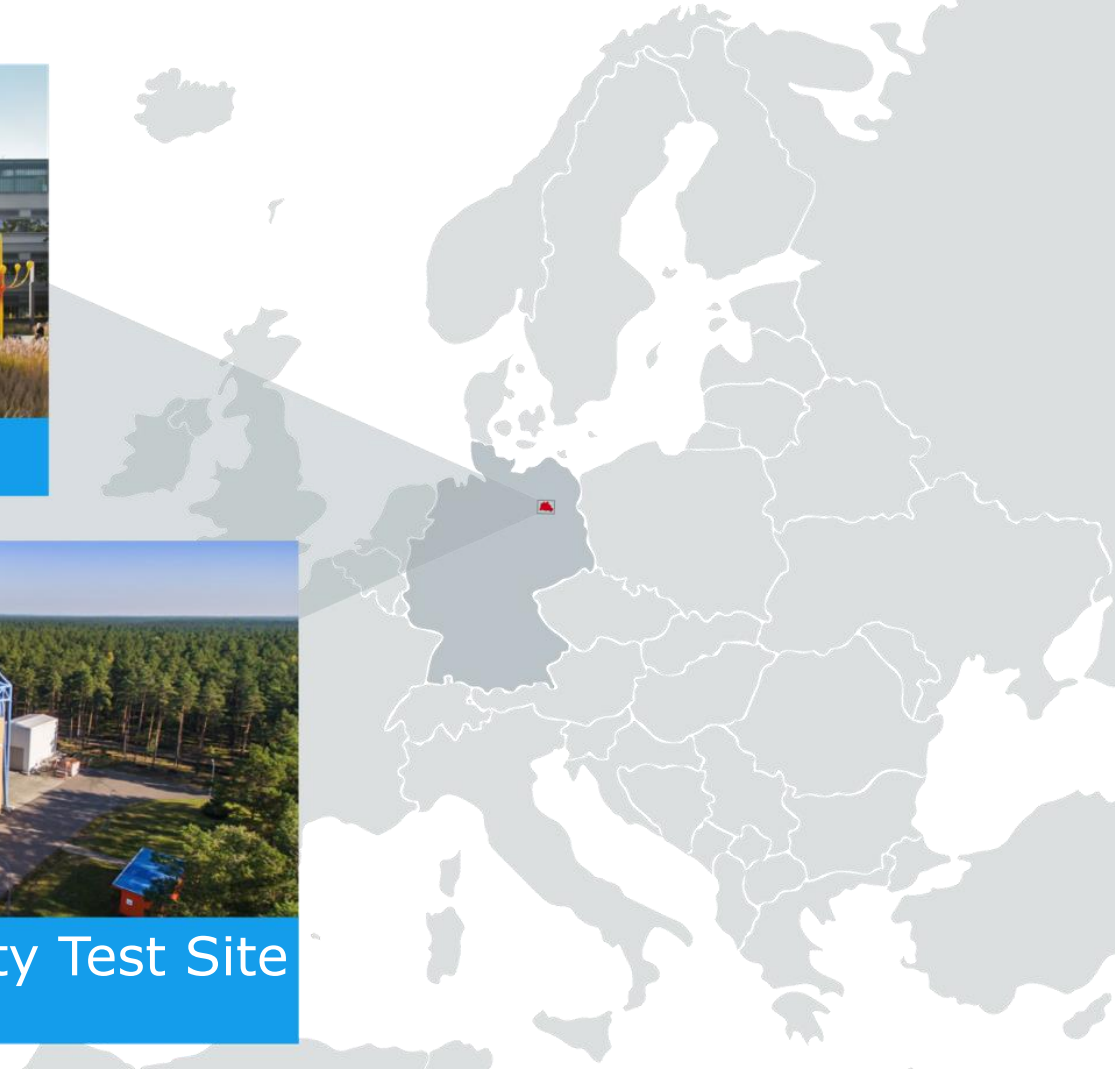
Adlershof branch



Lichterfelde headquarters



Technical Safety Test Site  
Horstwalde





# Testing of Internal Pressure Strength of CPVs

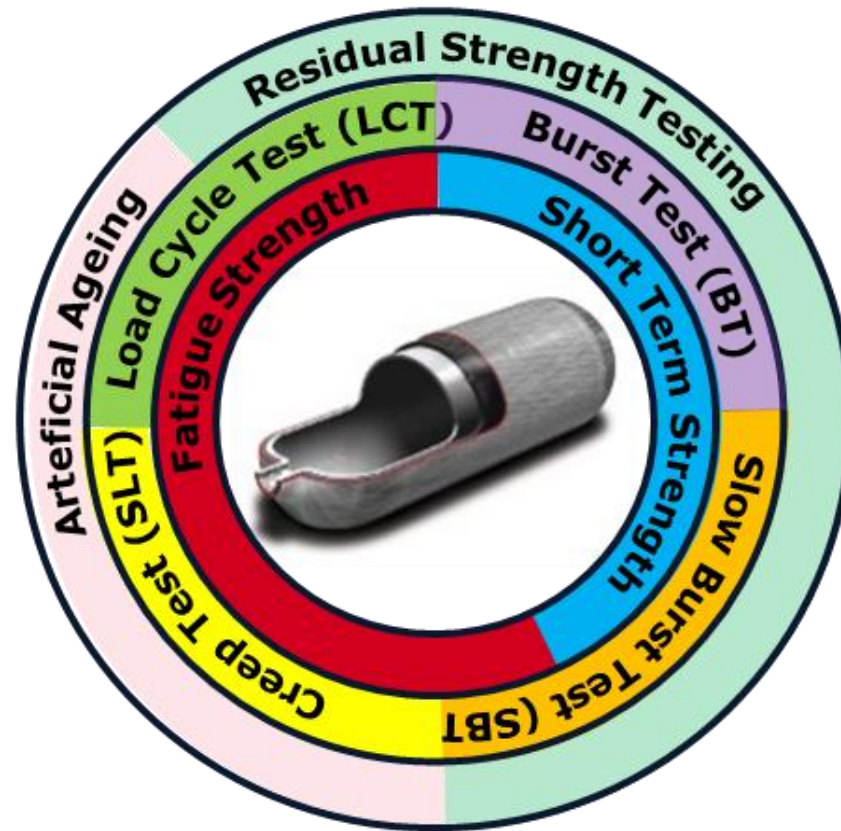
BAM runs 4 different stationary facilities for the wide range of test procedures for testing internal pressure strength of composite pressure vessels.

## Ambient Cycling Tests (ACT)

Load cycle facility



Sustained load facility



Rapid burst facility



Slow Burst Tests (SBT)



Slow burst facility



# ACT - Hydraulic cycling facility



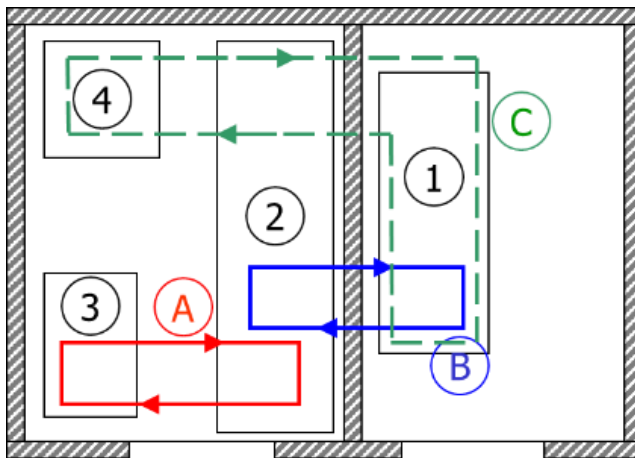
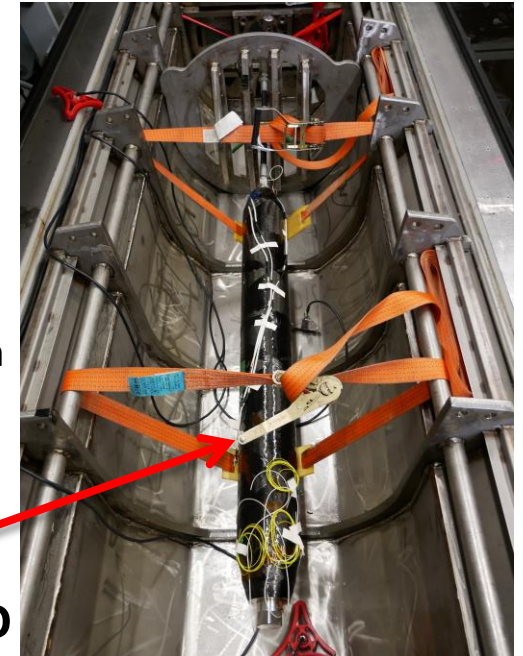
## Technical Data:

Cycling pressure (max.): 0.2 ... 60/ 120 MPa  
Cycling velocity: ≤30 cycles per min.  
Effective hydraulic power: > 30,000 bar l/min  
Temperature of chamber: -60 °C ... +95 °C  
Dimension of specimen (max): L 2,400 mm; D 500 mm

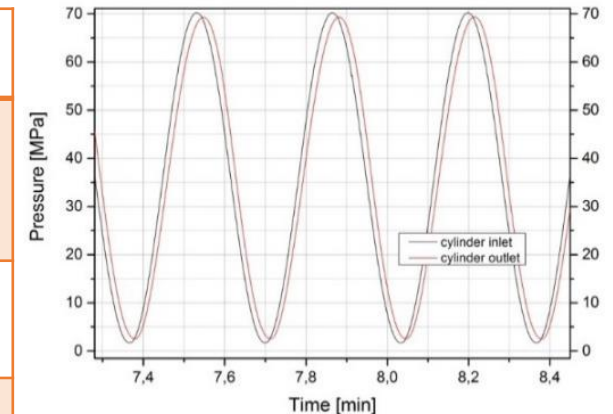
## ACT according to GTR13:

$f_{\max}$  1 ... 10 cycles /min  
 $p_{\text{Target}}$  1.25 NWP  
No. LC 22.000 or until leak occurs  
T  $20 \pm 15$  °C

**CPV**  
**SH2APED**



|   |                      |   |                                                         |
|---|----------------------|---|---------------------------------------------------------|
| 1 | Testing chamber      | A | Primary oil circuit (350 bar)                           |
| 2 | Pressure intensifier | B | Secondary circuit of test medium (Water-Glycol-mixture) |
| 3 | Hydraulic power unit | C | Air circuit for temperature controlling                 |
| 4 | Climate control unit |   |                                                         |



## ➤ CPV standard design



| No. of vessels |        | Test parameters        |  | Test results                       |
|----------------|--------|------------------------|--|------------------------------------|
| 4              | Test 1 | 20 - 700 bar/22,000 LC |  | No failure after 22,000 LC         |
|                | Test 2 | 20 - 875 bar/22,000 LC |  | Failure on average after 15,000 LC |

### Conditions:

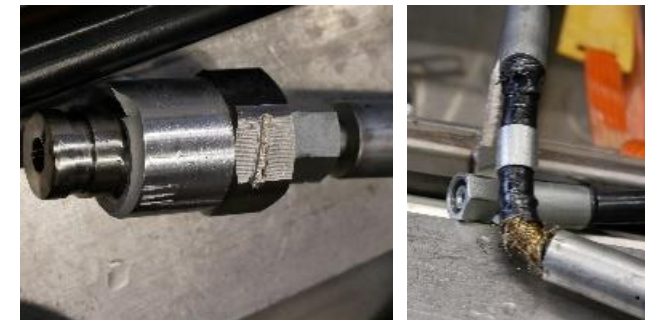
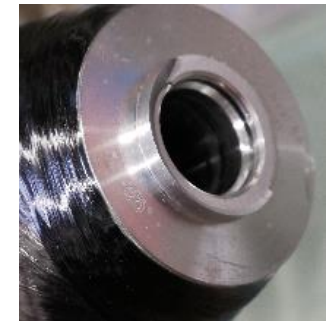
Cycle rate: 10 cycles/min

Environment at 20 °C

Hydraulic fluid (water-glycol mixture) at 20 °C

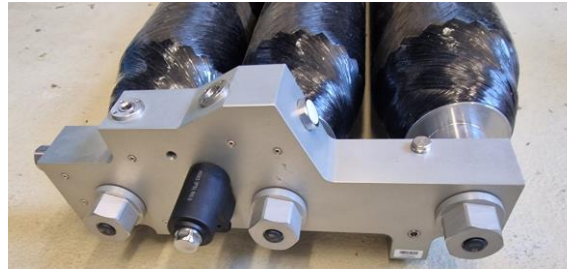
Sinusoidal LC

Typical failure patterns  
(adapter thread failure)





## ➤ CPV standard design – Module with manifold and 3 CPV



| Test parameters       | Test results           |
|-----------------------|------------------------|
| 20 - 875 bar/22000 LC | Failure after 12500 LC |

### Conditions:

Cycle rate: 10 cycles/min

Environment at 20 °C

Hydraulic fluid (water-glycol mixture) at 20 °C

Sinusoidal LC

adapter thread failure of middle CPV



## ➤ CPV standard design with Fiber Optic Sensors (FOS)



|          | Test parameters        | Test results               |
|----------|------------------------|----------------------------|
| CPV #003 | 20 - 700 bar/22,000 LC | No failure after 22,000 LC |
| CPV #032 | 20 - 875 bar/22,000 LC | Failure after 9,600 LC     |
| CPV #033 | 20 - 875 bar/22,000 LC | Failure after 7,870 LC     |

### Conditions:

Cycle rate: 3 cycles/min (CPV #003) and 10 cycles/min (rest)

Environment at 20 °C

Hydraulic fluid (water-glycol mixture) at 20 °C

Sinusoidal LC

Typical failure patterns (leakage at



## ➤ CPV MicroLeaks-No-Burst ( $\mu$ LNB) design



| No. of vessels | Test parameters       | Test results           |
|----------------|-----------------------|------------------------|
| 1              | 20 - 875 bar/22000 LC | Failure after 11000 LC |

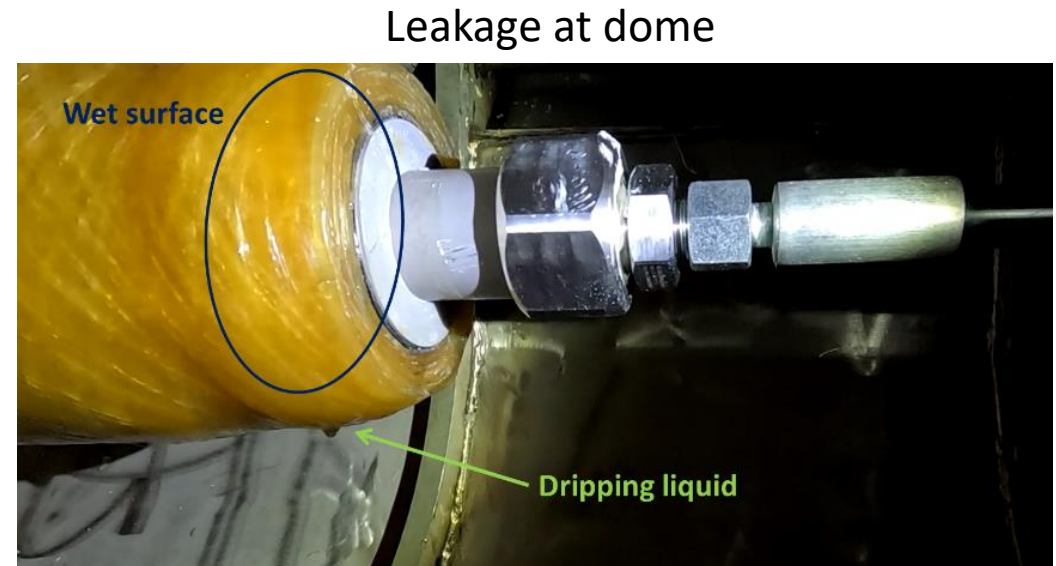
### Conditions:

Cycle rate: 10 cycles/min

Environment at 20 °C

Hydraulic fluid (water-glycol mixture) at 20 °C

Sinusoidal LC



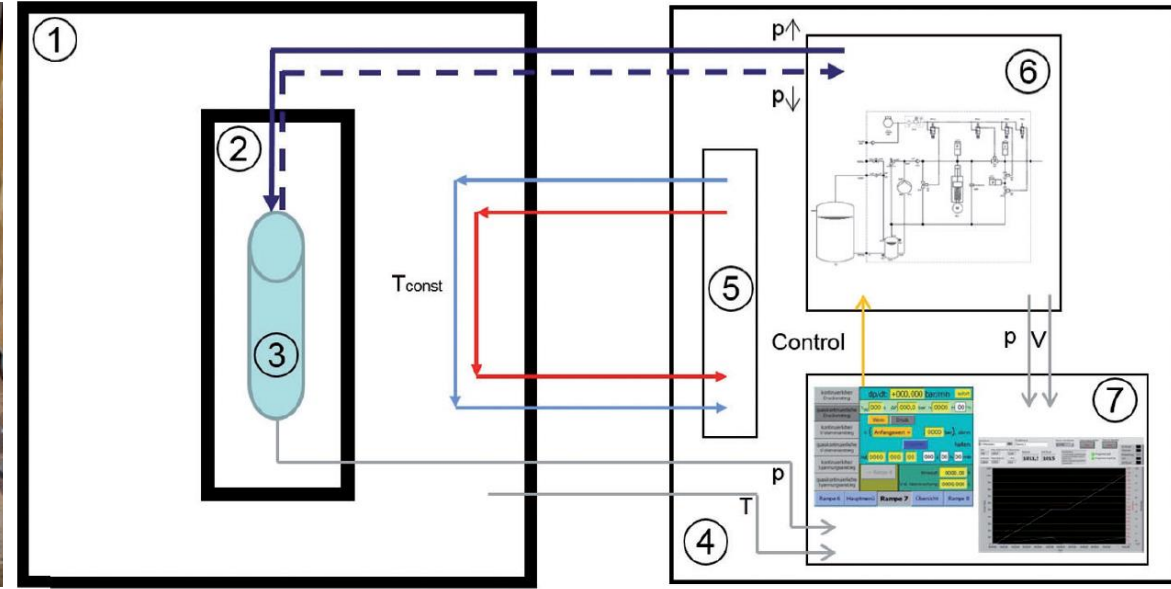


# SBT - Hydraulic slow burst test bench



**Equipment for hydraulic long-term burst tests**

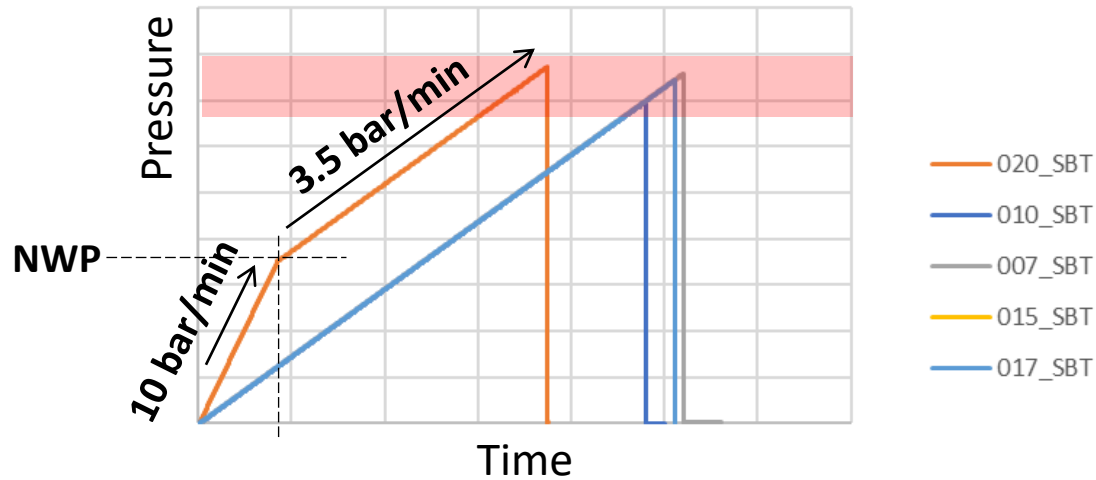
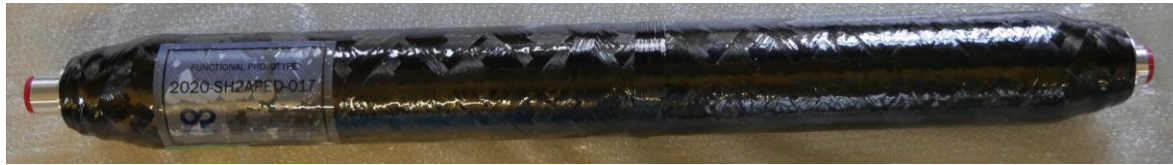
- (1) 20" container for burst test (left) and for technical equipment (right)
- (2) Inside view of the burst container with small protection chamber for composite test cylinder



**Schematic layout of burst test bench**

- (1) Testing container:
  - (2) Protective containment, (3) test specimen
- (4) Machine container with:
  - (5) climate control unit
  - (6) pressure generator, helicoidal pump)
  - (7) control and measuring station

## ➤ CPV standard design



### Conditions

NWP = 700 bar

Test pressure PH = 1.5 NWP (1050 bar)

Loading rate = 20 % PH

Pressure rate 3.5 bar/min

| No. of vessels | Avg. burst pressure $\bar{p}_i$ [bar] | NWP-Factor $\bar{p}_i/700$ bar [-] | MSP-Faktor $\bar{p}_i/875$ bar [-] |
|----------------|---------------------------------------|------------------------------------|------------------------------------|
| 5              | ~ 1500                                | 2.14                               | 1.71                               |



Typical  
damage  
patterns

## ➤ CPV standard design with Fiber Optic Sensors (FOS)



Conditions      Time

NWP = 700 bar

Test pressure PH = 1.5 NWP (1050 bar)

Loading rate = 20 % PH

Pressure rate 3.5 bar/min

| Vessel No. | Burst pressure<br>$p_i$ [bar] | NWP-Factor<br>$p_i/700$ bar [-] | MSP-Factor<br>$p_i/875$ bar [-] |
|------------|-------------------------------|---------------------------------|---------------------------------|
| # 003*     | 1560                          | 2.23                            | 1.78                            |
| # 031      | 1675                          | 2.39                            | 1.91                            |
| # 034      | 1696                          | 2.42                            | 1.94                            |

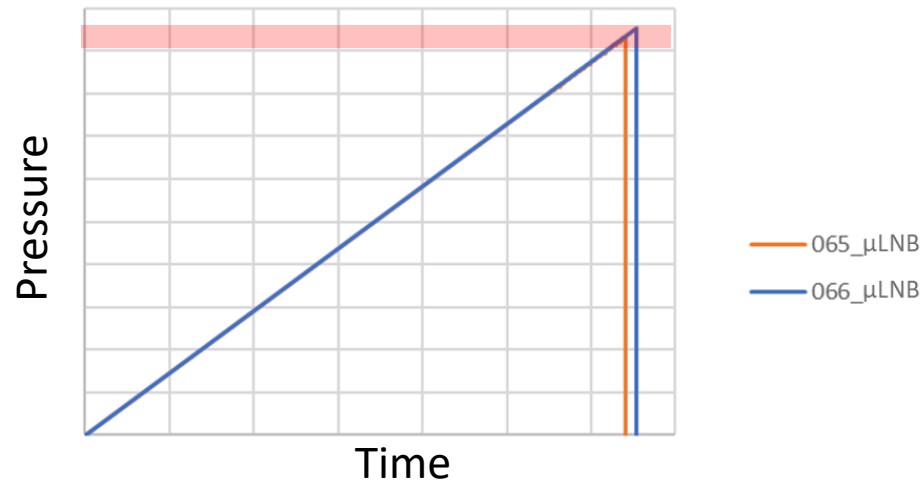
\*Pretested for 22000 LC with 3 load cycles per minute varying between 20 bar and 700 bar



Typical  
damage  
patterns



## ➤ CPV MicroLeaks-No-Burst ( $\mu$ LNB) design



### Conditions

NWP = 700 bar

Test pressure  $P_H$  = 1.5 NWP (1050 bar)

Loading rate = 20 %  $P_H$

Pressure rate 3.5 bar/min

| No. of vessels | Avg. burst pressure $\bar{p}_i$ [bar] | NWP-Factor $\bar{p}_i/700$ bar [-] | MSP-Faktor $\bar{p}_i/875$ bar [-] |
|----------------|---------------------------------------|------------------------------------|------------------------------------|
| 2              | ~ 1886                                | 2.69                               | 2.15                               |



Typical  
damage  
patterns

# Resistance against Accidental Loads of CPVs

BAM runs 4 different test arrangements for the simulation of accidental loads on composite pressure vessels filled with gas or water.

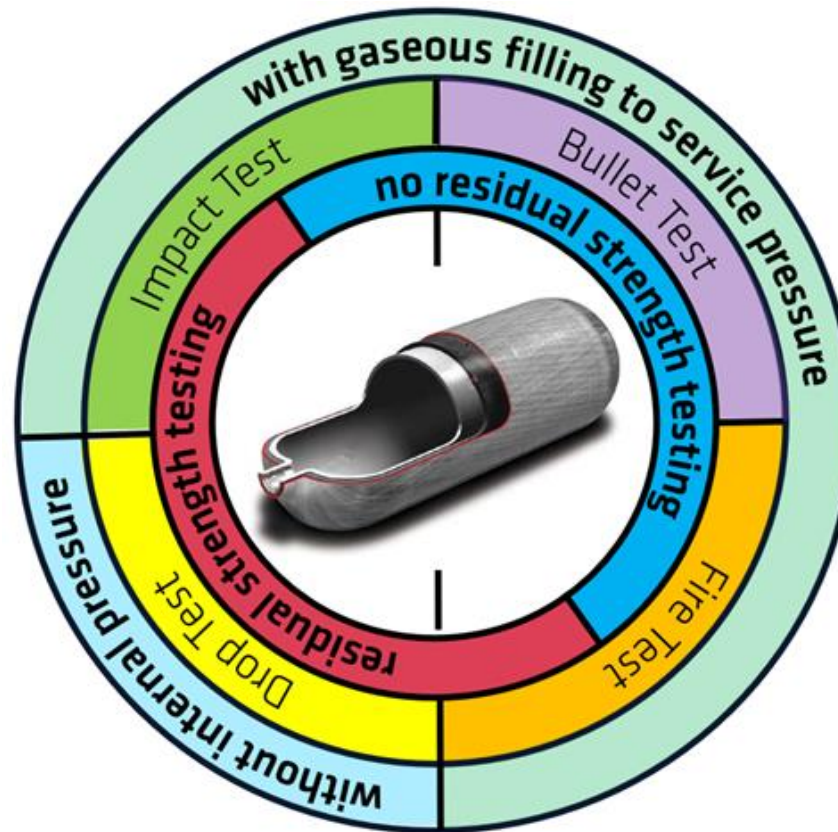
Impact test



Drop test



Drop test



Bullet test



Fire test



Fire test



# Drop/Impact testing - Overview



*Cylinder drop test*

## Drop Test bench

Drop height up to 12 m

Concrete foundation

6 m x 6 m x 3 m, m = 280 t  
with an impact pad (mild steel)

4 m x 2 m x 0.3m, m = 18.7 t



*Impact pad*

## Test procedure

Impact damage test: **EC 79/2009**; chapter 4.2.10.

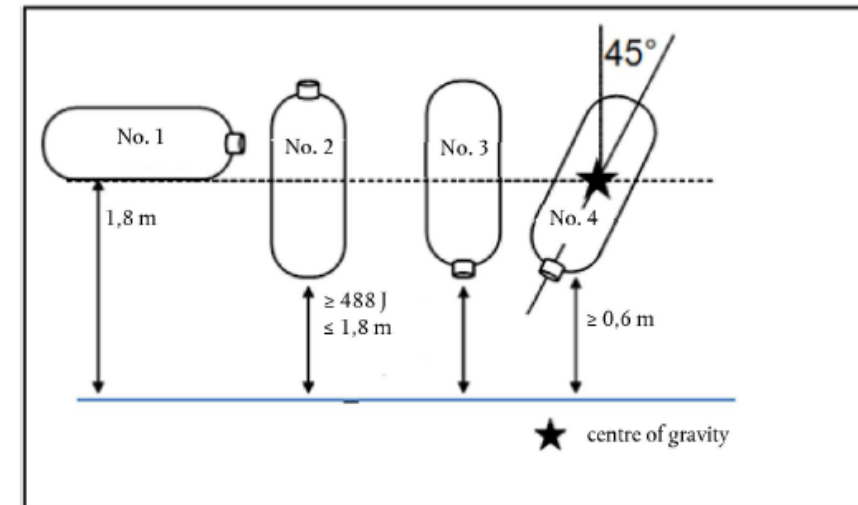
Drop (impact) test: **R 134**; chapter 5.2.2.

Requirements (EC79): 4 drop positions:

a) horizontal position 1.8 m above the ground

b) vertical position ( $E_{\text{pot}} \geq 488 \text{ J}$  ;  $h_{\text{bottom end}} \geq 1.8 \text{ m}$ )

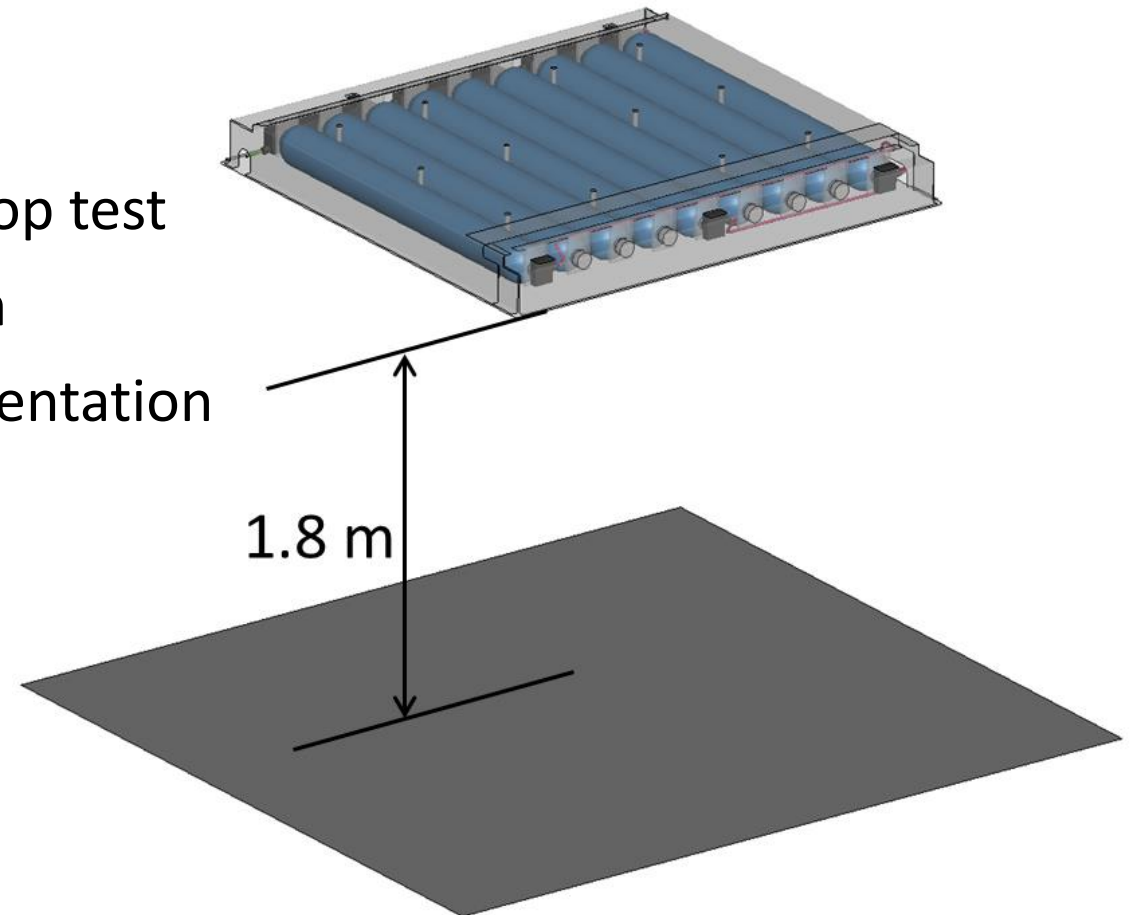
c) 45° angle position ( $h_{\text{min}} \geq 0.6 \text{ m}$ )



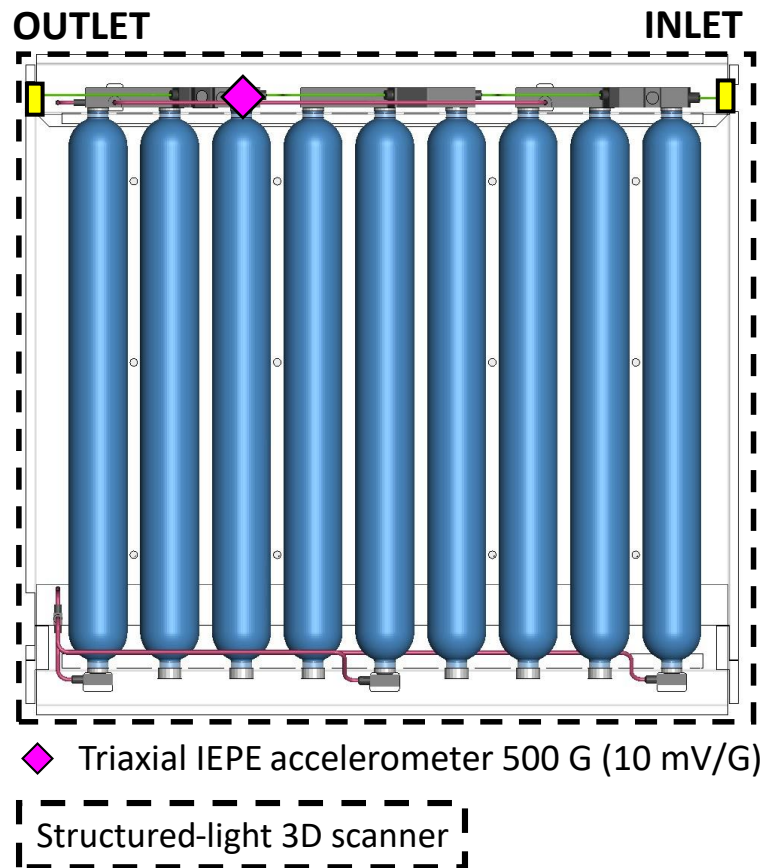
*Drop test positions*

## ➤ Testing overview of full-size demonstrator tank system

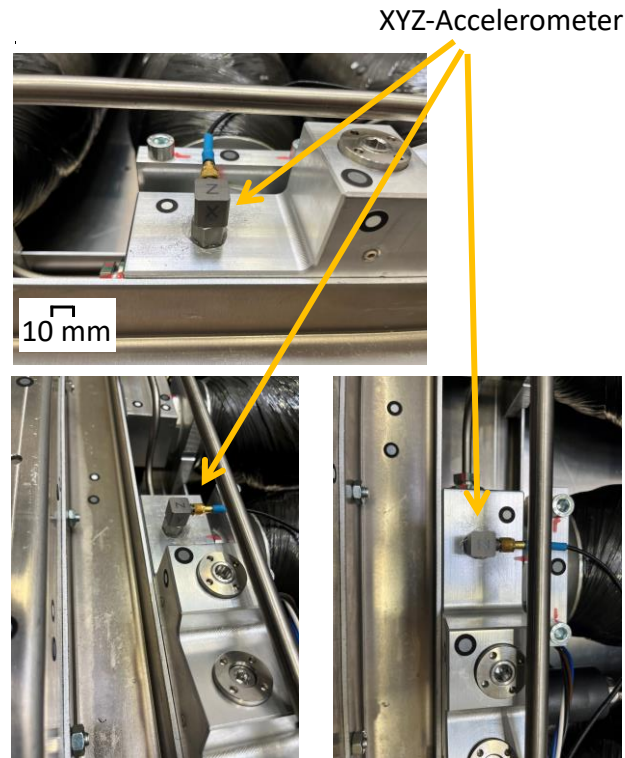
- Tightness test with 20 barG (He)
- 1<sup>st</sup> drop test: Horizontal drop
- Tightness test with 20 barG (He) after 1<sup>st</sup> drop test
- Most severe damage orientation calculation
- 2<sup>nd</sup> drop test in the most severe damage orientation



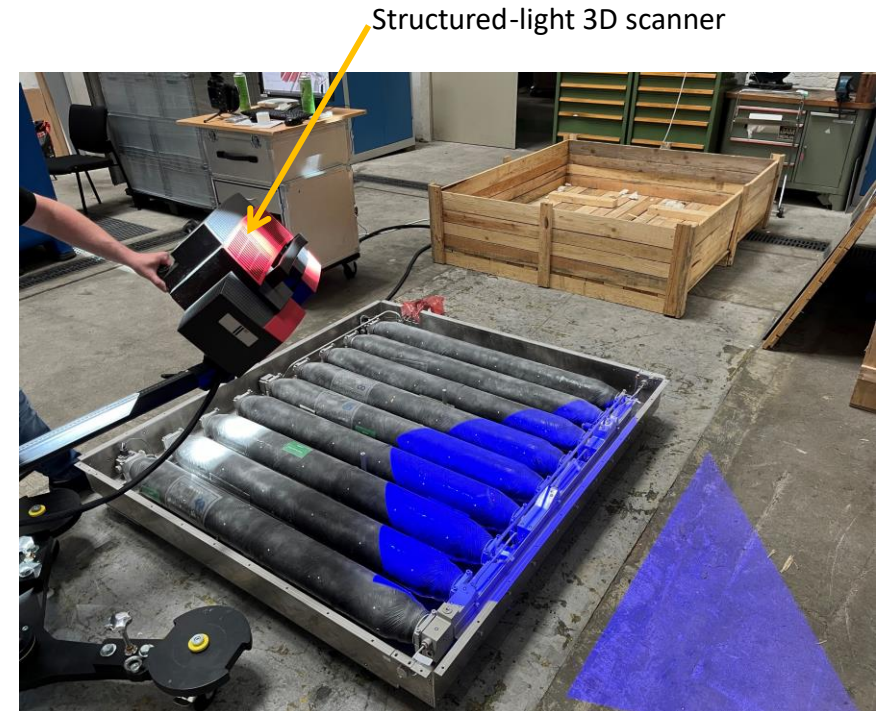
## ➤ Instrumentation



Measurement during impact



Measurement before and after impact





# Drop/Impact testing - 1<sup>st</sup> Drop test

## ➤ 1<sup>st</sup> drop - Horizontal drop test

### Drop test setup



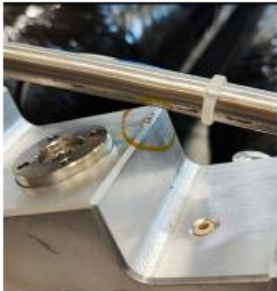
### Drop test



# Drop/Impact testing - 1<sup>st</sup> Drop test results

## ➤ 1<sup>st</sup> drop - Horizontal drop test results (visual inspection)

Slightly deformed pipes



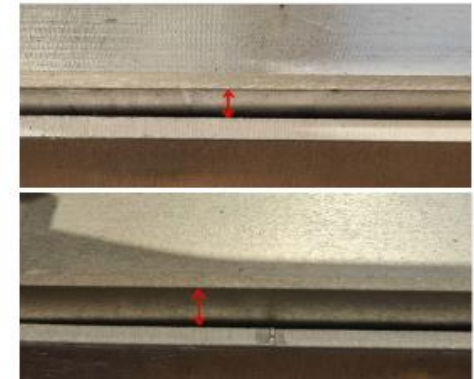
Screw rotation from initial fixing



Bent ventilation tube



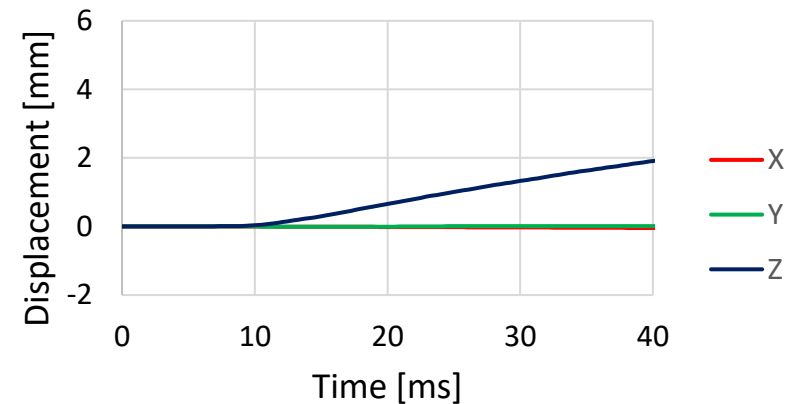
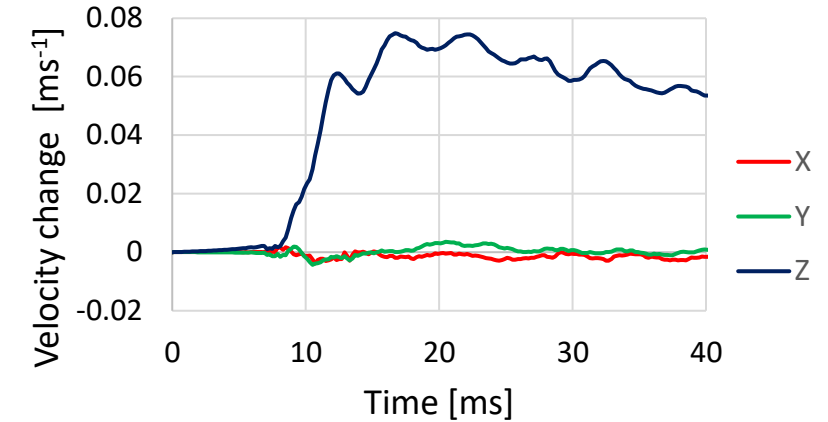
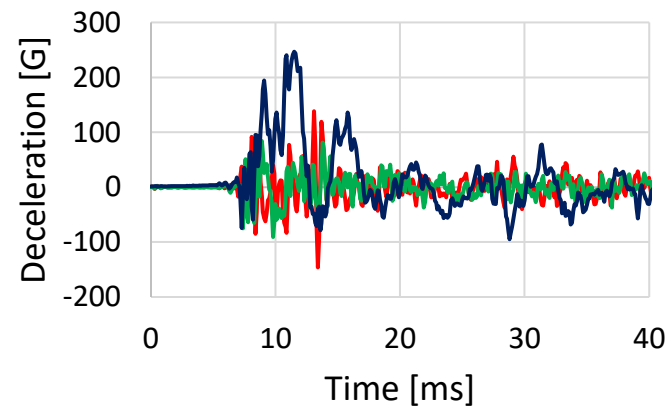
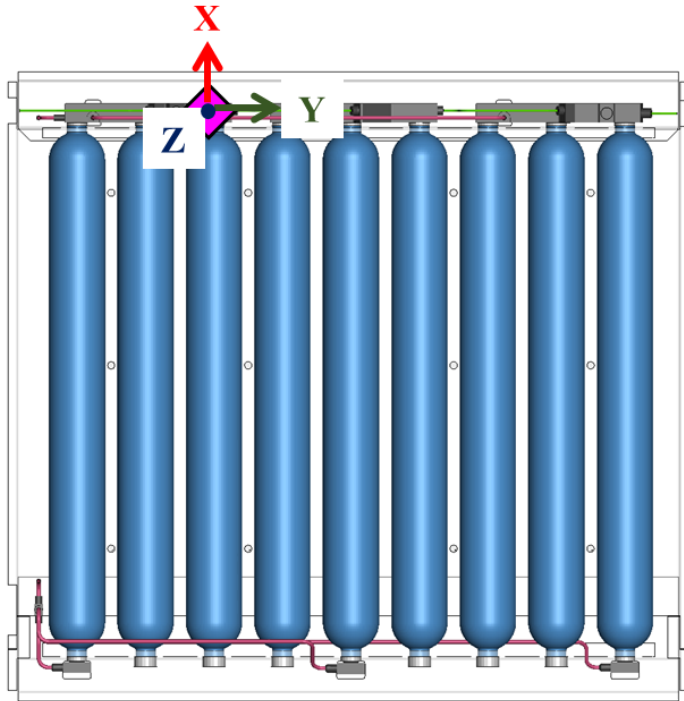
Change of vertical positioning of manifolds





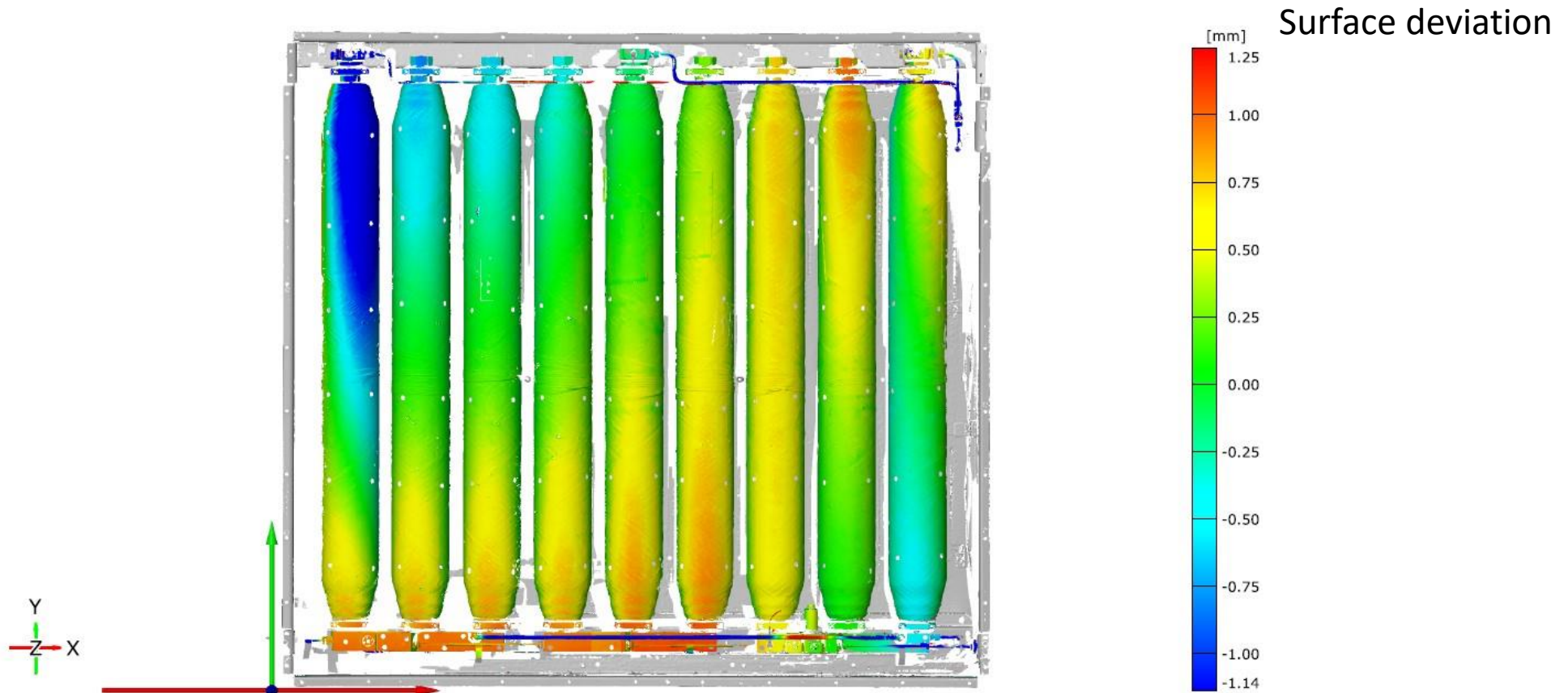
# Drop/Impact testing - 1<sup>st</sup> Drop test results

## ➤ 1<sup>st</sup> drop - Horizontal drop test results (deceleration)



# Drop/Impact testing - 1<sup>st</sup> Drop test results

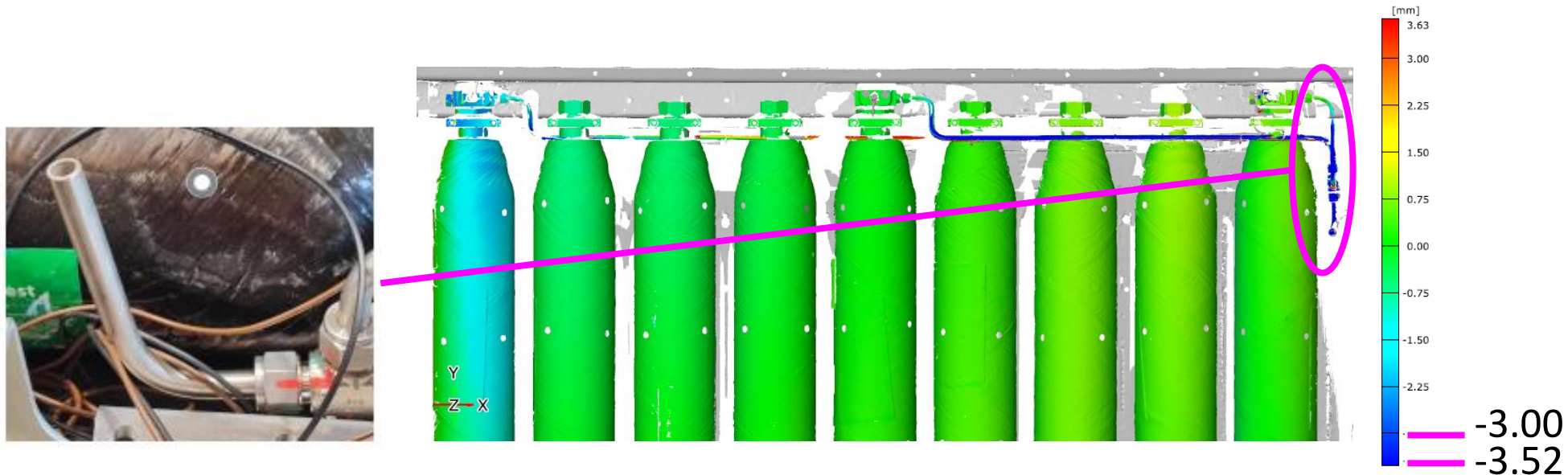
## ➤ 1<sup>st</sup> drop - Horizontal drop test results (3D scan)



# Drop/Impact testing - 1<sup>st</sup> Drop test results

## ➤ Tightness test after 1<sup>st</sup> drop

- **28 positions** were monitored before and after the drop
- Measured **leakage rate** within **acceptable** limits ( $<2.78\text{E-}3 \text{ mbar}\cdot\text{l/s}$ ) **after the drop**
- **Largest increase** in leakage rate ( $\sim 4.5$  times the initial value) at **depicted location**

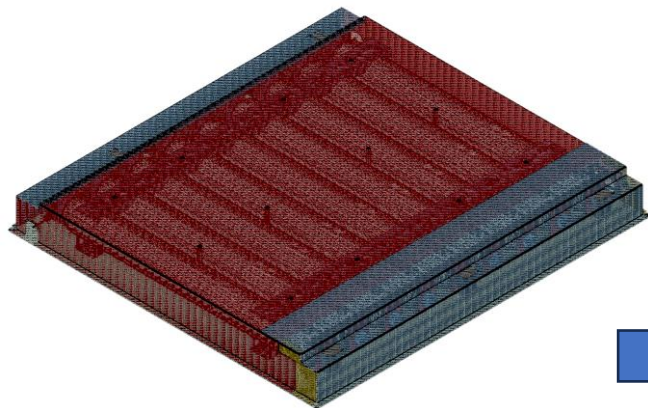




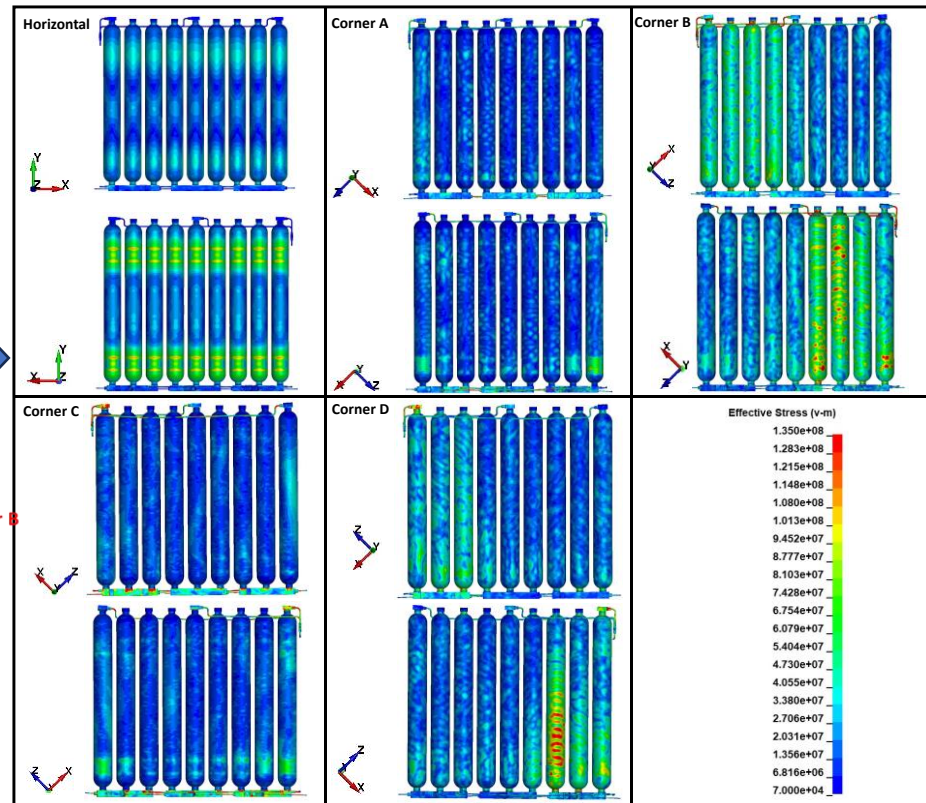
# Drop/Impact testing - FEM calculations

## ➤ FEM calculation of most severe damage orientation

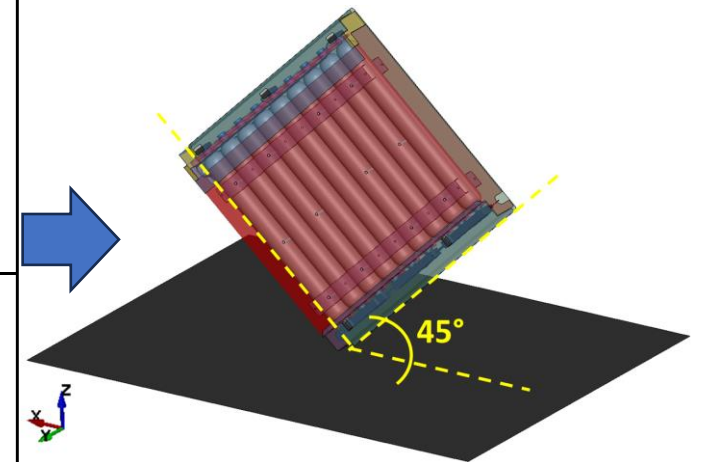
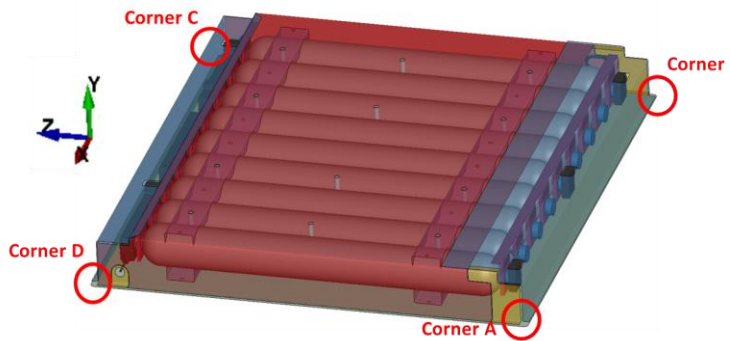
FEM model



Variation of drop orientation



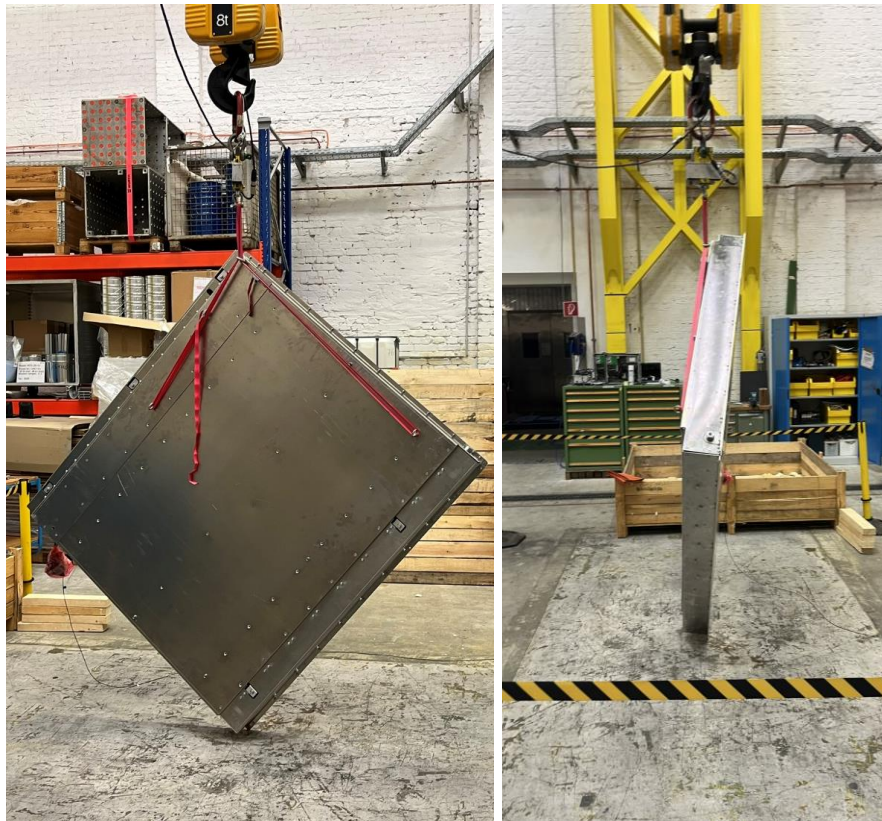
Most severe damage  
Corner drop (Corner C)



# Drop/Impact testing - 2<sup>nd</sup> Drop test

## ➤ 2<sup>nd</sup> drop - Most severe damage drop test

Drop test setup



Drop test





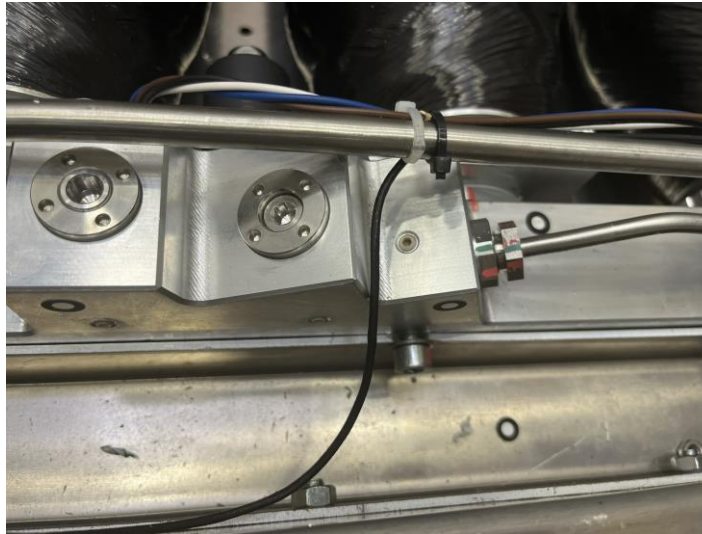
# Drop/Impact testing - 2<sup>nd</sup> Drop test results

## ➤ 2<sup>nd</sup> drop - Most severe damage drop test results (visual inspection)

Significant plastic deformation of enclosure



Slight loosening of connection to manifold

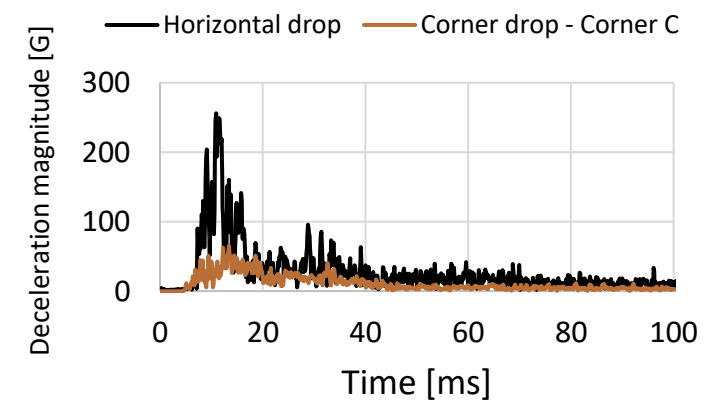
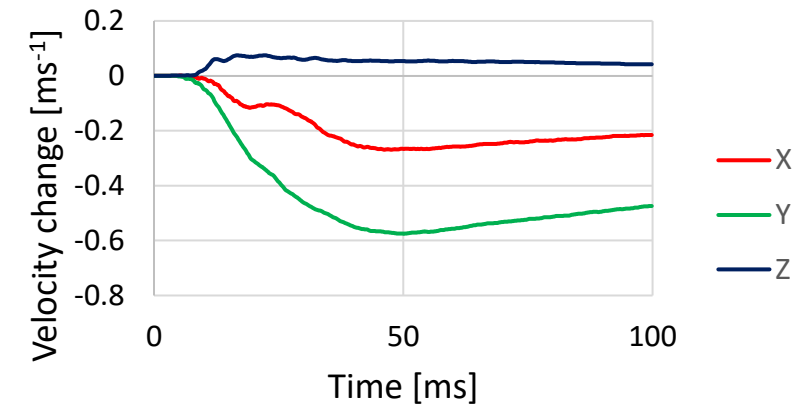
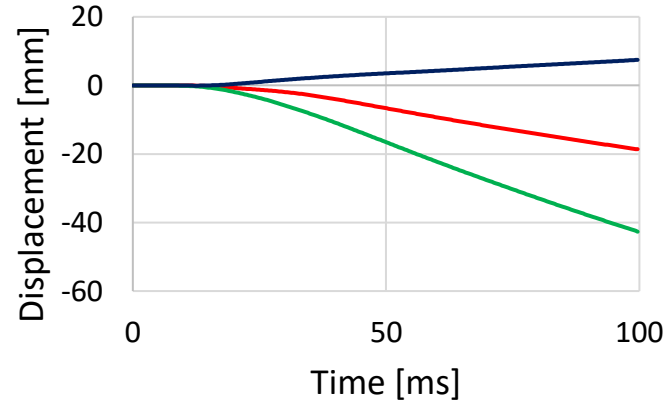
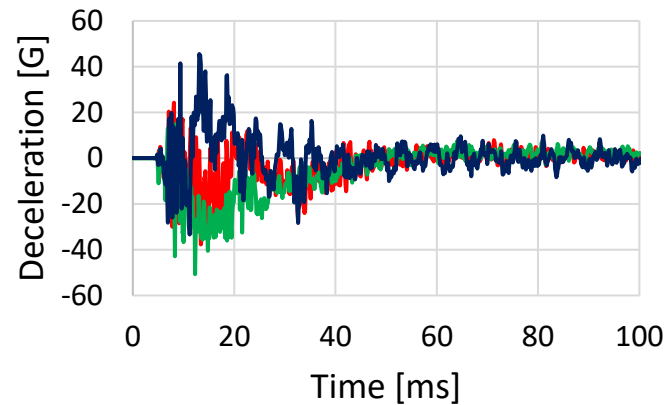
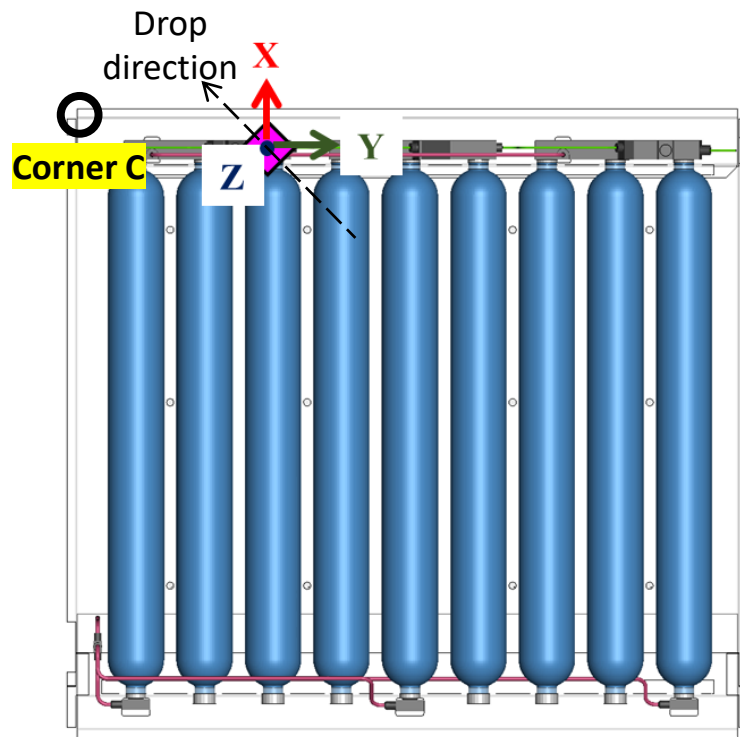


Significant plastic deformation of piping

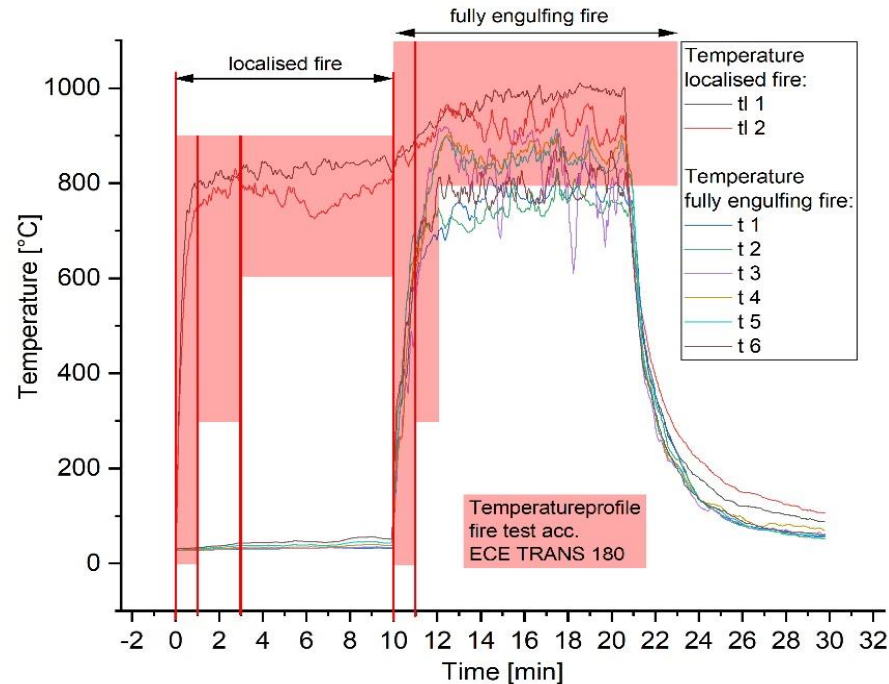
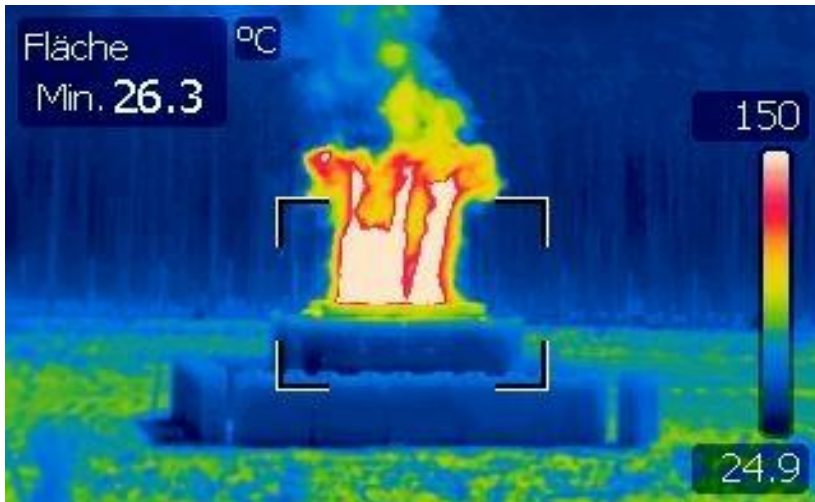


# Drop/Impact testing

## ➤ 2<sup>nd</sup> drop - Most severe damage drop test results (deceleration)



# Fire Testing – Localized and engulfing fire test



## Fire Test with Propane (Local and Full Engulfment)

|                    |                          |
|--------------------|--------------------------|
| $p_{\max}$         | 800 bars, filled by mass |
| $P_{\text{heat}}$  | 1000 °C                  |
| $t_{\text{range}}$ | 5 ... 300 hours          |
| $T_{\text{range}}$ | 600 ... 80 °C            |





# THANK YOU

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BAM Division 3.5 – Safety of Gas Storage Systems



This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.

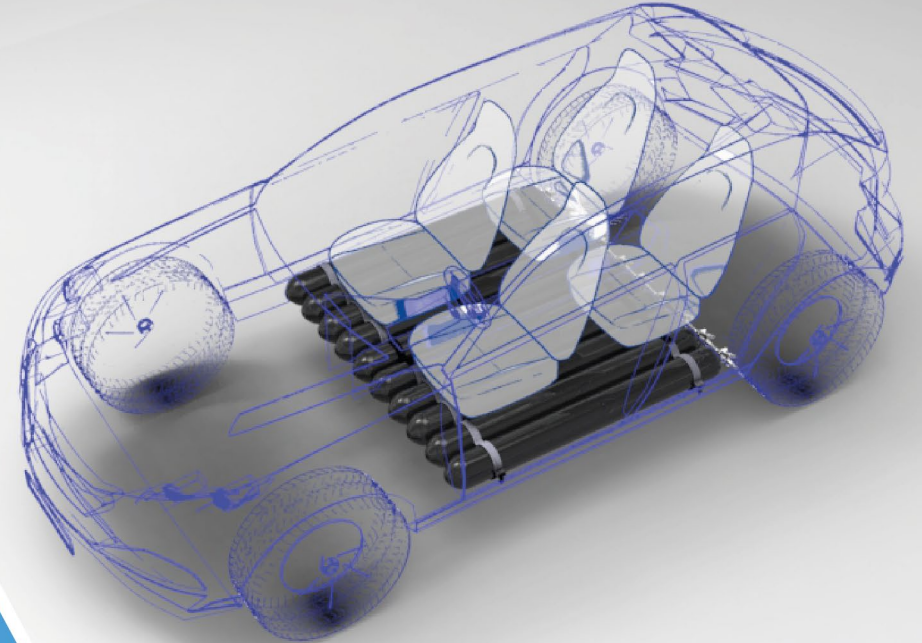


# Distributed fibre optic strain sensing for structural health monitoring of composite pressure vessels

Stakeholders' Meeting – September 26-27, 2024

BAM Division 8.6 Fibre Optic Sensors

A. Wosniok, M. Schukar, M. Breithaupt



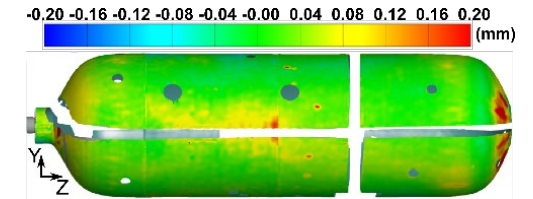
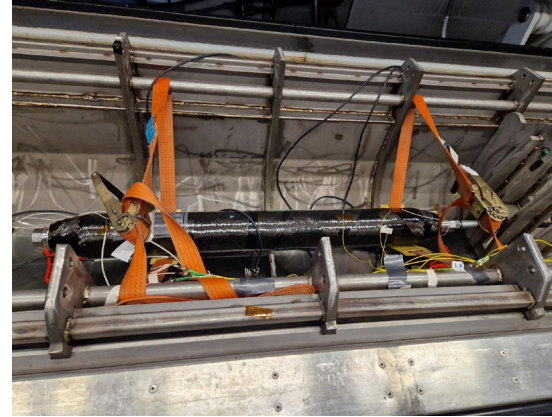
[www.sh2aped.eu](http://www.sh2aped.eu)



# Need of Structural Health Monitoring



Increase safety



*Source: R. Eisermann et al.,  
Proceedings of EWSHM, 2018.*

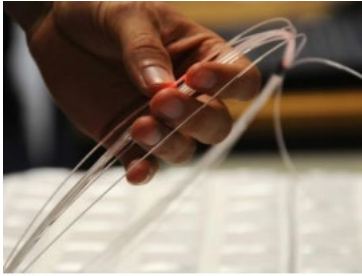


Reduce maintenance costs



Minimize regular inspections

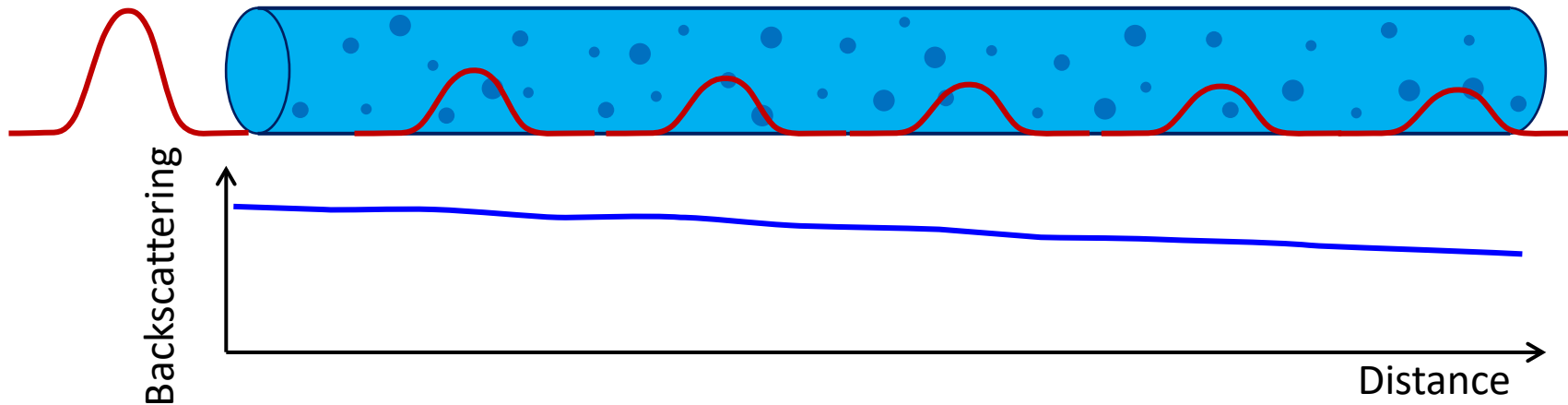
# Distributed Fibre Optic Sensors



Optical fibre itself is the distributed sensor!

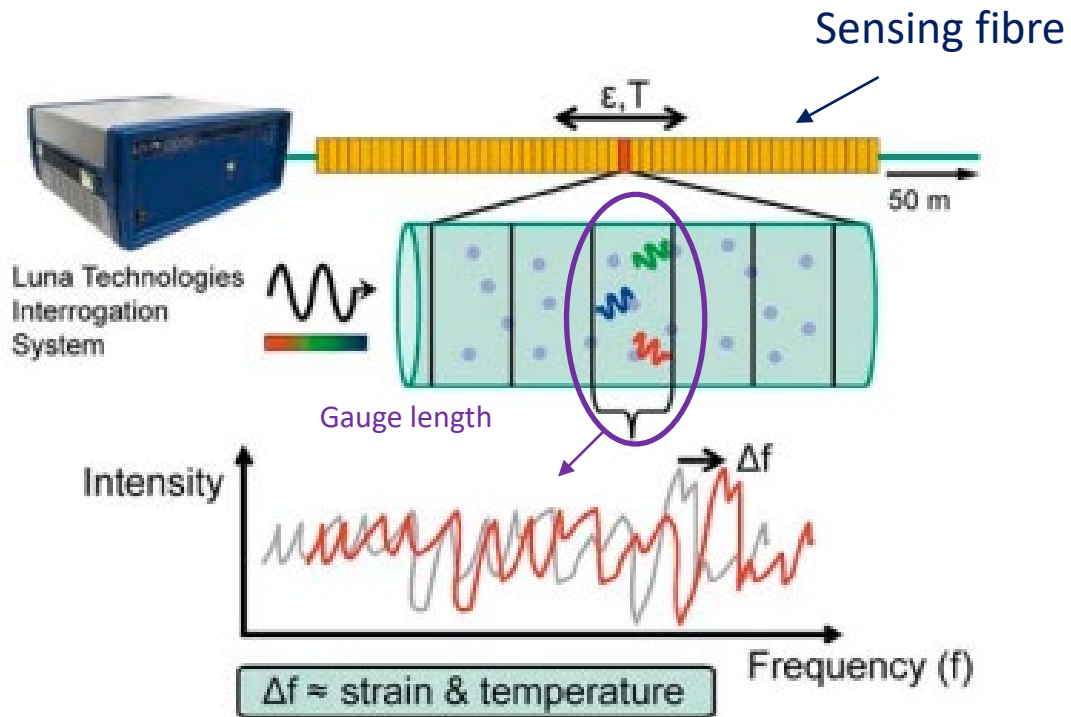
## Advantages:

- Gap-free measurements
- Standard silica glass optical fibre as sensor medium (immunity to electromagnetic interference, small and lightweight, chemically inert, high sensitivity)



Backscattered light carries information about the strain and temperature distribution along the sensing fibre.

# Optical Backscatter Reflectometry



The measurement principle is based on the swept wavelength interferometry.

- Determination of the Intensity profiles of the Rayleigh backscatter as a function of the swept laser frequency  $f$  along the entire sensing fiber divided into customizable gauge lengths.
- The gauge length defines the segment used to determine the cross-correlated spectral shift  $\Delta f$  giving information about local strain and temperature changes.

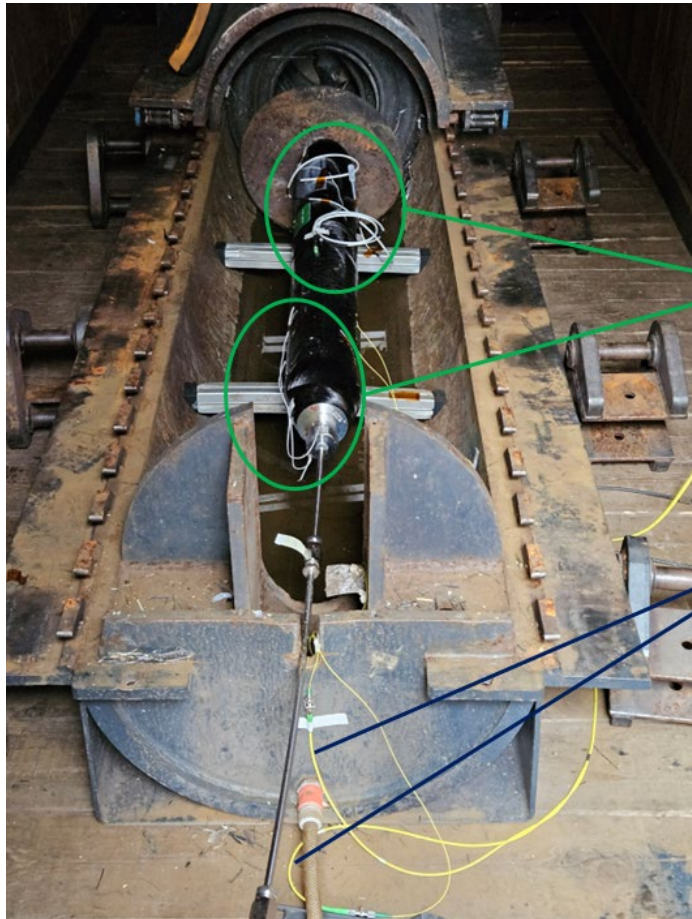
*Source: D. Samiec, Distributed fibre-optic temperature and strain measurement with extremely high spatial resolution, Photon Int., 2012.*

- **Fibre 1:** in the first innermost helical winding (directly on the liner) – in most cases 6.5 circuits, i.e. 13 lengths from dome to dome
- **Fibre 2:** in the circumferential winding placed in the middle between inner helical windings and outer helical windings – single track from dome A to the opposite dome B
- **Fibre 3:** in the penultimate outer helical winding – 6.5 circuits, i.e. 13 lengths from dome to dome



- The sensing fibre joined the carbon fibres at a point after the carbon fibres passed the resin bath, whereby the combined fibres were applied through the winding eye on the vessel surface.

# Slow Burst Tests



Sensing fibres lead at both ends of the vessel

Fibre optic patch cables for connection to the measuring device

- All sensing fibres were intruded in / extruded from SFRP at two opposite domes of each vessel enabling fibre optic measurements at both ends of the tested composite pressure vessels.



# Slow Burst Tests

Slow burst testing is preferred to account for the time-dependent degradation of the strength of composite pressure vessels.

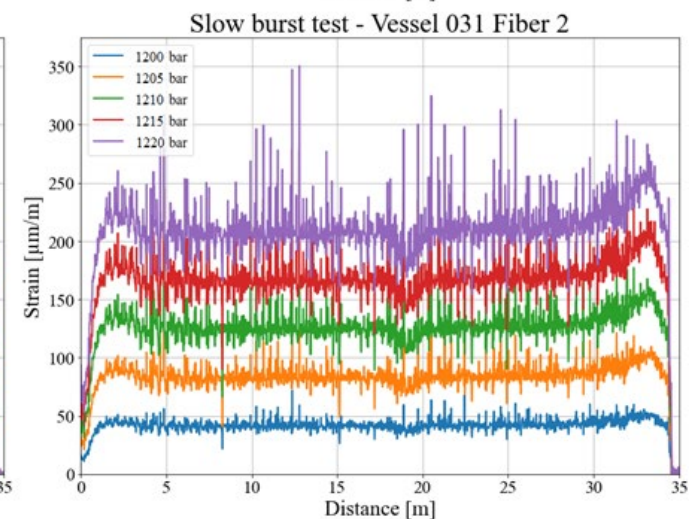
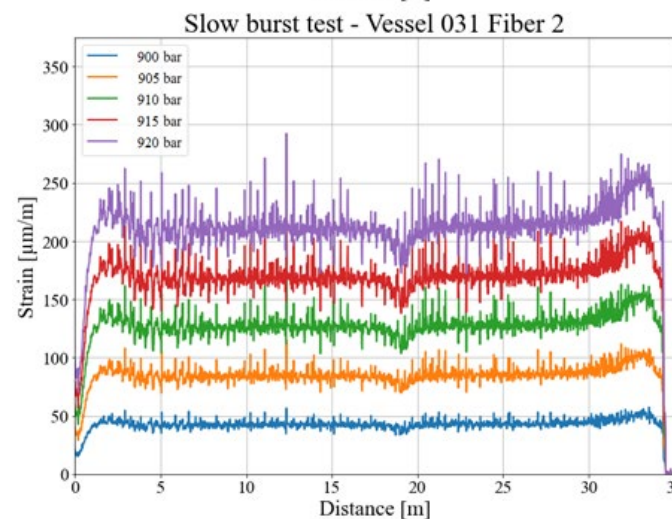
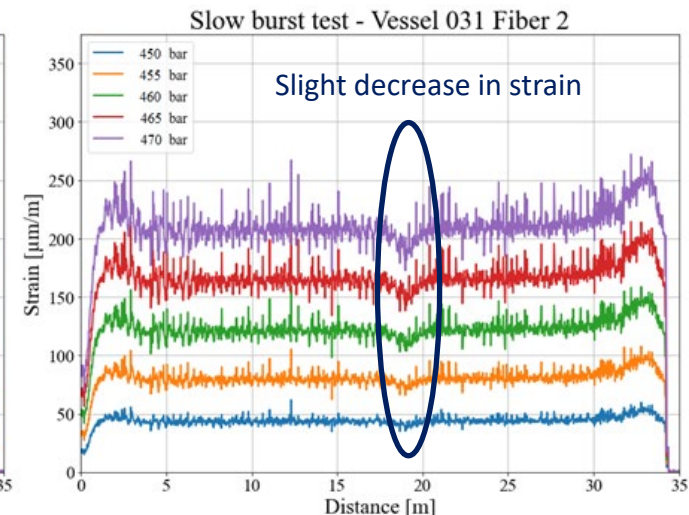
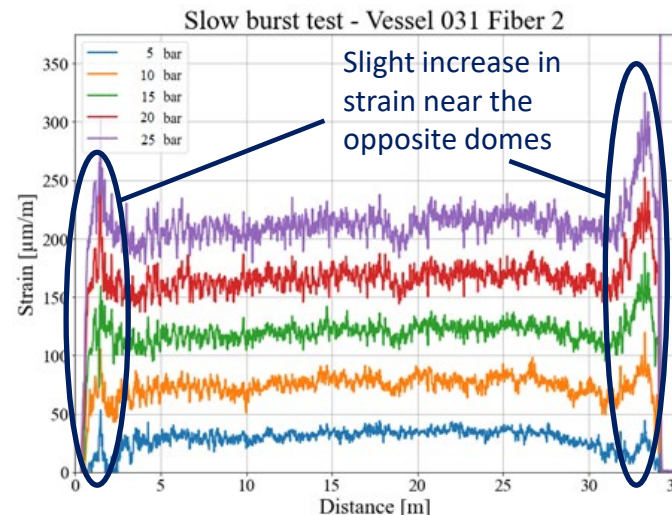
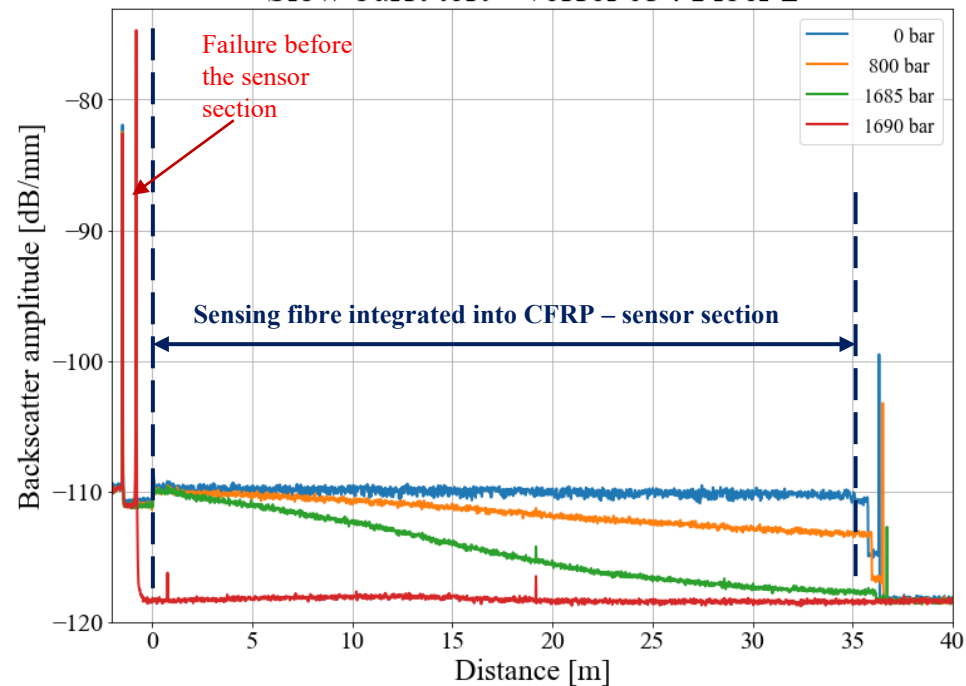
| Vessel | Burst Pressure [bar] | Burst Location          | Picture                                                                             |
|--------|----------------------|-------------------------|-------------------------------------------------------------------------------------|
| 003    | 1,560.2              | Dome, close to cylinder |   |
| 031    | 1,675.1              | Cylinder                |   |
| 034    | 1,695.9              | Cylinder & dome         |  |

- All specimens were loaded to failure at a pressure increasing at the rate of 3.5 bar/min.
- Pre-treatment of the vessel 003 in an ambient cycling test (22000 load cycles with 3 load cycles per minute varying between 20 bar and 700 bar).

# Slow Burst Tests

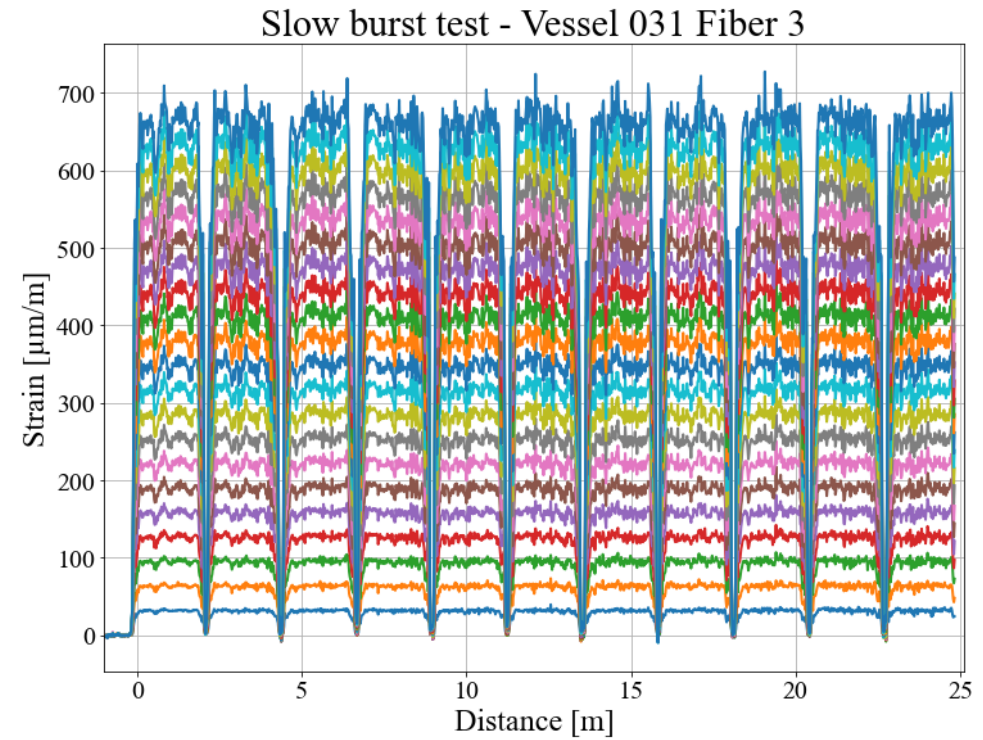
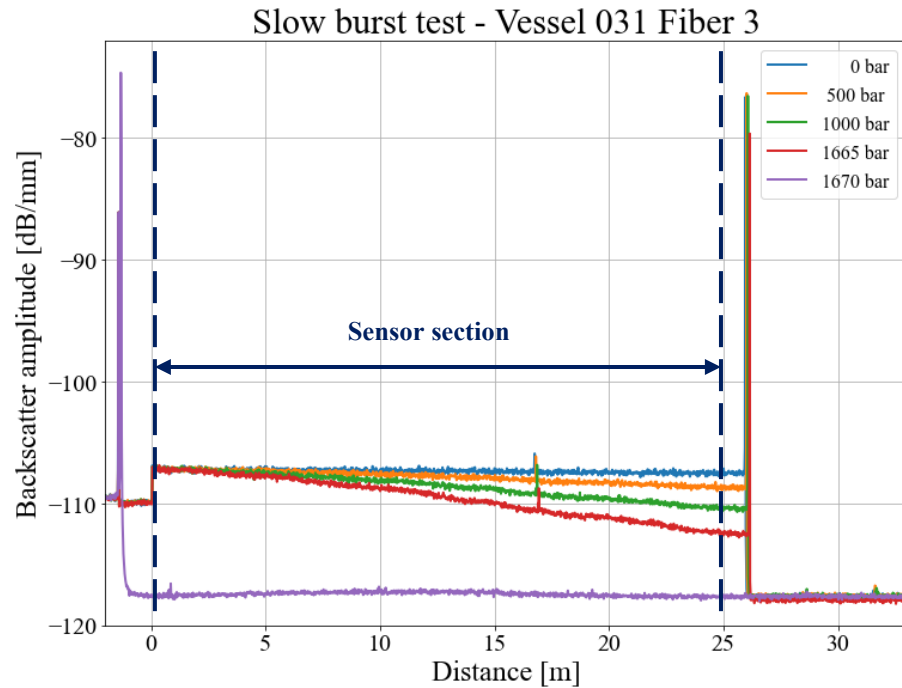
## Circumferential winding

Slow burst test - Vessel 034 Fiber 2



Spatial resolution of 2 cm

## Helical winding



Spatial resolution of 2 cm

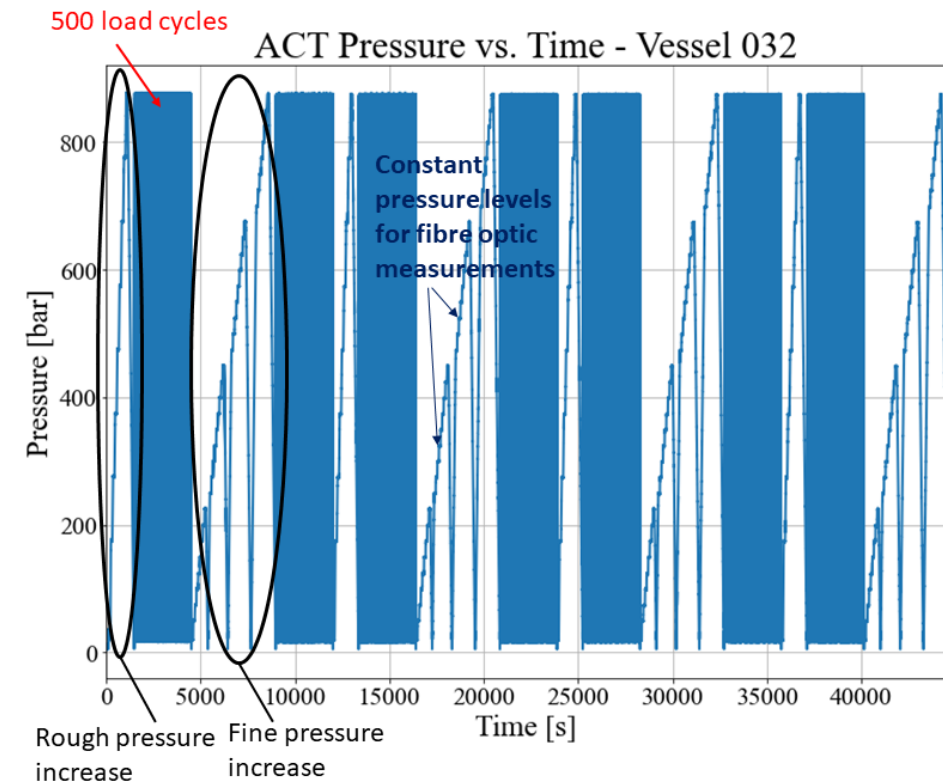


# Ambient Cycling Tests

## Selected test parameters and settings for conducted ACTs:

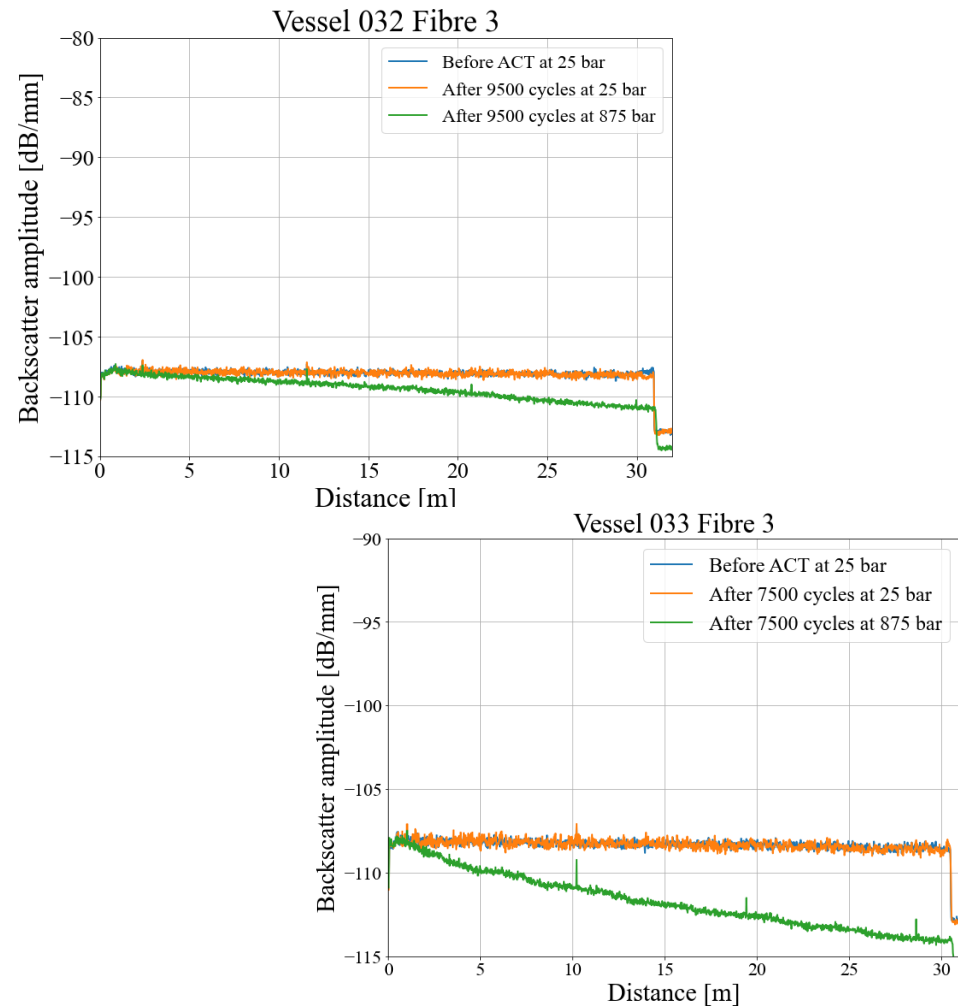
| Vessel         | Cycle Pressure Range [bar]  | ACT Procedure                                         | Distributed Fibre Optic Measurements                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|----------------|-----------------------------|-------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 003 (pre-test) | 20 – 700<br>Sinusoidal form | Cycle rate: 3 cycles/min<br>Test at room temperature  | Measurement series at gradually increasing pressure values with the 50 bar step up to 700 bar.*<br>The measurements series were conducted after 50, 200, 550, 1050, 5150, 9250, 13400, 18400 and 22000 hydraulic load tests.<br>*Pressure increase: 20 bar, 50 bar, 100 bar, ..., 700 bar                                                                                                                                                                                                                                                                                                                                                         |
| 032            | 20 – 875<br>Sinusoidal form | Cycle rate: 10 cycles/min<br>Test at room temperature | 1° <u>The first 1500 load cycles:</u> measurement series at gradually increasing pressure values with the 25 bar step starting at 25 bar (up to 675 bar) conducted every 75 load cycles<br>2° <u>After 1500 load cycles until failure:</u> measurement series at gradually increasing pressure values starting at 25 bar (up to 875 bar) conducted every 500 load cycles. The measurement series were performed alternating with a rough pressure step of 100 bar** and a fine pressure step of 25 bar***<br>**Rough pressure increase: 25 bar, 175 bar, 275 bar, ..., 875 bar<br>***Fine pressure increase: 25 bar, 50 bar, 75 bar, ..., 875 bar |
| 033            | 20 – 875<br>Sinusoidal form | Cycle rate: 10 cycles/min<br>Test at room temperature | 1° <u>The first 1500 load cycles:</u> measurement series at gradually increasing pressure values with the 25 bar step starting at 25 bar (up to 875 bar) conducted every 75 load cycles<br>2° <u>After 1500 load cycles until failure:</u> Same procedure as for #032 (see above)                                                                                                                                                                                                                                                                                                                                                                 |

- ACTs were performed in accordance with chapter 4.2.2. "Ambient temperature pressure cycle test" (Annex IV, Part 2 of the EC 79/2009, Commission Regulation No 406/2010) and chapter 5.1.2. "Baseline initial pressure cycle life" (Annex 4, R 134 (UN ECE/TRANS/180/Add.13)).

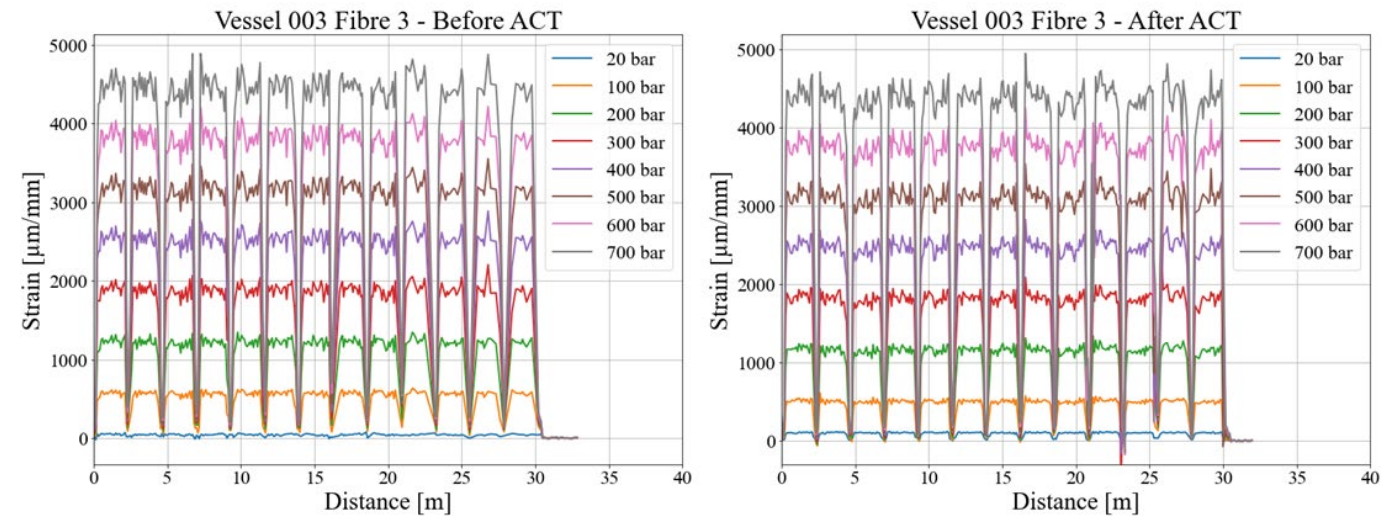


# Ambient Cycling Tests

Backscatter profiles recorded during ACTs:



Strain profiles recorded during ACTs:



- The required robustness of the FOSs with simultaneous assurance of their sensitivity can be achieved by suitable positioning the sensors in CFRP.

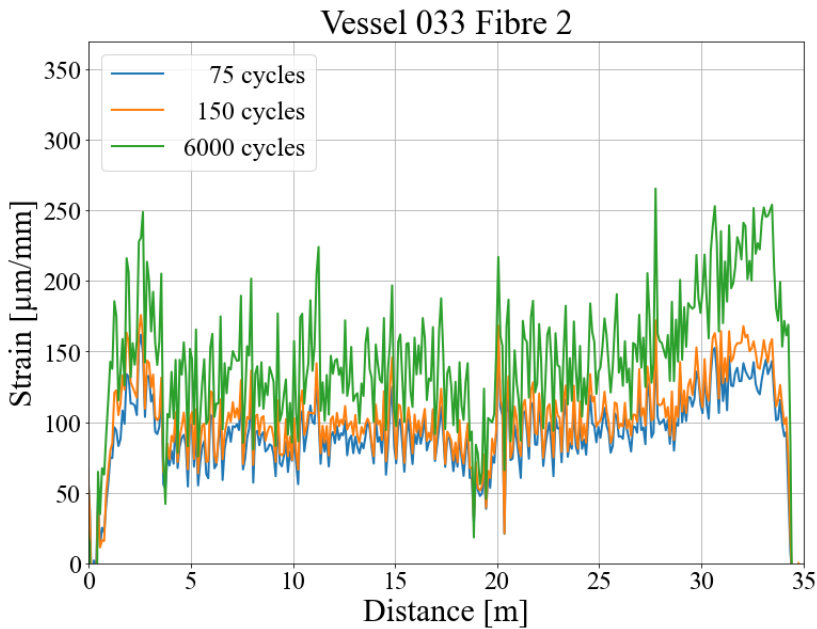


# Ambient Cycling Tests

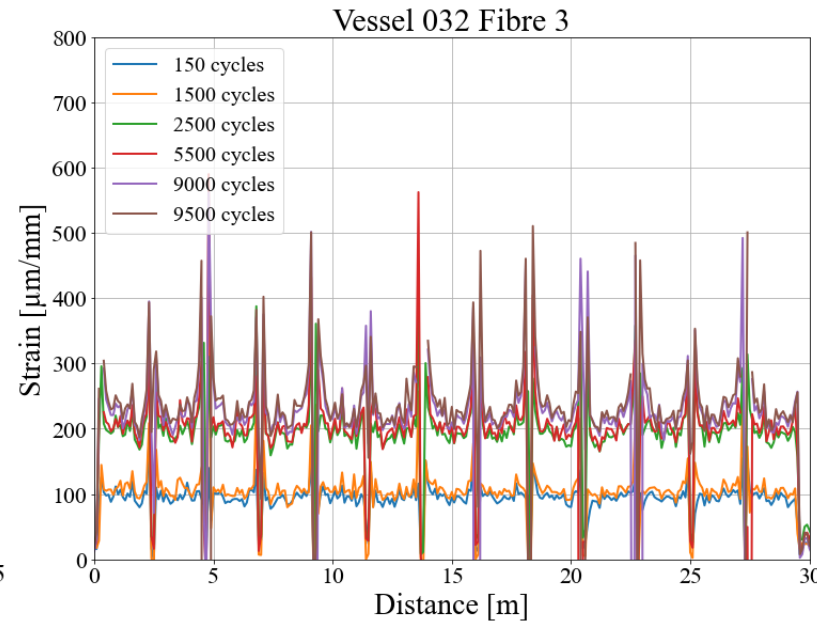
- ✓ Continuous and gap-free monitoring of cycling-induced strain distribution enables reliable detection of material degradation.

## Cycling-induced strain:

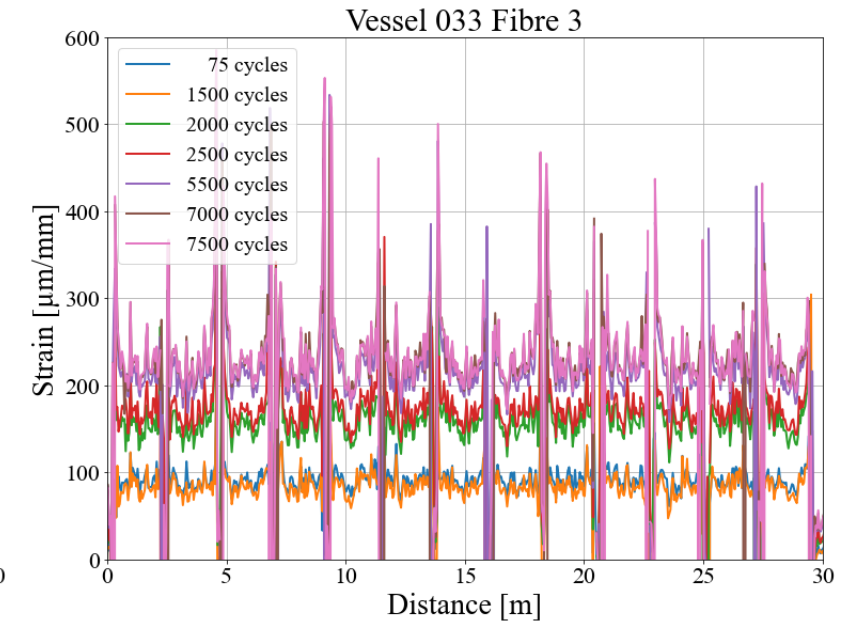
@ CPV pressure of 37 bar



@ CPV pressure of 25 bar



@ CPV pressure of 25 bar

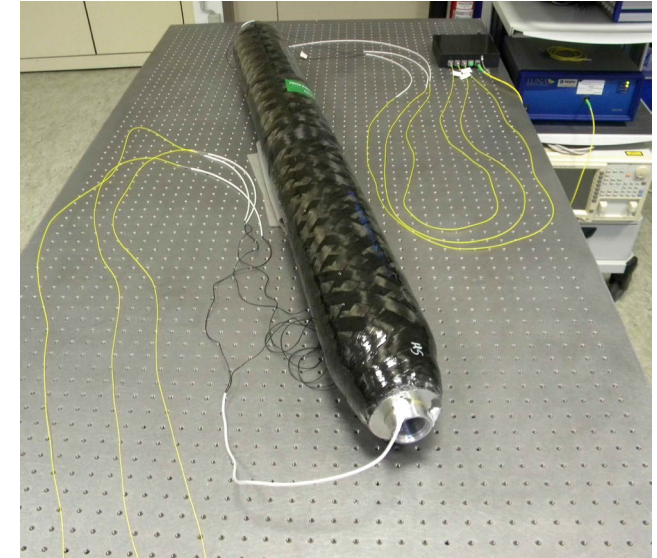


Distributed FOS is excellently suited for continuous and gapless:

- Condition monitoring of CPVs
- Comprehensive long-term measurements over the entire sensing fibre length

FOS integrated into CFRP proves to be:

- Resistant to pressure load above the nominal working pressure of 700 bar
- Sensitive with a nearly linear strain response to pressure



# THANK YOU

**Contact:**

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BAM Division 8.6 – Fibre Optic Sensors



This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.

# SH2APED Stakeholders' Workshop

Brussels, September, 26-27, 2024

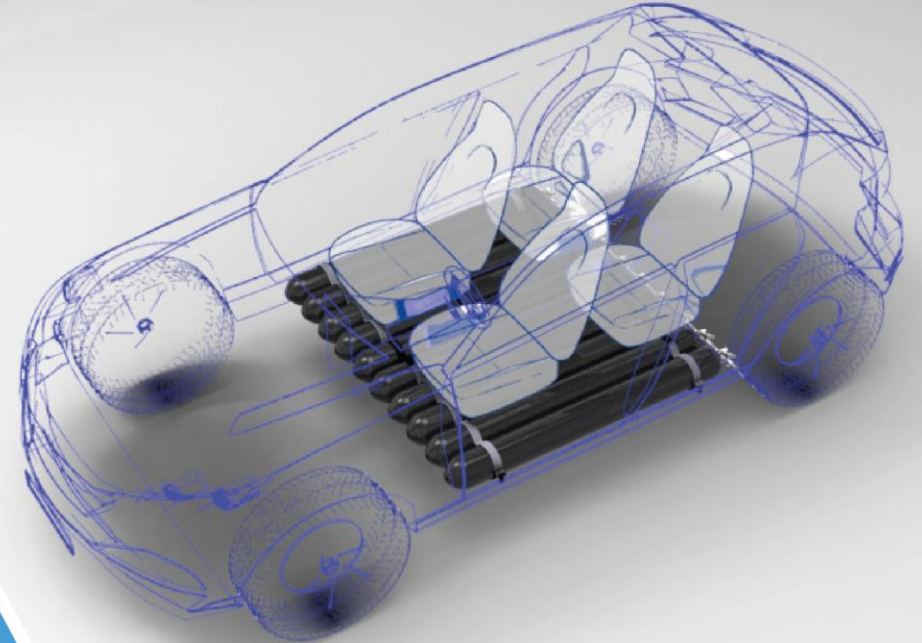


# Investigations on fire resistance of CPVs with respect to validation of fire test setup

Stakeholders' Meeting – September 26-27, 2024

BAM 3.5: Safety of Gas Storage Systems

C. Sklorz, G. Mair, K. Müller, N. Lengas



[www.sh2aped.eu](http://www.sh2aped.eu)



## ➤ Regulation

- Global Technical Regulations (GTR) 13-2 and Requirements

## ➤ Experimental methods and Investigations

- Development of experimental setup
- Verification and qualification

## ➤ Summary

## ➤ GTR for Hydrogen Fuel Cell Vehicles (HFCV)

- was adopted in June 2013 as GTR 13 – see also UN R134 for its transposal into 58 Agreement.

## ➤ Development of Phase 2

- started in 2017 with technical work taking place in 5 taskforces

## ➤ Taskforce 4: Fire Test

- to improve the repeatability and reproducibility of the fire test
- Burner specifications
- Pre-test check of fire test
- Accommodate vehicle specific components
- Extend the application of the fire test to containers on heavy vehicles and to conformable containers

## ➤ GTR13 – Phase 2

- was adopted in July 2023



<https://unece.org/transport/standards/transport/vehicle-regulations-wp29/global-technical-regulations-gtrs>

## ➤ Global Technical Regulations No. 13

### **Part I : Statement of technical rationale and justification**

e.g. Performance Requirements as

(d) Rationale for paragraphs 5.1.4. and 6.2.5. verification test for service-terminating performance in fire

### **Part II : Text of the regulation**

Chapter 6: Test Conditions and Procedures

## ➤ Fire resistance of Composite Pressure Vessels

### ■ Fire test conditions (GTR13-2)

- Fire test conditions have to be defined
- Qualification of fire test (e.g. with dummy cylinder)

### ■ Fire test setup

- Nozzles and burner rails: manufacturing and assembling
- Pre-testing (specific heat release rate)
- Local wind measurement
- Protective housing (splinter protection and pressure wave caused by explosion)
- Safety concept

# Fire Test: Allowable Range of Operations

## ➤ GTR 13-2 (§ 6.2.5.4.5.2. Table 9)

**Allowable range of operation and the suggested settings for the prescribed burner**

| <i>Fire Stage</i>       | <i>Allowable Range of Specific Heat Release Rate (HRR/A)</i> | <i>Suggested Setting of Specific Heat Release Rate (HRR/A)</i> |
|-------------------------|--------------------------------------------------------------|----------------------------------------------------------------|
| <b>Localized Burner</b> | <b>200 - 500 kW/m<sup>2</sup></b>                            | <b>300 kW/m<sup>2</sup></b>                                    |
| <b>Engulfing Burner</b> | <b>400 - 1000 kW/m<sup>2</sup></b>                           | <b>700 kW/m<sup>2</sup></b>                                    |



# Fire Test: Regulative requirements

**HRR/A** – Heat Release Rate ( $\dot{m}$ ;  $H_i$ ) per Burner area (loc; eng)

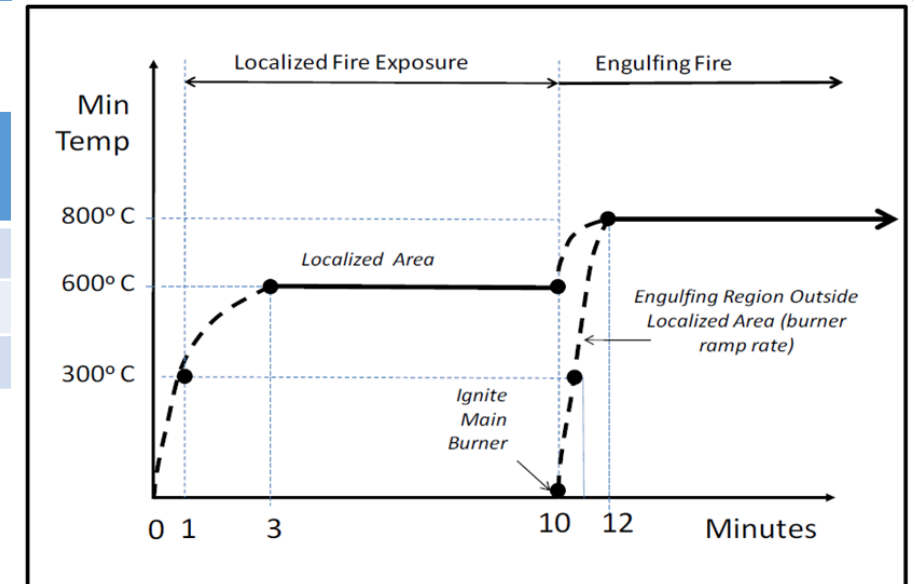
| Fire Stage             | Allowable range of Specific Heat Release Rate (HRR/A) | Suggested Setting of Specific Heat Release Rate (HRR/A) | Allowable Temperature Range |                            |                          |
|------------------------|-------------------------------------------------------|---------------------------------------------------------|-----------------------------|----------------------------|--------------------------|
|                        |                                                       |                                                         | Bottom of Pre-test cylinder | Sides of Pre-test cylinder | Top of Pre-test cylinder |
| Localized Zone GTR13-2 | 200 - 500 kW/m <sup>2</sup>                           | 300 kW/m <sup>2</sup>                                   | 450 - 750 °C                | <750 °C                    | < 300 °C                 |
| Engulfing Zone GTR13-2 | 400 - 1000 kW/m <sup>2</sup>                          | 700 kW/m <sup>2</sup>                                   | > 600 °C                    |                            | 100 °C - 750 °C          |

## Mass Flow for Fire Stages

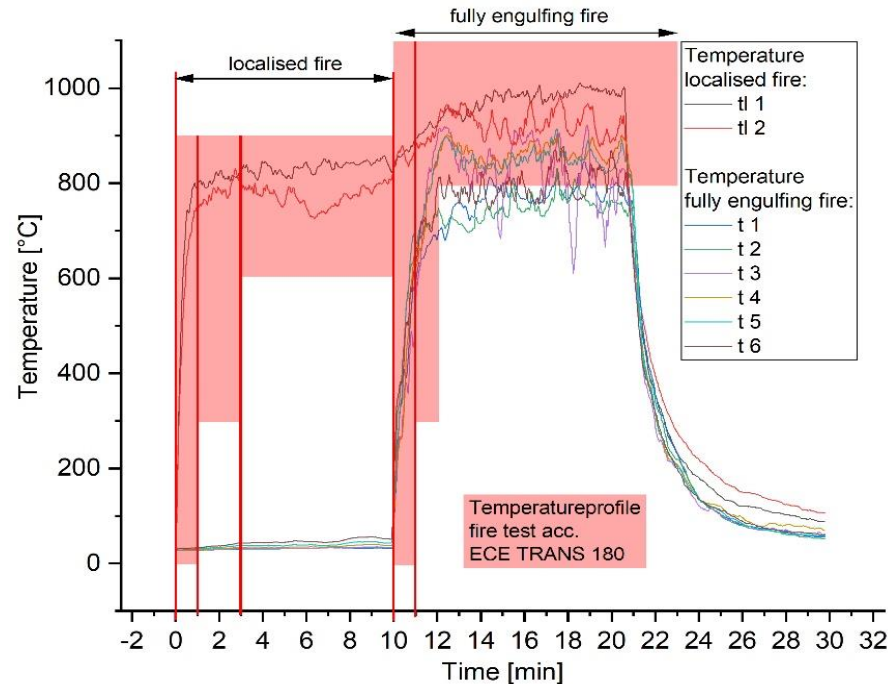
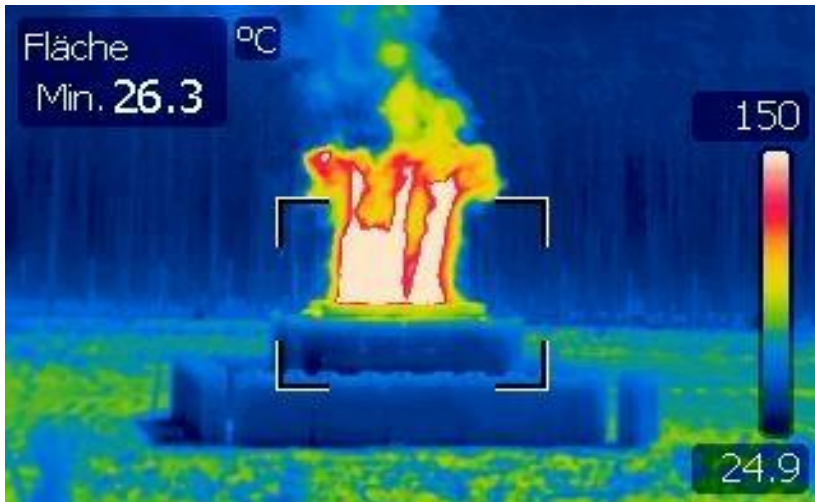
| Fire Stage             | Mass flow for allowable range of HRR/A | Mass flow for suggested setting of HRR/A |
|------------------------|----------------------------------------|------------------------------------------|
| Localized Zone GTR13-2 | 1.9 - 4.8 kg/h                         | 2.9 kg/h                                 |
| Engulfing Zone GTR13-2 | 21.7 - 54.2 kg/h                       | 38 kg/h                                  |
| Engulfing Zone SH2APED | 72.9 - 182.2 kg/h                      | 127.5 kg/h                               |

Test is finished if

- Vessel pressure is stable reduced  $\leq 1$  MPa or
- for Light Duty Vehicle Containers: 1 hour without vessel rupture (for HDVC: 2 hours)



# Localized and engulfing fire test (BAM)



## Fire Test with Propane (Local and Full Engulfment)

$p_{\max}$  800 bars, filled by mass  
 $P_{\text{heat}}$  1000 °C  
 $t_{\text{range}}$  5 ... 300 hours  
 $T_{\text{range}}$  600 ... 800 °C



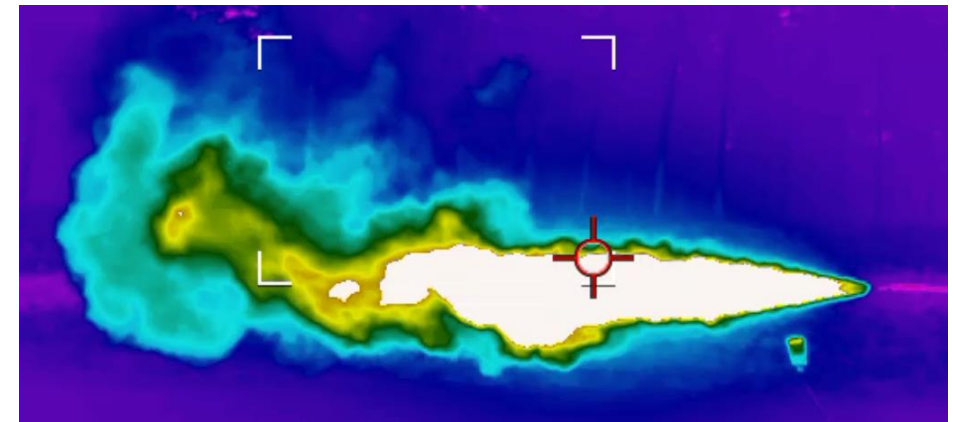
## ➤ Example of fire nozzles (GTR13-2)

**nozzles for localized  
and engulfing fire zones**

- **Jet flame test** (LPG and H<sub>2</sub>) with typical nozzles up to pressure of 50 bar
- Stable flame at **p ≤ 2 bar LPG / 50bar H<sub>2</sub>**
- Jet flame formation with dimension of app. 1.2m length

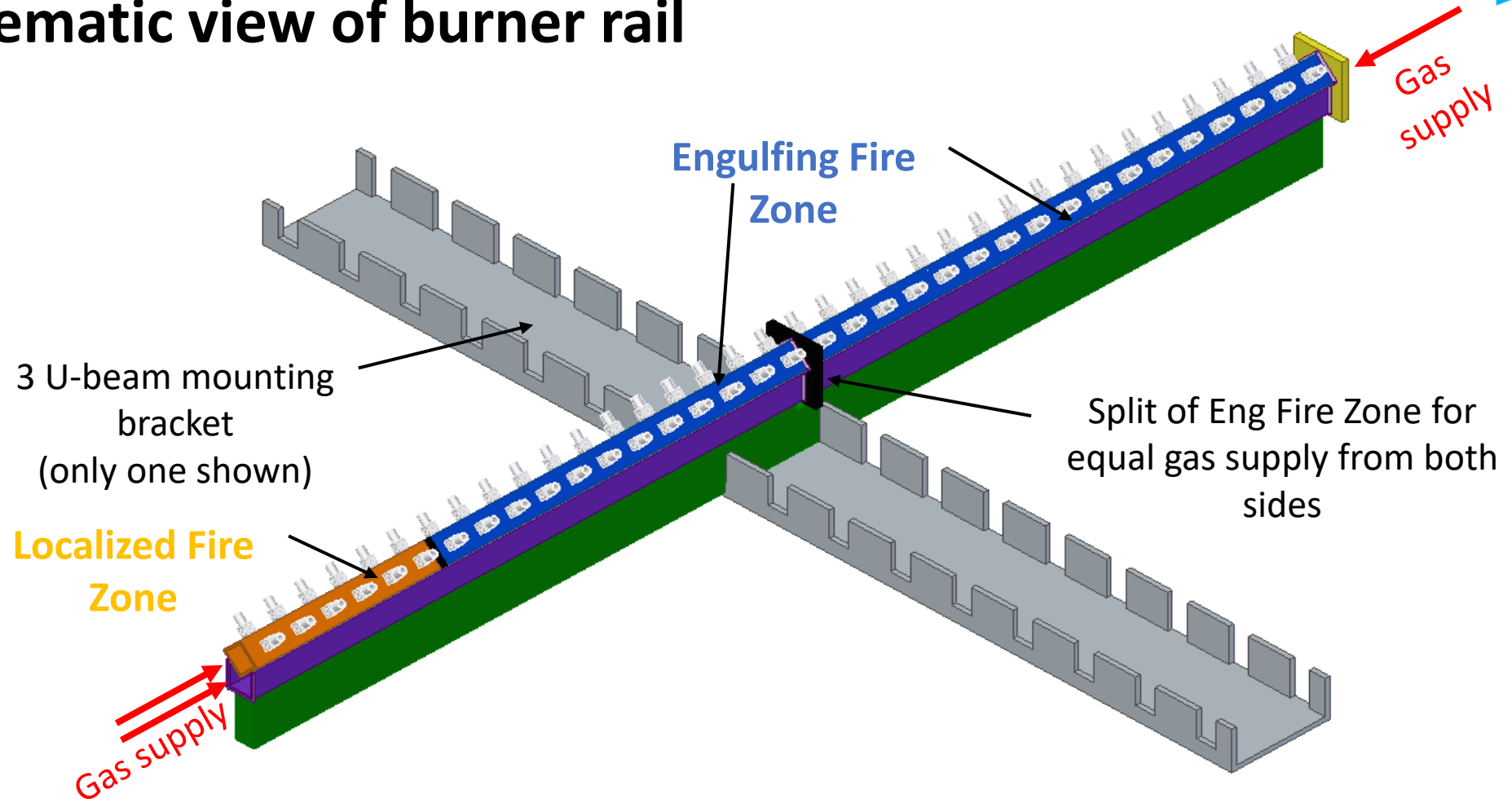


| Definition of Burner Nozzles for the Prescribed Burner |                                    |
|--------------------------------------------------------|------------------------------------|
| Item                                                   | Description                        |
| Nozzle Type                                            | LPG fuel nozzle with air pre-mix   |
| • LPG Orifice in Nozzle                                | 1mm ± 0.1mm ID                     |
| • Air Ports in Nozzle                                  | Four (4) holes, 6.4 mm ± 0.6 mm ID |
| • Fuel/Air Mixing Tube in Nozzle                       | 10 mm ± 1mm ID                     |



# Development of experimental setup

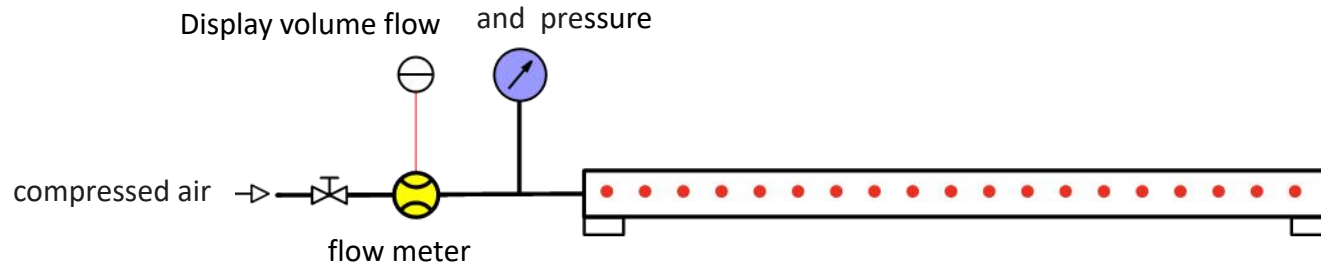
## ➤ Schematic view of burner rail



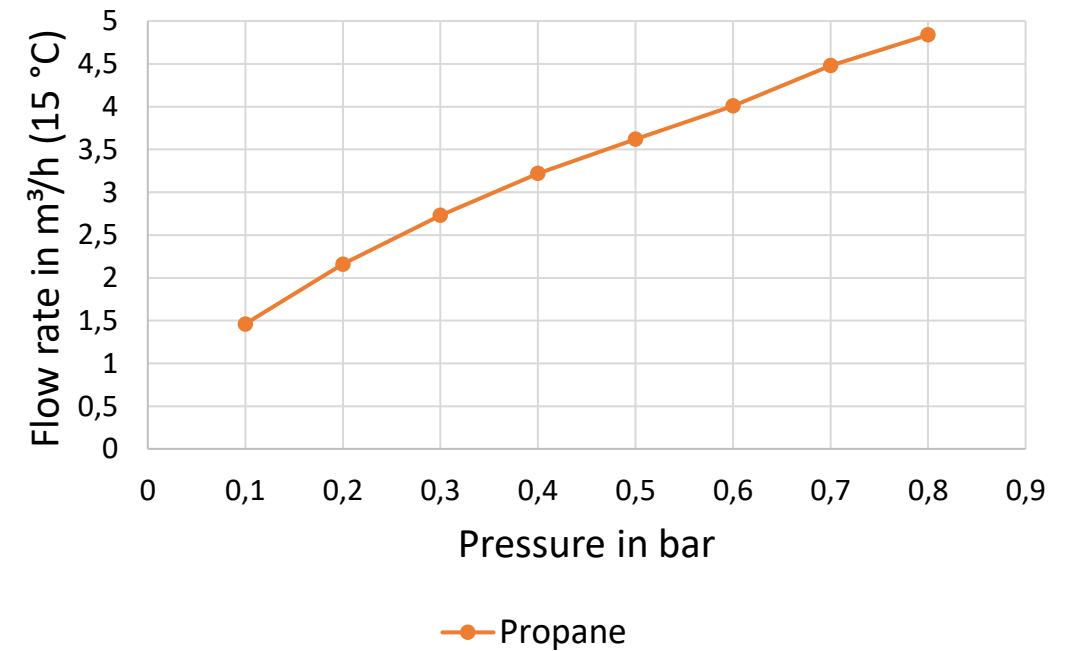


# Development of experimental setup

## ➤ Schematic view of burner rail



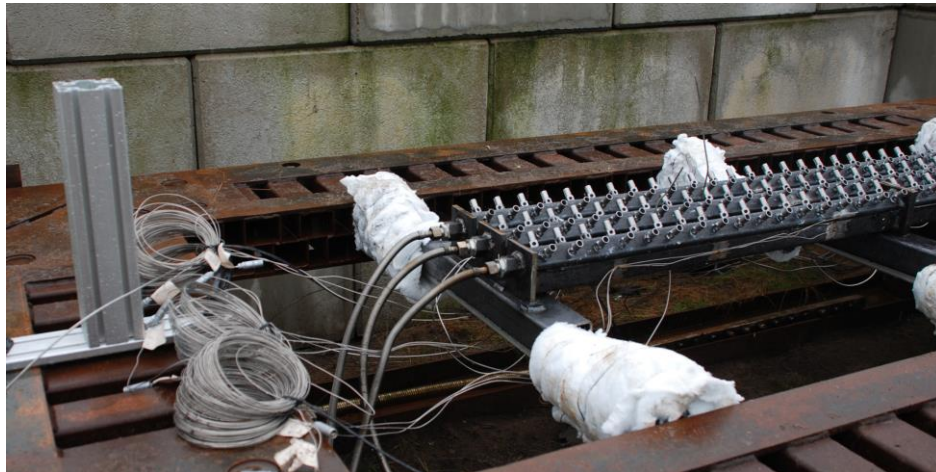
Flow rate of burner rail with 34 nozzles





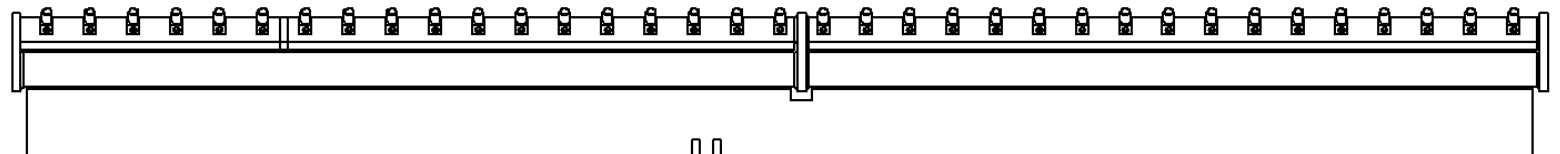
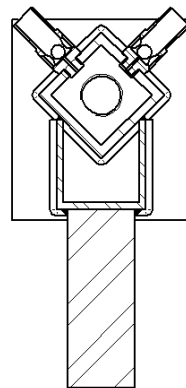
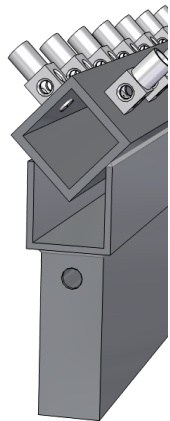
# Development of experimental setup

## ➤ Burner rail configuration and pre-testing



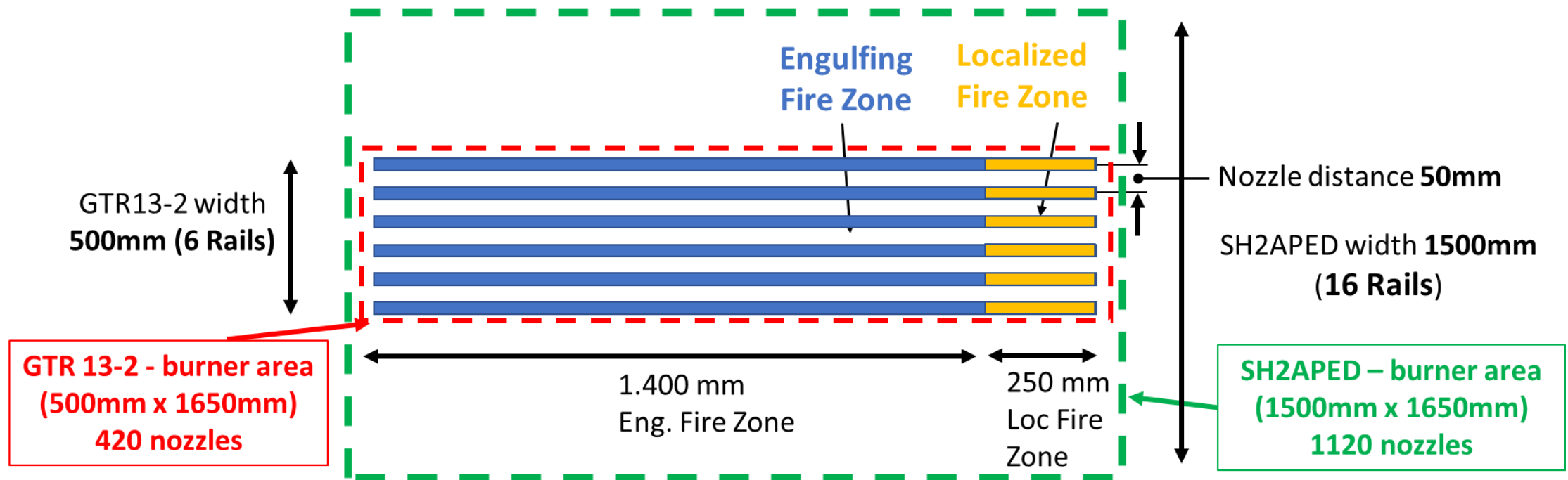
Primary  
gas path

Secondary  
gas path



# Development of experimental setup

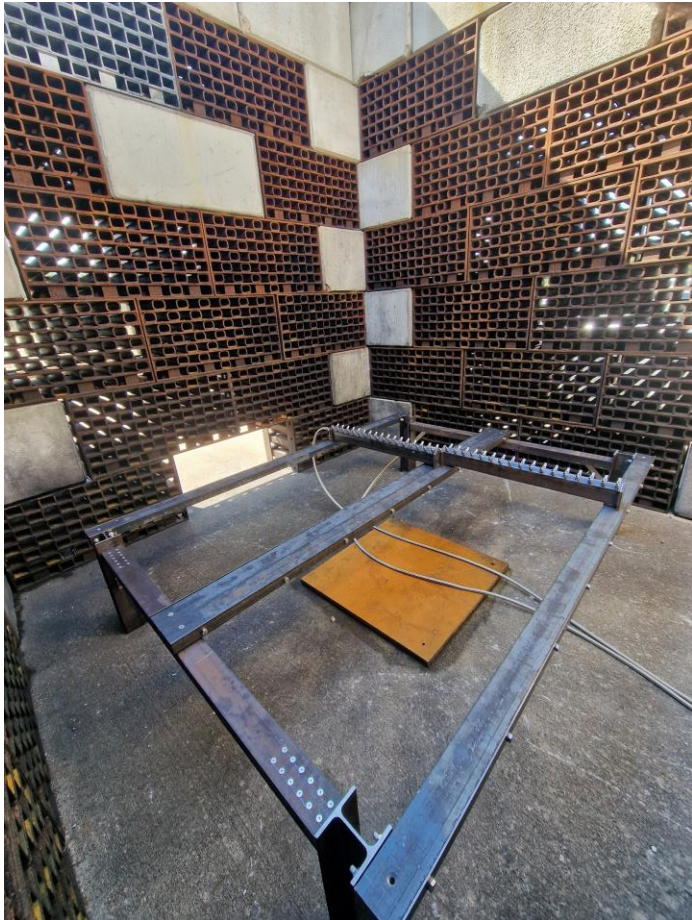
## ➤ Overview burner configurations



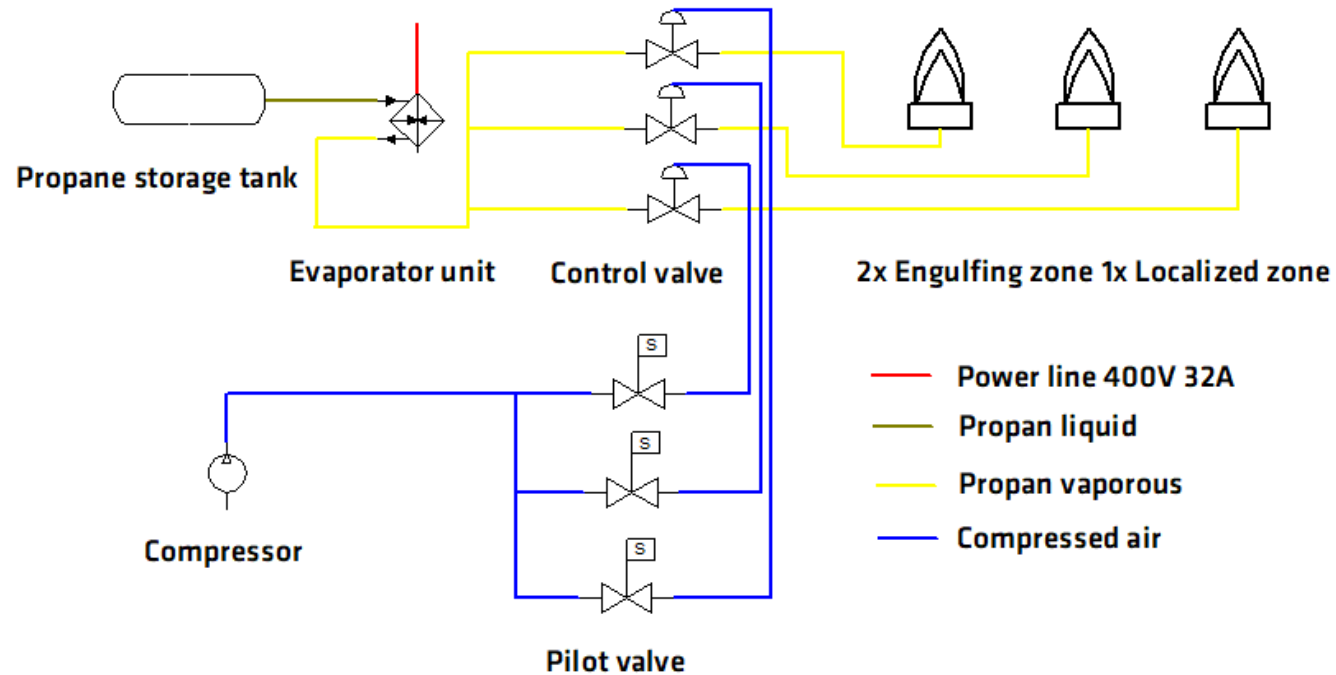


# Development of experimental setup

## ➤ Implementation of burner configurations



## ➤ Experimental setup and gas supply



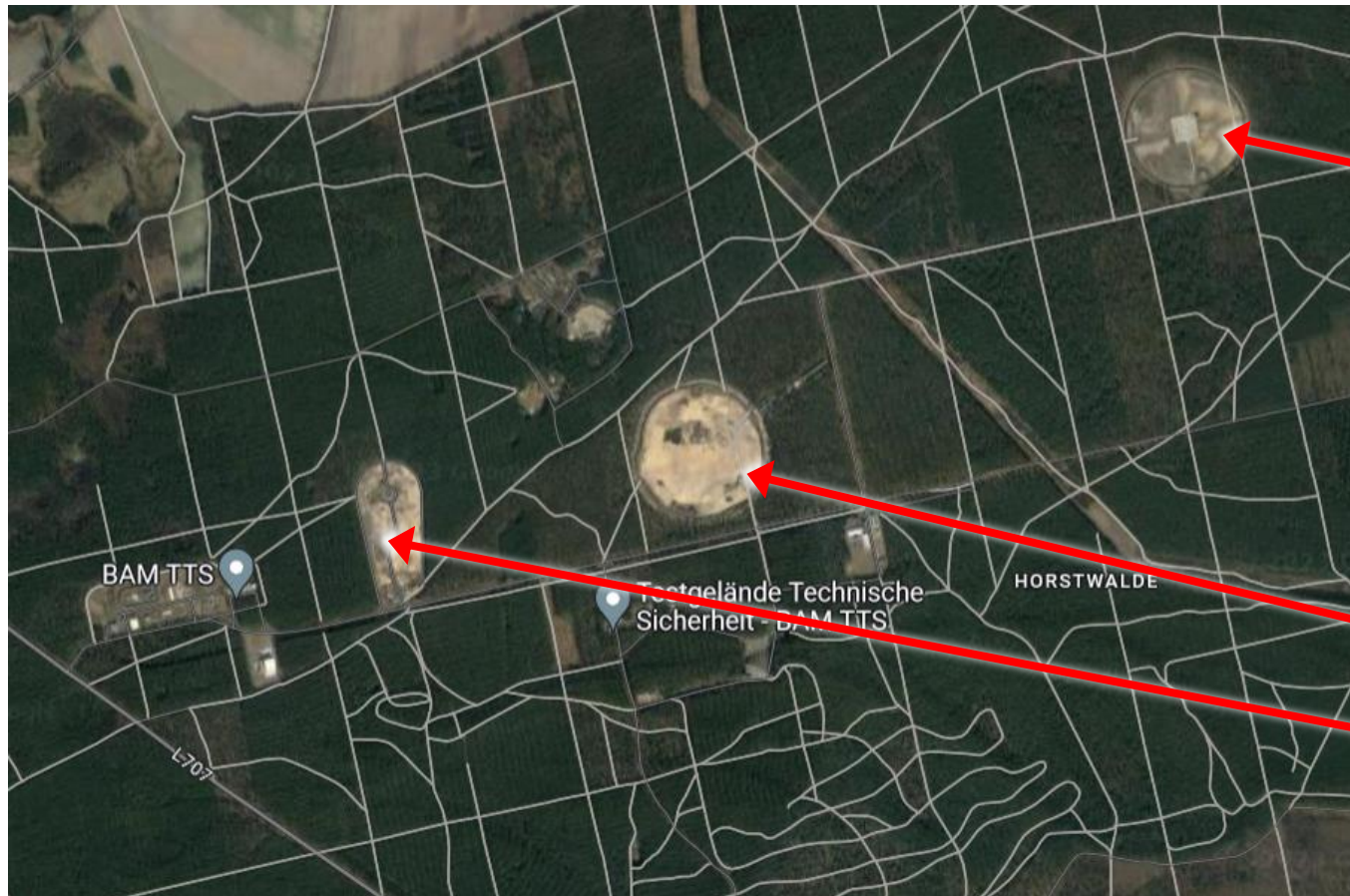
Test Areal H2 Safety





# Development of experimental setup

## ➤ BAM's open air test site for fire tests (destructive tests)



Test Areal H2 Safety

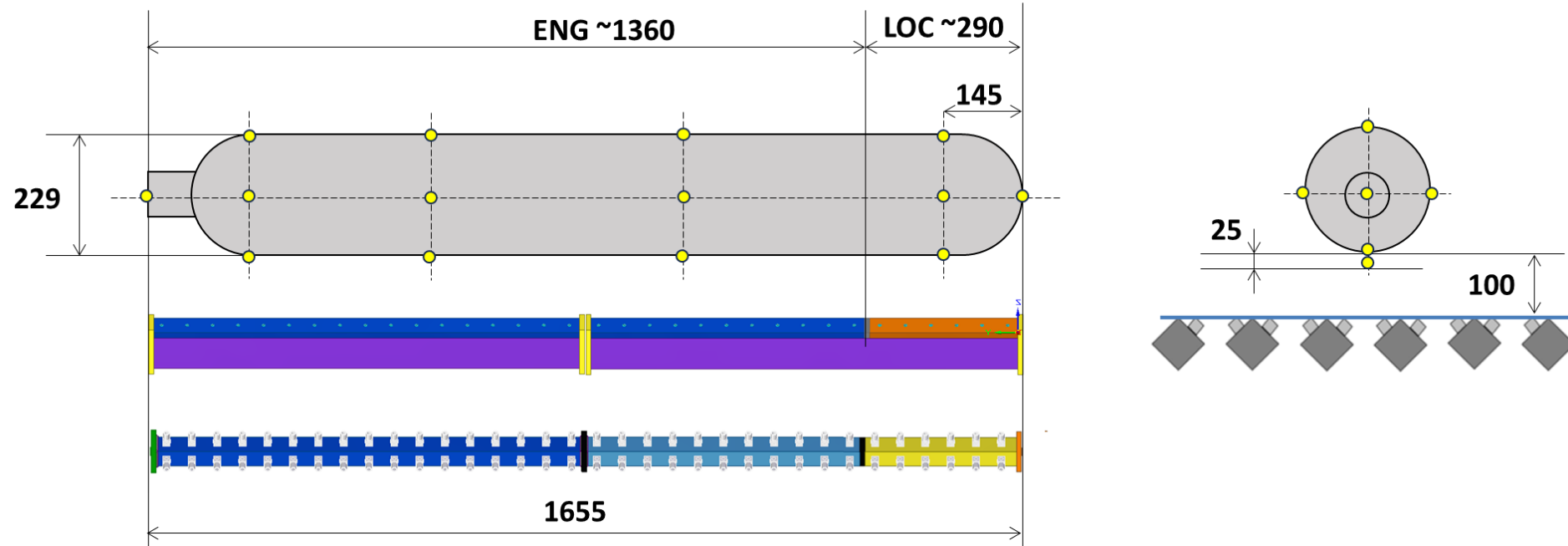


Explosion Ground No. 1

Fire test area for tanks



## ➤ Instrumentation of a reference vessel with thermocouples



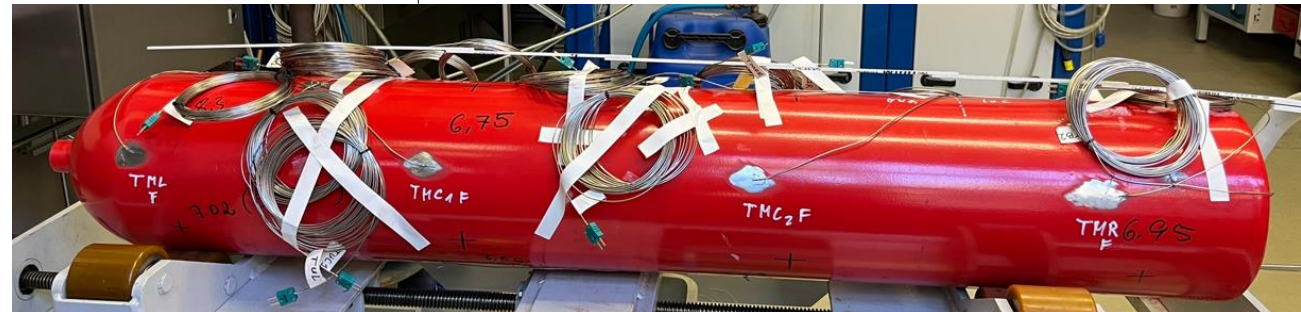
Dimensions:

D = 229 mm

L = 1450 mm

Thermocouples:

x22 Typ K thermocouples 1.5 mm

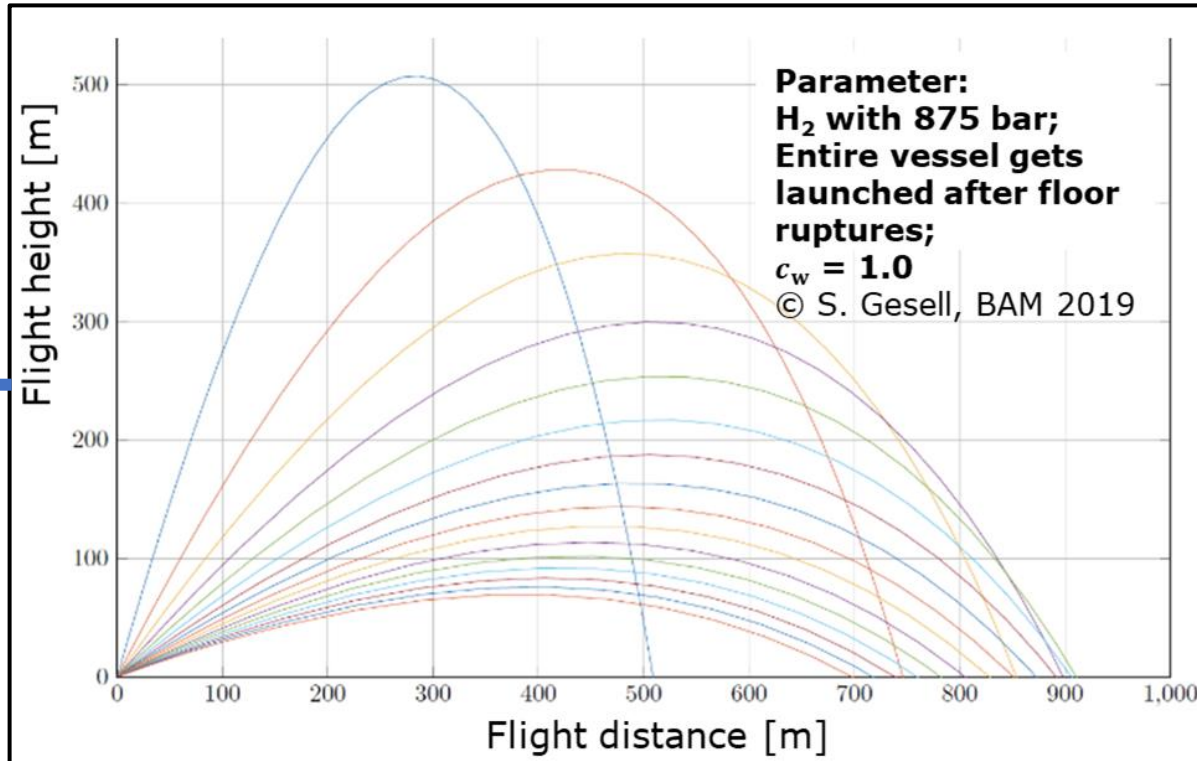


## ➤ Motivation and Background H2-Testing

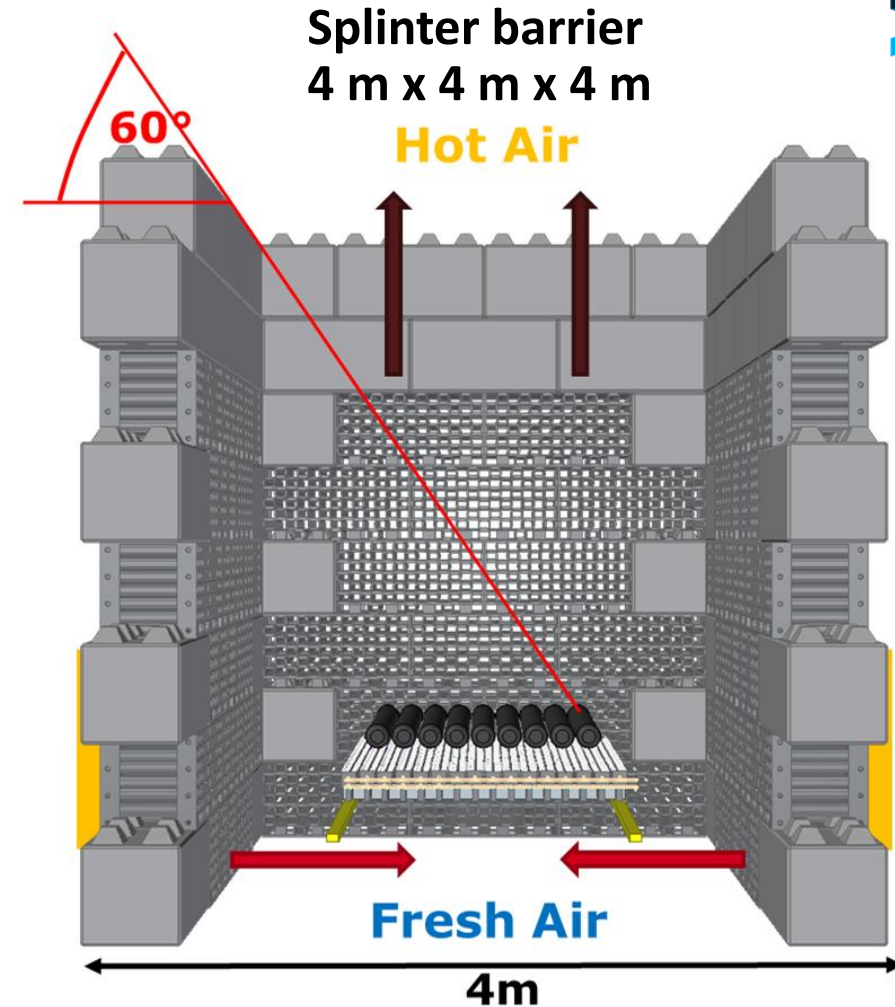
### ■ Requirements for splinter protection

- Reduce impact and fire loads for environment
- Gas storage systems with up to 700bar interior pressure (H<sub>2</sub>, CNG/LNG, LPG)
- Protection against **splinters** and **peak pressure**
- Reduction of restricted area to 500m radius at BAMs test site (TTS)

# Verification and qualification



Splinter flight dependent on  
departure angle

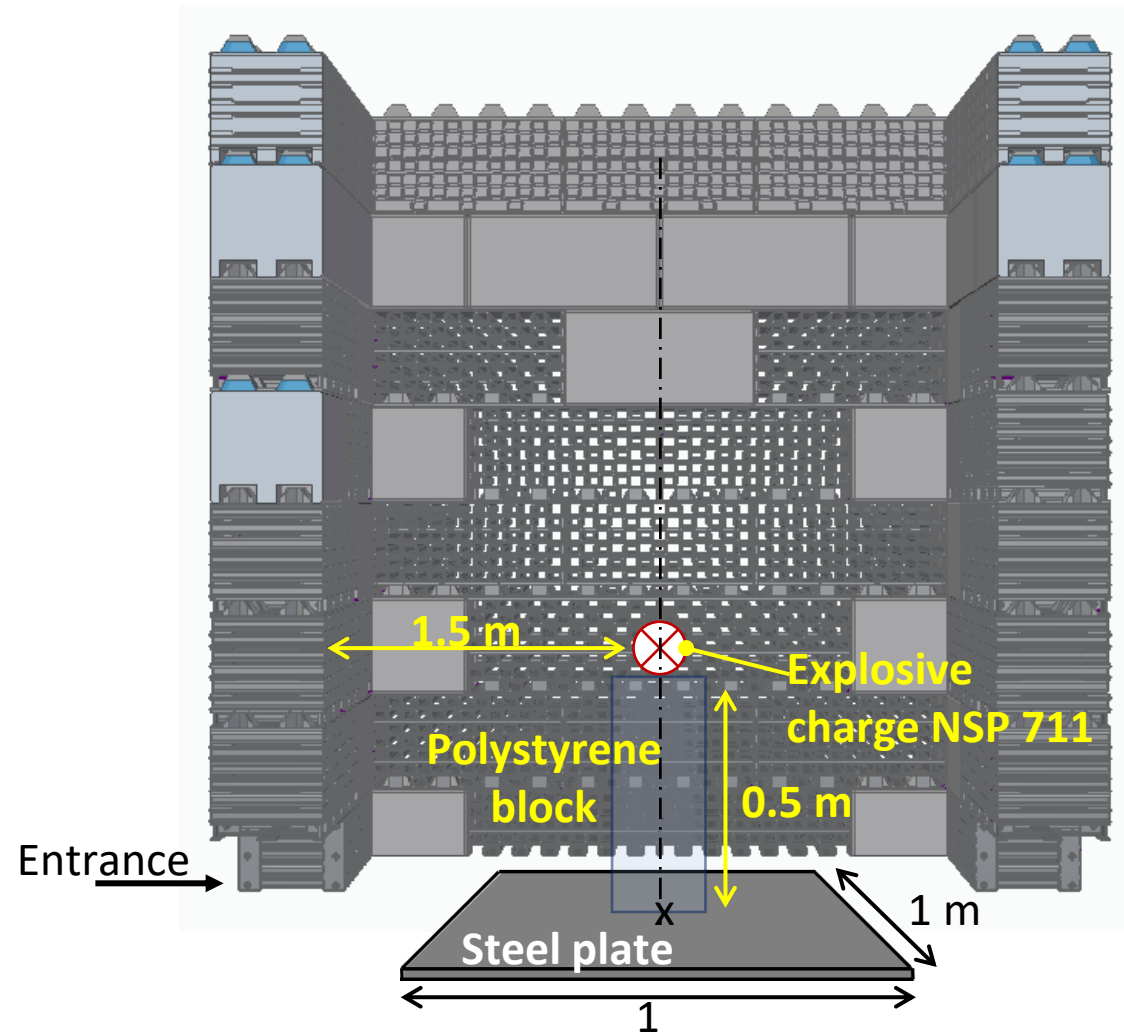
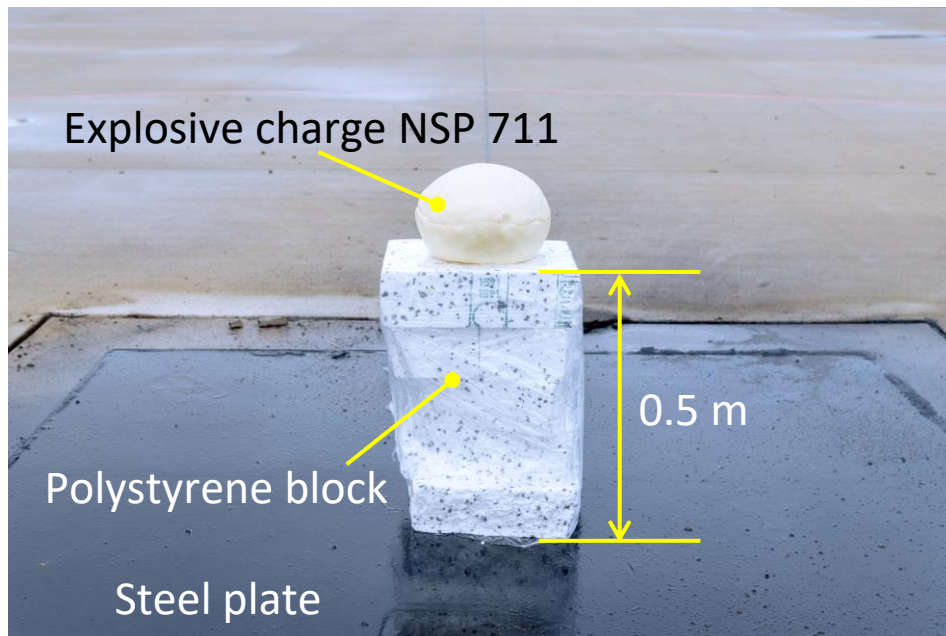


**Qualification?**

# Verification and qualification

## ➤ Blast impact tests

- Test conditions 14 blast tests
- 1 kg up to 10 kg TNT equiv.

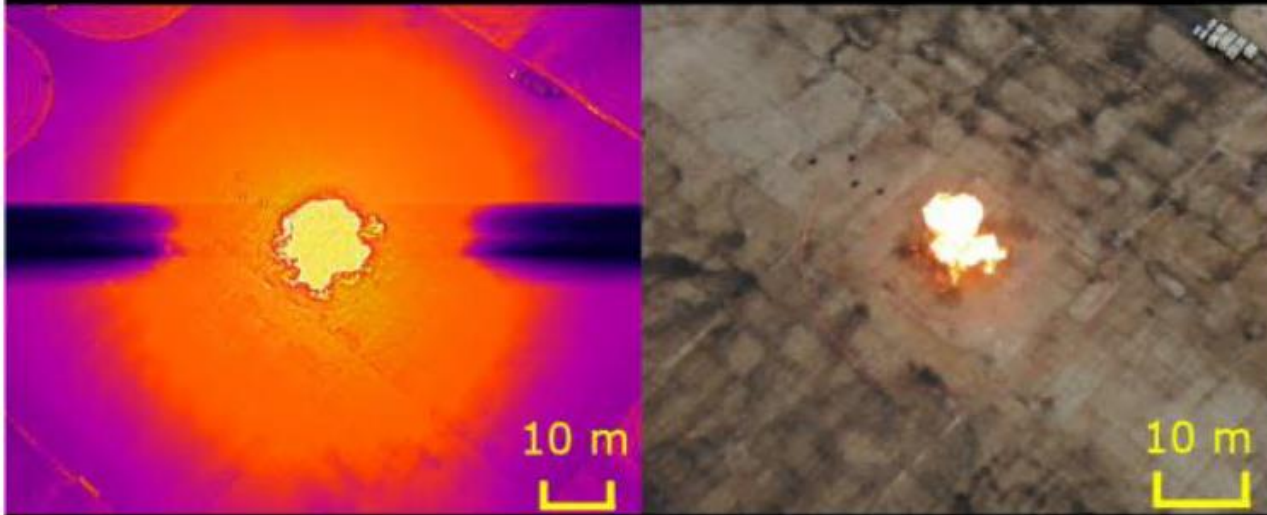




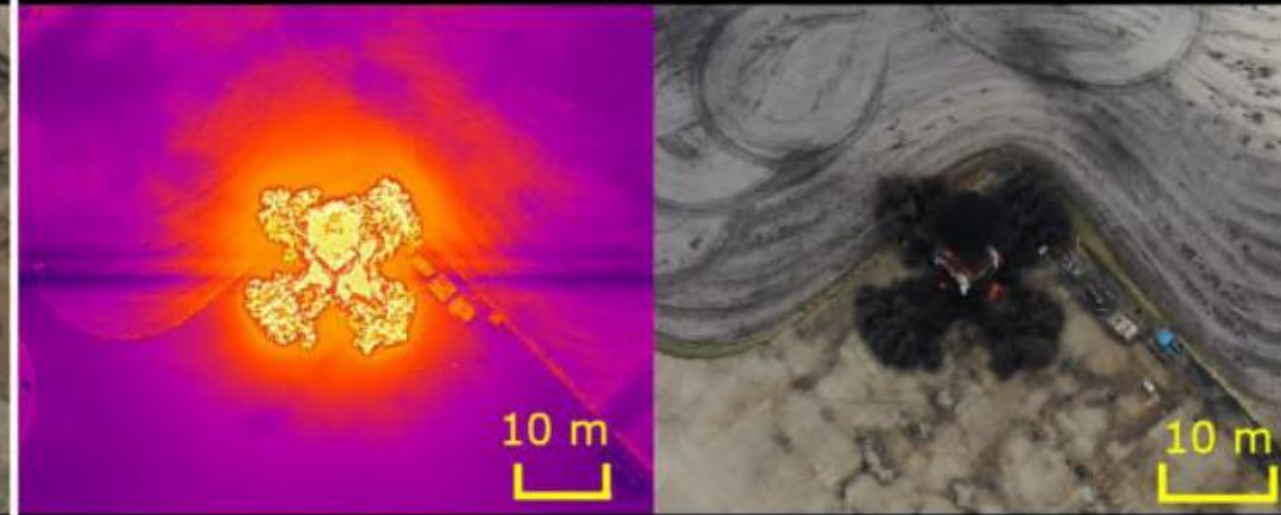
# Verification and qualification

➤ Tests with the highest blast load ( $M_{TNT} = 10$  kg)

**Free-field**



**Splinter barrier**





## ➤ Wind measurement

### ■ Test conditions

- Measurement period: December 2023 to January 2024
- Duration: approx. 1 month

### ■ Measurements and results

- Meteks ultrasonic anemometer (USA) uSonic-3, uSonic-2 and uSonic-1 are world leading sensors recognized for measuring wind and turbulence... source: Metek
- 1x uSonic 3 Scientific/Neo with turbulence expansion
- 1x uSonic 3 Omni



source: Metek

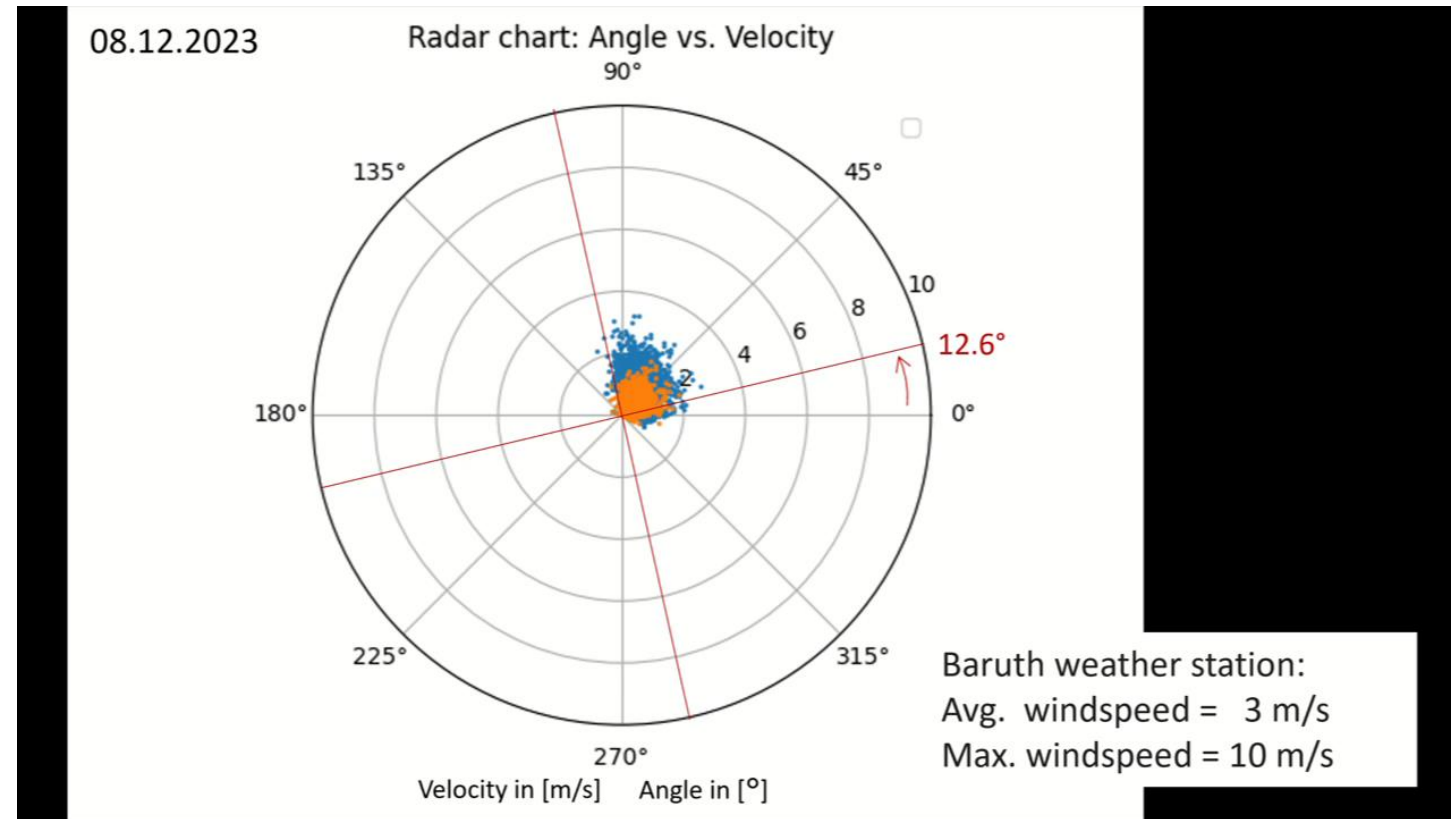
# Verification and qualification



## ➤ Wind measurements

- Local wind speed measurements including python software development
- 8640 lines/file 84 files over all
- Reduction of wind speed inside of barrier for fire testing
- Wind damping ~ 40%

● Inside of barrier ● Outside of barrier



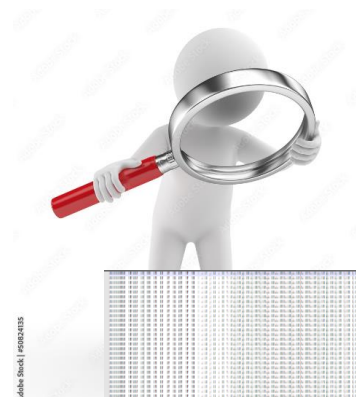
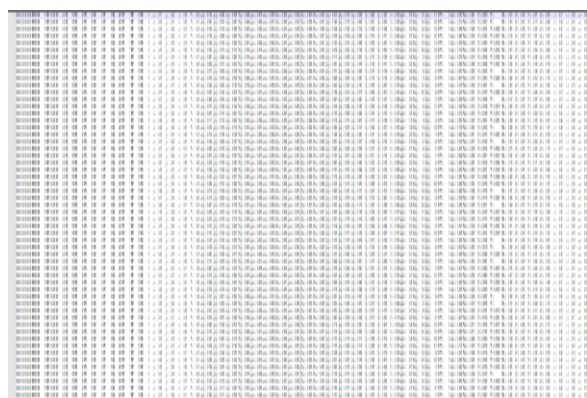
# Verification and qualification

Data collection  
(raw data )

create  
Data frame

Analysis of  
usable data

find matches  
line/file



line i (.inn)  
line i (.out)  
„timestamp“

```
3377 2024-01-05 09:18:37;E:invalid data (000)
3378 2024-01-05 09:18:47;M:x =      y =      z =      t =
3379 2024-01-05 09:18:47;E:invalid data (000)
3380 2024-01-05 09:18:57;M:x = 145 y = -52 z = -48 t = -83
3381 2024-01-05 09:18:57;E:quality < 10%
3382 2024-01-05 09:19:07;M:x = 133 y = -106 z = 5 t = -84
3383 2024-01-05 09:19:07;E:quality < 10%
3384 2024-01-05 09:19:17;M:x = 123 y = -41 z = -18 t = -78
3385 2024-01-05 09:19:17;E:quality < 10%
3386 2024-01-05 09:19:27;M:x = 111 y = -21 z = 24 t = -75
3387 2024-01-05 09:19:27;E:quality < 50%
3388 2024-01-05 09:19:37;M:x = 126 y = -28 z = 9 t = -72
3389 2024-01-05 09:19:47;M:x = 74 y = -54 z = -20 t = -71
```



- Fire tests according to GTR 13 are carried out at TTS
- Specific heat release rate is achievable with BAMs fire test stand by using an LPG vaporizer
- Fire test parameters have been investigated and evaluated
- LPG and Hydrogen can be used as fuel gas in order to realize localized and engulfing fire zones

# THANK YOU

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3.5: Safety of Gas Storage Systems



This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.



Storage of Hydrogen  
Alternative Pressure Enclosure Development

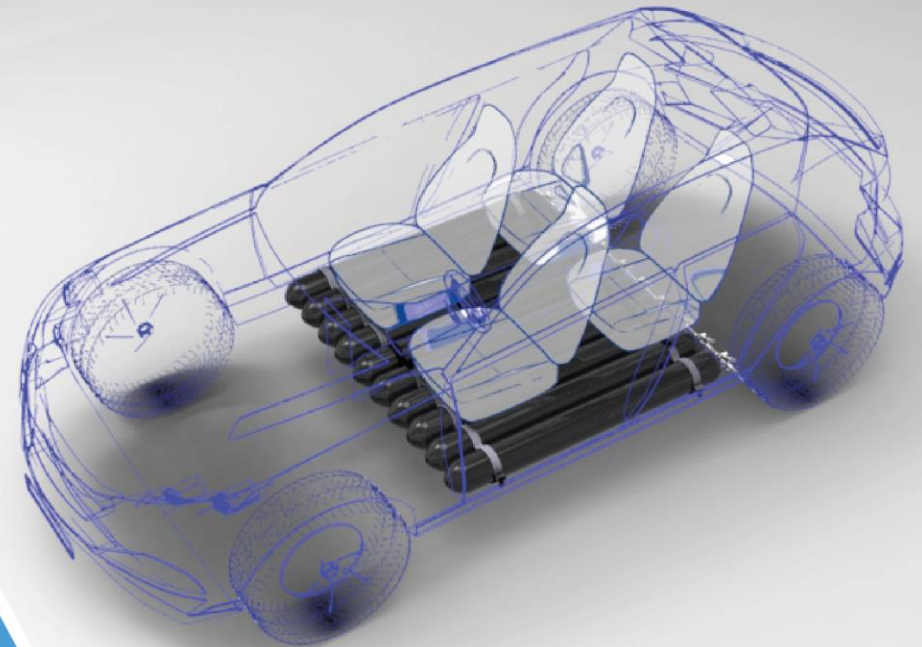


# Results of TPRD testing

Stakeholder's workshop, Brussel – 27/09/2024

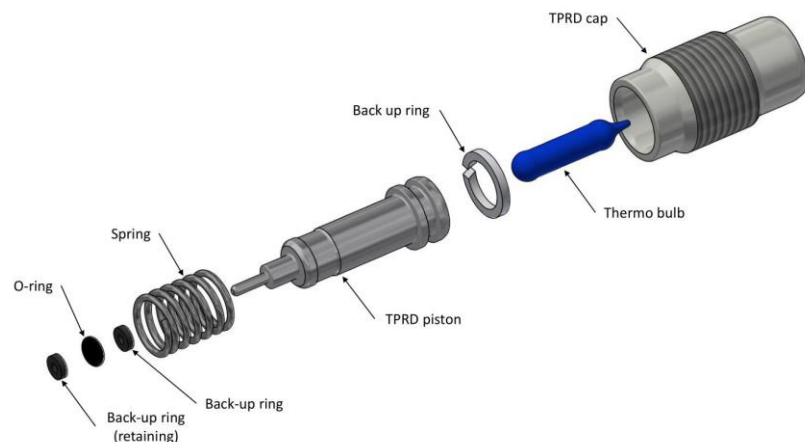
OMB Saleri Spa SB

PM: Elisabetta Dal Gal



[www.sh2aped.eu](http://www.sh2aped.eu)

# Validation tests in previous project



## EP Gen1 validation

### Seq 2 (6x EP)

- 2.1 Ext leakage test (3T)
- 2.2 K-01 High Low Temperature Storage
- 2.3 Ext leakage test (3T)
- 2.4 Dust Test
- 2.5 Ext leakage test (3T)
- 2.6 Mechanical Shock
- 2.7 Ext leakage test (3T)
- 2.8 Vibration Test
- 2.9 Ext leakage test (3T)
- 2.10 Thermal Shock Immersion
- 2.11 Ext leakage test (3T)
- 2.12 Water Protection
- 2.13 Int/Ext Leak test (3T)
- 2.14 High Pressure Steam-Jet cleaning
- 2.15 Int/Ext Leak test (3T)
- 2.16 Burst Test (1x EP)

### Seq 5 (3x EO)

- 5.1 Leakage test (3T)
- 5.2 High/Low Temperature Storage
- 5.3 Leakage test (3T)
- 5.4 Alternating climate corrosion
- 5.5 Leakage test (3T)

## OTV Gen1 validation

### Seq 3 (3x OTV)

- 3.1 Leakage test (3T)
- 3.2 K-01 High Low Temperature Storage
- 3.3 Leakage test (3T)
- 3.4 Lifetime Cycle Test
- 3.5 Burst Test

### Seq 4 (6x OTV)

- 4.1 Int/Ext leakage test (3T)
- 4.2 K-01 High Low Temperature Storage
- 4.3 Int/Ext leakage test (3T)
- 4.4 Dust Test
- 4.5 Int/Ext leakage test (3T)
- 4.6 Mechanical Shock
- 4.7 Int/Ext leakage test (3T)
- 4.8 Vibration Test
- 4.9 Int/Ext leakage test (3T)
- 4.10 Thermal Shock Immersion
- 4.11 Int/Ext leakage test (3T)
- 4.12 Water Protection
- 4.13 Int/Ext Leak test (3T)
- 4.14 High Pressure Steam-Jet cleaning
- 4.15 Int/Ext Leak test (3T)
- 4.16 Burst Test

### Seq 5 (3x OTV)

- 5.1 Leakage test (3T)
- 5.2 K-03 Low Temperature Operation
- 5.3 Leakage test (3T)
- 5.4 Lifetime Cycle Test
- 5.5 Burst Test

### Seq 6 (1x OTV)

- 6.1 Leakage test (3T)
- 6.2 Hydraulic Pressure Cycle Test
- 6.3 Leakage test (3T)
- 6.4 Burst Test

### Seq 8 (6x OTV)

- 8.1 Leakage test (3T)
- 8.2 High/Low Temperature Storage
- 8.3 Leakage test (3T)

### Seq 9 (6x OTV)

- 9.1 Leakage test (3T)
- 9.2 High/Low Temperature Storage
- 9.3 Leakage test (3T)
- 9.4 Temperature Cycle Endurance Test
- 9.5 Leakage test (3T)

### Seq 10 (3x OTV)

- 10.1 Leakage test (3T)
- 10.2 High/Low Temperature Storage
- 10.3 Leakage test (3T)
- 10.4 Damp Heat, Cyclic (with frost)
- 10.5 Leakage test (3T)
- 10.6 Free Fall
- 10.7 Leakage test (3T)
- 10.8 Burst test (1 OTV)

### Seq 11 (3x OTV)

- 11.1 Leakage test (3T)
- 11.2 High/Low Temperature Storage
- 11.3 Leakage test (3T)
- 11.4 Alternating climate corrosion
- 11.5 Leakage test (3T)



# Certifications and R134 tests

## CERTIFICATIONS

|                   |
|-------------------|
| EC 79/2009        |
| EU535/2021        |
| ANSI HGV 3.1-2015 |
| HPRD 1:2021       |
| R134              |

## Test Plan acc. ECE-R134 Annex 4

| ECE R 134<br>Ann. 4 | Test                                         | Remarks | Results |
|---------------------|----------------------------------------------|---------|---------|
| 1.                  | <b>TPRD Qualification Performance Tests:</b> |         |         |
| 1.1.                | Pressure cycling test                        | -       | passed  |
| 1.2.                | Accelerated life test                        | -       | passed  |
| 1.3.                | Temperature cycling test                     | -       | passed  |
| 1.4.                | Salt corrosion resistance test               | -       | passed  |
| 1.5.                | Vehicle environment test                     | -       | passed  |
| 1.6.                | Stress corrosion cracking test               | n/a     | n/a     |
| 1.7.                | Drop and vibration test                      | -       | passed  |
| 1.8.                | Leak test                                    | -       | passed  |
| 1.9.                | Bench top activation test                    | -       | passed  |
| 1.10.               | Flow rate test                               | -       | passed  |

## 1.1. Pressure cycling test

tested acc. **ECE R 134** Annex 4 Section 1.1.

## Test description

Five TPRD units undergo 11,000 internal pressure cycles with hydrogen gas having gas quality compliant with ISO 14687-2/SAE J2719. The first five pressure cycles are between 2 ( $\pm 1$ ) MPa and 150 per cent NWP ( $\pm 1$  MPa); the remaining cycles are between 2 ( $\pm 1$ ) MPa and 125 per cent NWP ( $\pm 1$  MPa). The first 1,500 pressure cycles are conducted at a TPRD temperature of 85 °C or higher. The remaining cycles are conducted at a TPRD temperature of 55 ( $\pm 5$ ) °C. The maximum pressure cycling rate is ten cycles per minute.

## Test parameter settings

| NWP<br>[MPa] | step | Test<br>temperature<br>[°C] | pressure<br>cycles | cycle rate<br>[cycle/min] | Pressure [MPa] |       | Test medium |
|--------------|------|-----------------------------|--------------------|---------------------------|----------------|-------|-------------|
|              |      |                             |                    |                           | lower          | upper |             |
| 70.0         | 1    | + 85                        | 5                  | < 10                      | 2.0            | 105.0 | Hydrogen    |
|              | 2    | + 85                        | 1,495              | < 10                      | 2.0            | 87.5  |             |
|              | 3    | + 55                        | 9,500              | < 10                      | 2.0            | 87.5  |             |

## Test samples

| No. | Sample number | Description | Requirements                     | Result |
|-----|---------------|-------------|----------------------------------|--------|
| 1   | 1809006961    | virgin part | requirements of subsequent tests | passed |
| 2   | 1809006962    | virgin part |                                  | passed |
| 3   | 1809006963    | virgin part |                                  | passed |
| 4   | 1809006964    | virgin part |                                  | passed |
| 5   | 1809006965    | virgin part |                                  | passed |

## Requirements (subsequent tests)

| Requirements (subsequent tests)  | Result: |
|----------------------------------|---------|
| leak test (1.8.)                 | passed  |
| Bench top activation test (1.9.) | passed  |
| Flow rate test (1.10.)           | passed  |

# R134 tests - I

| 1.2. Accelerated life test                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |               |                                       |                                              |                     |              |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|---------------------------------------|----------------------------------------------|---------------------|--------------|
| tested acc.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |               | ECE R 134                             |                                              | Annex 4             | Section 1.2. |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |               |                                       |                                              |                     |              |
| Test description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |               |                                       |                                              |                     |              |
| Eight TPRD units undergo testing; three at the manufacturer's specified activation temperature, $T_{act}$ , and five at an accelerated life temperature, $T_{life} = 9.1 \times T_{act} - 50.3$ . The TPRD is placed in an oven or liquid bath with the temperature held constant ( $\pm 1^\circ\text{C}$ ). The hydrogen gas pressure on the TPRD inlet is 125 per cent NWP ( $\pm 1$ MPa). The pressure supply may be located outside the controlled temperature oven or bath. Each device is pressured individually or through a manifold system. If a manifold system is used, each pressure connection includes a check valve to prevent pressure depletion of the system when one specimen fails. The three TPRDs tested at $T_{act}$ shall activate in less than ten hours. The five TPRDs tested at $T_{life}$ shall not activate in less than 500 hours. |               |                                       |                                              |                     |              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |               |                                       |                                              |                     |              |
| Test parameter settings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |               |                                       |                                              |                     |              |
| NWP [MPa]                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | step          | Test temperature [ $^\circ\text{C}$ ] | Test Pressure [MPa]                          | test duration t [h] | Test medium  |
| 70.0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 1             | + 110 ( $T_{act}$ )                   | 87.5                                         | < 10                | Hydrogen     |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 2             | + 97 ( $T_{life}$ )                   | 87.5                                         | > 500               |              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |               |                                       |                                              |                     |              |
| Test samples                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |               |                                       |                                              |                     |              |
| No.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Sample number | Description                           | Requirements                                 |                     | Result       |
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 1708004121    | virgin part                           | $T_{act} < 10$ h<br>when tested acc. step 1  |                     | passed       |
| 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 1708004131    | virgin part                           |                                              |                     | passed       |
| 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 1708004136    | virgin part                           |                                              |                     | passed       |
| 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 1708004123    | virgin part                           | $T_{act} > 500$ h<br>when tested acc. step 2 |                     | passed       |
| 5                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 1708004125    | virgin part                           |                                              |                     | passed       |
| 6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 1708004126    | virgin part                           |                                              |                     | passed       |
| 7                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 1708004129    | virgin part                           |                                              |                     | passed       |
| 8                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 1708004134    | virgin part                           |                                              |                     | passed       |

| 1.3. Temperature cycling test                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |               |                       |                                  |                                        |                |                |             |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|-----------------------|----------------------------------|----------------------------------------|----------------|----------------|-------------|
| tested acc.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |               | ECE R 134             |                                  | Annex 4                                | Section 1.3.   |                |             |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |               |                       |                                  |                                        |                |                |             |
| Test description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |               |                       |                                  |                                        |                |                |             |
| <p>(a) An unpressurized TPRD is placed in a liquid bath maintained at -40 °C or lower at least two hours. The TPRD is transferred to a liquid bath maintained at +85 °C or higher within five minutes, and maintained at that temperature at least two hours. The TPRD is transferred to a liquid bath maintained at -40 °C or lower within five minutes;</p> <p>(b) Step (a) is repeated until 15 thermal cycles have been achieved;</p> <p>(c) With the TPRD conditioned for a minimum of two hours in the -40 °C or lower liquid bath, the internal pressure of the TPRD is cycled with hydrogen gas between 2 MPa (+1/-0 MPa) and 80 per cent NWP (+2/-0 MPa) for 100 cycles while the liquid bath is maintained at -40 °C or lower;</p> <p>(d) Following the thermal and pressure cycling, the pressure relief device shall comply with the requirements of Leak test (Annex 4, paragraph 1.8.), except that the Leak test shall be conducted at -40 °C (+5/-0 °C). After the Leak test, the TPRD shall comply with the requirements of Bench top activation test (Annex 4, paragraph 1.9.) and then Flow rate test (Annex 4, paragraph 1.10.).</p> |               |                       |                                  |                                        |                |                |             |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |               |                       |                                  |                                        |                |                |             |
| Test parameter settings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |               |                       |                                  |                                        |                |                |             |
| NWP [MPa]                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | step          | Test temperature [°C] |                                  | Cycles                                 | Pressure [MPa] |                | Test medium |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |               | t <sub>1</sub>        | t <sub>2</sub>                   |                                        | p <sub>1</sub> | p <sub>2</sub> |             |
| 70.0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 1             | - 40                  | + 85                             | 15 (t <sub>1</sub> - t <sub>2</sub> )  | unpressurized  |                | n/a         |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 2             | - 40                  | n/a                              | 100 (p <sub>1</sub> - p <sub>2</sub> ) | 2.0            | 70.0           | Hydrogen    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |               |                       |                                  |                                        |                |                |             |
| Test samples                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |               |                       |                                  |                                        |                |                |             |
| No.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Sample number | Description           | Requirements                     |                                        |                | Result         |             |
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 1650006687    | virgin part           | requirements of subsequent tests |                                        |                | passed         |             |
| Requirements (subsequent tests)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |               |                       |                                  |                                        |                |                | Result:     |
| leak test (but conducted at -40°C only) (1.8.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |               |                       |                                  |                                        |                |                | passed      |
| Bench top activation test (1.9.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |               |                       |                                  |                                        |                |                | passed      |
| Flow rate test (1.10.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |               |                       |                                  |                                        |                |                | passed      |

# R134 tests - II

| 1.4 Salt Corrosion Resistance test                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                                     |                              |                                  |         |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|------------------------------|----------------------------------|---------|
| tested acc.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | ECE R 134                                                                           | Annex 4                      | Section 1.4                      |         |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                                     |                              |                                  |         |
| Test description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                     |                              |                                  |         |
| Two TPRD units are tested. Any non-permanent outlet caps are removed. Each TPRD unit is installed in a test fixture in accordance with the manufacturer's recommended procedure so that external exposure is consistent with realistic installation. Each unit is exposed for 500 hours to a salt spray (fog) test as specified in ASTM B117 (Standard Practice for Operating Salt Spray (Fog) Apparatus) except that in the test of one unit, the pH of the salt solution shall be adjusted to 4.0 ± 0.2 by the addition of sulphuric acid and nitric acid in a 2:1 ratio, and in the test of the other unit, the pH of the salt solution shall be adjusted to 10.0 ± 0.2 by the addition of sodium hydroxide. The temperature within the fog chamber is maintained at 30-35 °C).<br>Following these tests, each pressure relief device shall comply with the requirements of<br>Leak test (Annex 3, paragraph 6.1.8.),<br>Flow rate test (Annex 3, paragraph 6.1.10.) and<br>Bench top activation test (Annex 3, paragraph 6.1.9.). |                                                                                     |                              |                                  |         |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                                     |                              |                                  |         |
| Test parameter settings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                                                                     |                              |                                  |         |
| step                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Test medium fog<br>(Salt Spray)                                                     | Test temperature<br>[°C]     | Test duration<br>[h]             |         |
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | ph 4.0 ± 0.2<br>by the addition of sulphuric acid and<br>nitric acid in a 2:1 ratio | 30 - 35                      | 500                              |         |
| 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | ph 10.0 ± 0.2<br>by the addition of sodium hydroxide                                |                              | 500                              |         |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                                     |                              |                                  |         |
| Test samples                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                                                                     |                              |                                  |         |
| No.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Sample number                                                                       | description / previous test  | Requirements                     | Result  |
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 1650000825                                                                          | virgin part, used for step 1 | requirements of subsequent tests | passed  |
| 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 1650000828                                                                          | virgin part, used for step 2 |                                  | passed  |
| Requirements (subsequent tests)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                                     |                              |                                  | Result: |
| leak test (1.8.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                     |                              |                                  | passed  |
| Bench top activation test (1.9.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                     |                              |                                  | passed  |
| Flow rate test (1.10.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                     |                              |                                  | passed  |

| 1.5 Vehicle environment test                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                   |                                     |                                                                                                                                                                          |                      |
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| tested acc.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | ECE R 134                                                         | Annex 4                             | Section 1.5.                                                                                                                                                             |                      |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                   |                                     |                                                                                                                                                                          |                      |
| Test description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                   |                                     |                                                                                                                                                                          |                      |
| <p>(a) The inlet and outlet connections of the TPRD are connected or capped in accordance with the manufacturers installation instructions. The external surfaces of the TPRD are exposed for 24 hours at 20 (±5) °C to each of the following fluids:</p> <p>(i) Sulphuric acid (19 per cent solution by volume in water);</p> <p>(ii) Sodium hydroxide (25 per cent solution by weight in water);</p> <p>(iii) Ammonium nitrate (28 per cent by weight in water); and</p> <p>(iv) Windshield washer fluid (50 per cent by volume methyl alcohol and water).</p> <p>The fluids are replenished as needed to ensure complete exposure for the duration of the test. A distinct test is performed with each of the fluids. One component may be used for exposure to all of the fluids in sequence.</p> <p>(b) After exposure to each fluid, the component is wiped off and rinsed with water;</p> <p>(c) The component shall not show signs of physical degradation that could impair the function of the component, specifically: cracking, softening, or swelling. Cosmetic changes such as pitting or staining are not failures.</p> <p>At the conclusion of all exposures, the unit(s) shall comply with the requirements of</p> <p>Leak test (Annex 4, paragraph 1.8.),</p> <p>Flow rate test (Annex 4, paragraph 1.10.) and</p> <p>Bench top activation test (Annex 4, paragraph 1.9.).</p> |                                                                   |                                     |                                                                                                                                                                          |                      |
| Test parameter settings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                                                   |                                     |                                                                                                                                                                          |                      |
| step                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Test medium                                                       |                                     | Test temperature<br>[°C]                                                                                                                                                 | Test duration<br>[h] |
| (a)(i)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Sulphuric acid - 19 % solution by volume in water                 |                                     | 20                                                                                                                                                                       | 24                   |
| (a)(ii)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Sodium hydroxide - 25 % solution by weight in water               |                                     | 20                                                                                                                                                                       | 24                   |
| (a)(iii)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | Ammonium nitrate - 28 % by weight in water                        |                                     | 20                                                                                                                                                                       | 24                   |
| (a)(iv)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Windshield washer fluid (50 % by volume methyl alcohol and water) |                                     | 20                                                                                                                                                                       | 24                   |
| Test samples                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                   |                                     |                                                                                                                                                                          |                      |
| No.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Sample number                                                     | description / previous test         | Requirements                                                                                                                                                             | Result               |
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 1650000823                                                        | virgin part, used for step (a)(i)   | - no signs of physical degradation that could impair the function of the component, specifically: cracking, softening, or swelling<br>- requirements of subsequent tests | passed               |
| 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 1708004122                                                        | virgin part, used for step (a)(ii)  |                                                                                                                                                                          | passed               |
| 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 1708004124                                                        | virgin part, used for step (a)(iii) |                                                                                                                                                                          | passed               |
| 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 1708004132                                                        | virgin part, used for step (a)(iv)  |                                                                                                                                                                          | passed               |
| Requirements (subsequent tests)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                   |                                     |                                                                                                                                                                          | Result:              |
| leak test (1.8.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                   |                                     |                                                                                                                                                                          | passed               |
| Bench top activation test (1.9.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                   |                                     |                                                                                                                                                                          | passed               |
| Flow rate test (1.10.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                   |                                     |                                                                                                                                                                          | passed               |

# R134 tests - III

| 1.7 Drop and vibration test                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                 |                      |                                                                                                                                         |                       |                                                                                                                                            |        |
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| tested acc.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | ECE R 134                       | Annex 4              | Section 1.7.                                                                                                                            |                       |                                                                                                                                            |        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                 |                      |                                                                                                                                         |                       |                                                                                                                                            |        |
| Test description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                 |                      |                                                                                                                                         |                       |                                                                                                                                            |        |
| <p>(a) Six TPRD units are dropped from a height of 2 m at ambient temperature (<math>20 \pm 5\text{ }^{\circ}\text{C}</math> ) onto a smooth concrete surface. Each sample is allowed to bounce on the concrete surface after the initial impact. One unit is dropped in six orientations (opposing directions of 3 orthogonal axes: vertical, lateral and longitudinal). If each of the six dropped samples does not show visible exterior damage that indicates that the part is unsuitable for use, it shall proceed to step (b) ;</p> <p>(b) Each of the six TPRD units dropped in step (a) and one additional unit not subjected to a drop are mounted in a test fixture in accordance with manufacturer's installation instructions and vibrated 30 minutes along each of the three orthogonal axes (vertical, lateral and longitudinal) at the most severe resonant frequency for each axis. The most severe resonant frequencies are determined using an acceleration of 1.5 g and sweeping through a sinusoidal frequency range of 10 to 500 Hz within 10 minutes. The resonance frequency is identified by a pronounced increase in vibration amplitude. If the resonance frequency is not found in this range, the test shall be conducted at 40 Hz.</p> <p>Following this test, each sample shall not show visible exterior damage that indicates that the part is unsuitable for use. It shall subsequently comply with the requirements of</p> <p>Leak test (Annex 4, paragraph 1.8.),</p> <p>Flow rate test (Annex 4, paragraph 1.10.) and</p> <p>Bench top activation test (Annex 4, paragraph 1.9.).</p> |                                 |                      |                                                                                                                                         |                       |                                                                                                                                            |        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                 |                      |                                                                                                                                         |                       |                                                                                                                                            |        |
| Test parameter settings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                                 |                      |                                                                                                                                         |                       |                                                                                                                                            |        |
| Test frequency<br>[Hz]                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Test duration per axis<br>[min] | Acceleration<br>[g]  | Test temperature<br>[°C]                                                                                                                |                       |                                                                                                                                            |        |
| 40                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | x: 30; y:30; z:30               | 1.5                  | ambient                                                                                                                                 |                       |                                                                                                                                            |        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                 |                      |                                                                                                                                         |                       |                                                                                                                                            |        |
| Test samples                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                 |                      |                                                                                                                                         |                       |                                                                                                                                            |        |
| No.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Sample<br>number                | description          | Requirements<br>Drop (a)                                                                                                                | Result<br>of step (a) | Requirements<br>vibration (b)                                                                                                              | Result |
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 1650006697                      | Drop + Vibration     | proceed with step<br>(b) vibration only<br>if no visible<br>exterior damage<br>that indicates that<br>the part is<br>unsuitable for use | unsuitable for (b)    | - no visible<br>exterior damage<br>that indicates<br>that the part is<br>unsuitable for<br>use<br>- requirements<br>of subsequent<br>tests | n/a    |
| 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 1650006714                      |                      |                                                                                                                                         | unsuitable for (b)    |                                                                                                                                            | n/a    |
| 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 1650006715                      |                      |                                                                                                                                         | unsuitable for (b)    |                                                                                                                                            | n/a    |
| 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 1650006717                      |                      |                                                                                                                                         | ok                    |                                                                                                                                            | passed |
| 5                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 1650006721                      |                      |                                                                                                                                         | unsuitable for (b)    |                                                                                                                                            | n/a    |
| 6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 1650006724                      |                      |                                                                                                                                         | ok                    |                                                                                                                                            | passed |
| 7                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 1650006727                      | virgin part vibrated | n/a                                                                                                                                     | n/a                   |                                                                                                                                            | passed |
| Requirements (subsequent tests)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                 |                      |                                                                                                                                         |                       | Result:                                                                                                                                    |        |
| leak test (1.8.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                 |                      |                                                                                                                                         |                       | passed                                                                                                                                     |        |
| Bench top activation test (1.9.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                 |                      |                                                                                                                                         |                       | passed                                                                                                                                     |        |
| Flow rate test (1.10.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                 |                      |                                                                                                                                         |                       | passed                                                                                                                                     |        |

| 1.8 Leak test                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                |                                       |                                                       |                                                       |                      |        |
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| tested acc.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | ECE R 134 Annex 4 Section 1.8. |                                       |                                                       |                                                       |                      |        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                |                                       |                                                       |                                                       |                      |        |
| Test description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                |                                       |                                                       |                                                       |                      |        |
| <p>A TPRD that has not undergone previous testing is tested at ambient, high and low temperatures without being subjected to other design qualification tests. The unit is held for one hour at each temperature and test pressure before testing. The three temperature test conditions are:</p> <p>(a) Ambient temperature: condition the unit at 20 (±5) °C; test at 5 % NWP (+0/-2 MPa) and 150 % NWP (+2/-0 MPa);</p> <p>(b) High temperature: condition the unit at 85 °C or higher; test at 5 % NWP (+0/-2 MPa) and 150 % NWP (+2/-0 MPa);</p> <p>(c) Low temperature: condition the unit at -40 °C or lower; test at 5 % NWP (+0/-2 MPa) and 100 % NWP (+2/-0 MPa).</p> <p>Additional units undergo leak testing as specified in other tests in Annex 4, paragraph 1. with uninterrupted exposure at the temperature specified in those tests.</p> <p>At all specified test temperatures, the unit is conditioned for one minute by immersion in a temperature controlled fluid (or equivalent method). If no bubbles are observed for the specified time period, the sample passes the test. If bubbles are detected, the leak rate is measured by an appropriate method. The total hydrogen leak rate shall be less than 10 Nm<sup>3</sup>/hr.</p> |                                |                                       |                                                       |                                                       |                      |        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                |                                       |                                                       |                                                       |                      |        |
| Test parameter settings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                |                                       |                                                       |                                                       |                      |        |
| NWP [MPa]                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | step                           | Temperature<br>t [°C]                 | 1 <sup>st</sup> test pressure<br>p <sub>t</sub> [MPa] | 2 <sup>nd</sup> test pressure<br>p <sub>t</sub> [MPa] | Test medium          |        |
| 70.0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | (a)                            | 20                                    | 3.5                                                   | 105.0                                                 | Hydrogen             |        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | (b)                            | +85                                   | 3.5                                                   | 105.0                                                 |                      |        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | (c)                            | -40                                   | 3.5                                                   | 70.0                                                  |                      |        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                |                                       |                                                       |                                                       |                      |        |
| Test samples                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                |                                       |                                                       |                                                       |                      |        |
| No.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Sample number                  | description / previous test           |                                                       | Comment                                               | Leak rate<br>[Ncc/h] | Result |
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 1708004130                     | virgin part                           |                                                       | -                                                     | ≤ 10                 | passed |
| 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 1809006961                     | Pressure cycling test (1.1.)          |                                                       | -                                                     | ≤ 10                 | passed |
| 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 1809006962                     |                                       |                                                       | -                                                     | ≤ 10                 | passed |
| 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 1809006963                     |                                       |                                                       | -                                                     | ≤ 10                 | passed |
| 5                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 1809006964                     |                                       |                                                       | -                                                     | ≤ 10                 | passed |
| 6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 1809006965                     |                                       |                                                       | -                                                     | ≤ 10                 | passed |
| 7                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 1650006687                     | Temperature cycling test (1.3.)       |                                                       | -                                                     | ≤ 10                 | passed |
| 8                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 1650000825                     | Salt Corrosion Resistance test (1.4.) |                                                       | -                                                     | ≤ 10                 | passed |
| 9                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 1650000828                     |                                       |                                                       | -                                                     | ≤ 10                 | passed |
| 10                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 1650006717                     | Vehicle environment test (1.5.)       |                                                       | -                                                     | ≤ 10                 | passed |
| 11                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 1708004122                     |                                       |                                                       | -                                                     | ≤ 10                 | passed |
| 12                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 1708004124                     |                                       |                                                       | -                                                     | ≤ 10                 | passed |
| 13                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 1708004132                     |                                       |                                                       | -                                                     | ≤ 10                 | passed |
| 14                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 1650006717                     | Drop and vibration test (1.7.)        |                                                       | -                                                     | ≤ 10                 | passed |
| 15                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 1650006724                     |                                       |                                                       | -                                                     | ≤ 10                 | passed |
| 16                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 1650006727                     |                                       |                                                       | -                                                     | ≤ 10                 | passed |
| Requirements (subsequent tests)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                |                                       |                                                       |                                                       | Result:              |        |
| Bench top activation test (1.9.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                |                                       |                                                       |                                                       | passed               |        |
| Flow rate test (1.10.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                |                                       |                                                       |                                                       | passed               |        |



# R134 tests

| 1.9 Bench top activation test                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |               |                                       |                                                                                  |                          |             |  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|---------------------------------------|----------------------------------------------------------------------------------|--------------------------|-------------|--|
| tested acc.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | ECE R 134     |                                       | Annex 4                                                                          | Section 1.9.             |             |  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |               |                                       |                                                                                  |                          |             |  |
| Test description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |               |                                       |                                                                                  |                          |             |  |
| <p>Two new TPRD units are tested without being subjected to other design qualification tests in order to establish a baseline time for activation. Additional pre-tested units (pre-tested according to Annex 4, paragraphs 1.1., 1.3., 1.4., 1.5. or 1.7.) undergo bench top activation testing as specified in other tests in Annex 4, paragraph 1.</p> <p>(a) The test setup consists of either an oven or chimney which is capable of controlling air temperature and flow to achieve 600 (±10) °C in the air surrounding the TPRD. The TPRD unit is not exposed directly to flame. The TPRD unit is mounted in a fixture according to the manufacturer's installation instructions; the test configuration is to be documented;</p> <p>(b) A thermocouple is placed in the oven or chimney to monitor the temperature. The temperature remains within the acceptable range for two minutes prior to running the test;</p> <p>(c) The pressurized TPRD unit is inserted into the oven or chimney, and the time for the device to activate is recorded. Prior to insertion into the oven or chimney, one new (not pre-tested) TPRD unit is pressurized to no more than 25 per cent NWP (the pre-tested); TPRD units are pressurized to no more than 25 per cent NWP; and one new (not pre-tested) TPRD unit is pressurized to 100 per cent NWP;</p> <p>(d) TPRD units previously subjected to other tests in Annex 4, paragraph 1. shall activate within a period no more than two minutes longer than the baseline activation time of the new TPRD unit that was pressurized to up to 25 per cent NWP;</p> <p>(e) The difference in the activation time of the two TPRD units that had not undergone previous testing shall be no more than 2 minutes.</p> |               |                                       |                                                                                  |                          |             |  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |               |                                       |                                                                                  |                          |             |  |
| Test parameter settings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |               |                                       |                                                                                  |                          |             |  |
| NWP [MPa]                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | step          | Oven temperature t [°C]               | test pressure p <sub>t</sub> [MPa]                                               |                          | Test medium |  |
| 70.0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | sample 1      | 600 (±10)                             | 70.0                                                                             |                          | Hydrogen    |  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | sample 2 - 17 |                                       | 1.9 – 2.2                                                                        |                          |             |  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |               |                                       |                                                                                  |                          |             |  |
| Test samples                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |               |                                       |                                                                                  |                          |             |  |
| No.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Sample number | description / previous test           | Requirements                                                                     | t <sub>act</sub> [sec]   | Result      |  |
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 1708004130    | virgin part                           | t <sub>act</sub> of sample 1 and 2 not differ more than 120 s                    | 156                      | passed      |  |
| 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 1709000615    |                                       |                                                                                  | 158 = t <sub>act,0</sub> | passed      |  |
| 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 1809006961    | Pressure cycling test (1.1.)          | $\leq 120 \text{ sec} + t_{act,0}$<br>$\rightarrow t_{act} \leq 278 \text{ sec}$ | 191                      | passed      |  |
| 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 1809006962    |                                       |                                                                                  | 139                      | passed      |  |
| 5                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 1809006963    |                                       |                                                                                  | 175                      | passed      |  |
| 6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 1809006964    |                                       |                                                                                  | 188                      | passed      |  |
| 7                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 1809006965    |                                       |                                                                                  | 182                      | passed      |  |
| 8                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 1650006687    | Temperature cycling test (1.3.)       |                                                                                  | 200                      | passed      |  |
| 9                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 1650000825    | Salt Corrosion Resistance test (1.4.) |                                                                                  | 135                      | passed      |  |
| 10                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 1650000828    | Vehicle environment test (1.5.)       |                                                                                  | 143                      | passed      |  |
| 11                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 1650000823    |                                       |                                                                                  | 230                      | passed      |  |
| 12                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 1708004122    |                                       |                                                                                  | 210                      | passed      |  |
| 13                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 1708004124    |                                       |                                                                                  | 184                      | passed      |  |
| 14                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 1708004132    | Drop and vibration test (1.7.)        |                                                                                  | 173                      | passed      |  |
| 15                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 1650006717    |                                       |                                                                                  | 202                      | passed      |  |
| 16                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 1650006724    |                                       |                                                                                  | 208                      | passed      |  |
| 17                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 1650006727    |                                       |                                                                                  | 191                      | passed      |  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |               |                                       |                                                                                  |                          |             |  |
| Requirements (subsequent tests)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |               |                                       |                                                                                  |                          | Result:     |  |
| Flow rate test (1.10.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |               |                                       |                                                                                  |                          | passed      |  |

| 1.10                                                                                                                                                                                                                           |                            | Flow rate test                        |                                                                                                   |                      |        |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------|---------------------------------------|---------------------------------------------------------------------------------------------------|----------------------|--------|
| tested acc.                                                                                                                                                                                                                    | ECE R 134                  | Annex 4                               | Section 1.10.                                                                                     |                      |        |
|                                                                                                                                                                                                                                |                            |                                       |                                                                                                   |                      |        |
| Test description                                                                                                                                                                                                               |                            |                                       |                                                                                                   |                      |        |
| (a) Eight TPRD units are tested for flow capacity. The eight units consist of three new TPRD units and one TPRD unit from each of the following previous tests: Annex 4, paragraphs 1.1., 1.3., 1.4., 1.5. and 1.7. ;          |                            |                                       |                                                                                                   |                      |        |
| (b) Each TPRD unit is activated according to Annex 4, paragraph 1.9. After activation and without cleaning, removal of parts, or reconditioning, each TPRD unit is subjected to flow test using hydrogen, air or an inert gas; |                            |                                       |                                                                                                   |                      |        |
| (c) Flow rate testing is conducted with a gas inlet pressure of 2 (±0.5) MPa. The outlet is at ambient pressure. The inlet temperature and pressure are recorded;                                                              |                            |                                       |                                                                                                   |                      |        |
| (d) Flow rate is measured with accuracy within ±2 per cent. The lowest measured value of the eight pressure relief devices shall not be less than 90 per cent of the highest flow value.                                       |                            |                                       |                                                                                                   |                      |        |
|                                                                                                                                                                                                                                |                            |                                       |                                                                                                   |                      |        |
| Test parameter settings                                                                                                                                                                                                        |                            |                                       |                                                                                                   |                      |        |
| NWP [MPa]                                                                                                                                                                                                                      | test temperature<br>t [°C] | test pressure<br>p <sub>t</sub> [MPa] | Test medium                                                                                       |                      |        |
| 70.0                                                                                                                                                                                                                           | ambient                    | 1.7 – 1.8                             | Hydrogen                                                                                          |                      |        |
|                                                                                                                                                                                                                                |                            |                                       |                                                                                                   |                      |        |
| Test samples                                                                                                                                                                                                                   |                            |                                       |                                                                                                   |                      |        |
| No.                                                                                                                                                                                                                            | Sample number              | description / previous test           | Requirements                                                                                      | flow rate<br>[l/min] | Result |
| 1                                                                                                                                                                                                                              | 1708004130                 | virgin part                           | Minimum<br>permitted flow rate<br>of the 8 samples<br>(90% of highest<br>rate)<br><br>= 608 l/min | 613                  | passed |
| 2                                                                                                                                                                                                                              | 1709000615                 |                                       |                                                                                                   | 620                  | passed |
| 3                                                                                                                                                                                                                              | 1709000614                 |                                       |                                                                                                   | 617                  | passed |
| 4                                                                                                                                                                                                                              | 1809006964                 | Pressure cycling test (1.1.)          |                                                                                                   | 631                  | passed |
| 5                                                                                                                                                                                                                              | 1650006687                 | Temperature cycling test (1.3.)       |                                                                                                   | 653                  | passed |
| 6                                                                                                                                                                                                                              | 1650000828                 | Salt Corrosion Resistance test (1.4.) |                                                                                                   | 621                  | passed |
| 7                                                                                                                                                                                                                              | 1708004132                 | Vehicle environment test (1.5.)       |                                                                                                   | 626                  | passed |
| 8                                                                                                                                                                                                                              | 1650006724                 | Drop and vibration test (1.7.)        |                                                                                                   | 676                  | passed |

# Internal – Activation temperature test on TPRD samples

## 2.1 - Test parameters

- Test Medium: Air
- Test pressure: 20 bar
- Temperature increase: 1°C/10 min above 95°C

**Acceptance criteria:** *Temperature=110°C ± 5°C*

| Attrezzature utilizzate / Used tools |                                     |
|--------------------------------------|-------------------------------------|
| Thermal chamber                      | -75°/180°C ACS DM250C 15 ESS SPEEDY |
| Digital gauge                        | 0-50 bar AEP bit02                  |
| Thermocouple                         | Testo AG 207 1ST - 2mt              |

## 2.2 - Test procedure

1. Place the samples into the thermal chamber
2. Connect the samples to the test bench
3. Pressurize the DU|T from the VMD
4. Condition the sample to 95°C
5. Heat the sample up to activation temperature with a gradient of 1°C/10 min

## 2.3 - Results

| Sample     | Activation temperature [°C] | Result |
|------------|-----------------------------|--------|
| 2203013306 | 110                         | Passed |
| 2202004768 | 113                         | Passed |
| 2203013311 | 111                         | Passed |
| 2202004668 | 112                         | Passed |

# Bench top activation test – different medium

## R134 Bench top activation test

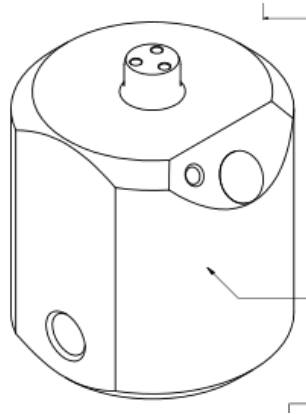
### Bench top activation test

Two new TPRD units are tested without being subjected to other design qualification tests in order to establish a baseline time for activation. Additional pre-tested units (pre-tested according to Annex 4, paragraphs 1.1., 1.3., 1.4., 1.5. or 1.7.) undergo bench top activation testing as specified in other tests in Annex 4, paragraph 1.

- The test setup consists of either an oven or chimney which is capable of controlling air temperature and flow to achieve 600 (±10) °C in the air surrounding the TPRD. The TPRD unit is not exposed directly to flame. The TPRD unit is mounted in a fixture according to the manufacturer's installation instructions; the test configuration is to be documented;
- A thermocouple is placed in the oven or chimney to monitor the temperature. The temperature remains within the acceptable range for two minutes prior to running the test;
- The pressurized TPRD unit is inserted into the oven or chimney, and the time for the device to activate is recorded. Prior to insertion into the oven or chimney, one new (not pre-tested) TPRD unit is pressurized to no more than 25 per cent NWP (the pre-tested); TPRD units are pressurized to no more than 25 per cent NWP; and one new (not pre-tested) TPRD unit is pressurized to 100 per cent NWP;
- TPRD units previously subjected to other tests in Annex 4, paragraph 1. shall activate within a period no more than two minutes longer than the baseline activation time of the new TPRD unit that was pressurized to up to 25 per cent NWP;
- The difference in the activation time of the two TPRD units that had not undergone previous testing shall be no more than 2 minutes.

**Source: Regulation No. 134-2015**

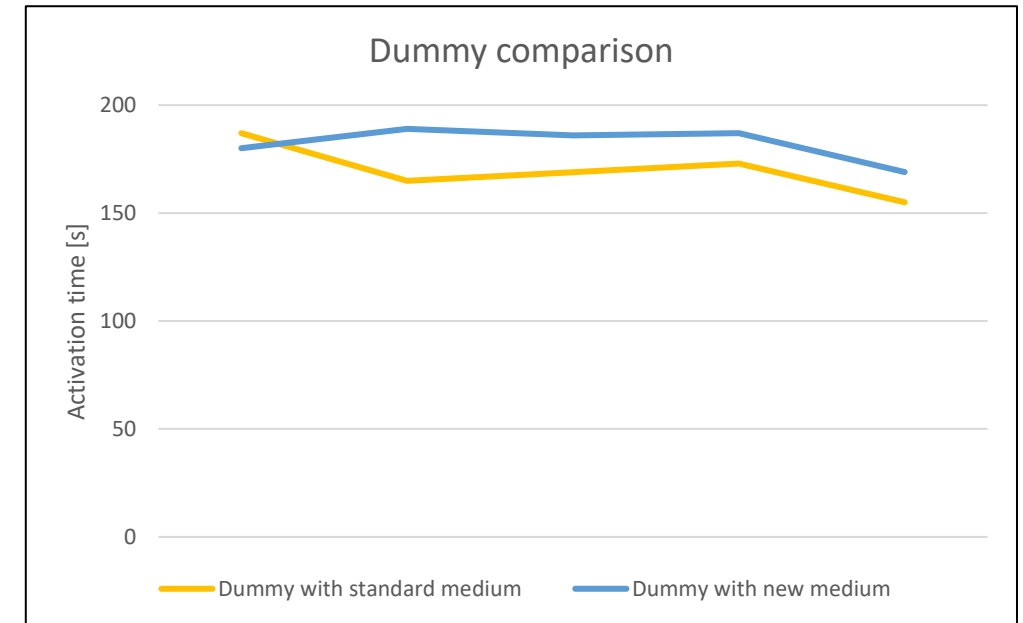
*Explanation of Bench top activation test according to R134*



- 5 virgin samples of standard medium (FL108)
- 5 virgin samples of new medium (FL110)
- **Identical bulb geometry and material**
- Medium with different composition but **same thermal properties**

# Bench top activation test

|         | Dummy with standard medium (FL108) @OMB |                       | Dummy with new medium (FL110) @OMB |                       |
|---------|-----------------------------------------|-----------------------|------------------------------------|-----------------------|
| SAMPLES | Pressure [bar]                          | Activation time [min] | Pressure [bar]                     | Activation time [min] |
| Virgin  | 20                                      | 3:07                  | 20                                 | 3:00                  |
| Virgin  | 20                                      | 2:45                  | 20                                 | 3:09                  |
| Virgin  | 20                                      | 2:49                  | 20                                 | 3:06                  |
| Virgin  | 20                                      | 2:53                  | 20                                 | 3:07                  |
| Virgin  | 20                                      | 2:35                  | 20                                 | 2:49                  |





# Thank you for your attention

OMB contact: [francesca.frialdi@omb-saleri.it](mailto:francesca.frialdi@omb-saleri.it)

My contact: [elisabetta.dalgal@tmaceurope.com](mailto:elisabetta.dalgal@tmaceurope.com)

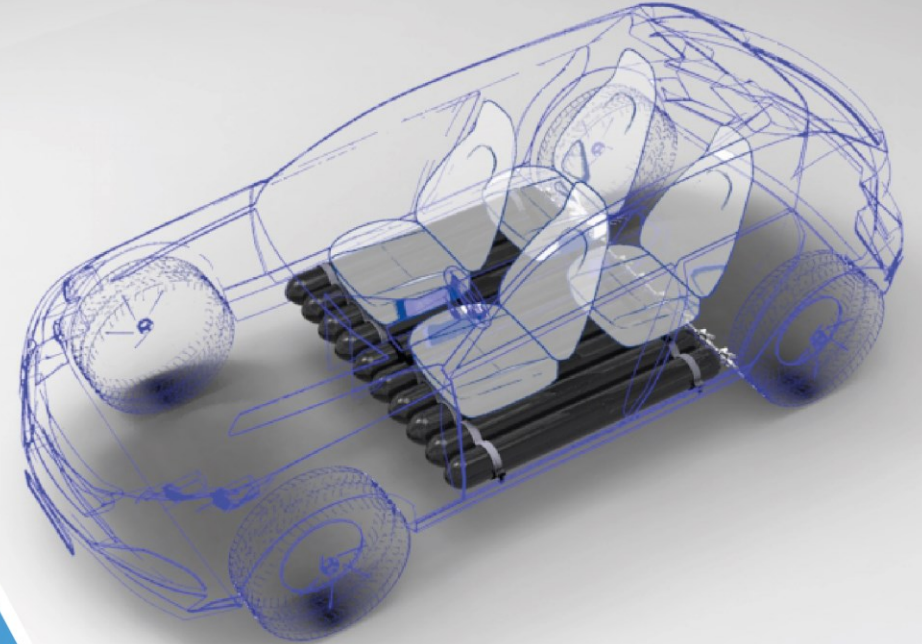


This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.

# Stakeholder Workshop

## Cost-effective analysis

STAKEHOLDER's Workshop Brussel  
September 26<sup>th</sup> – 27<sup>th</sup>, 2024

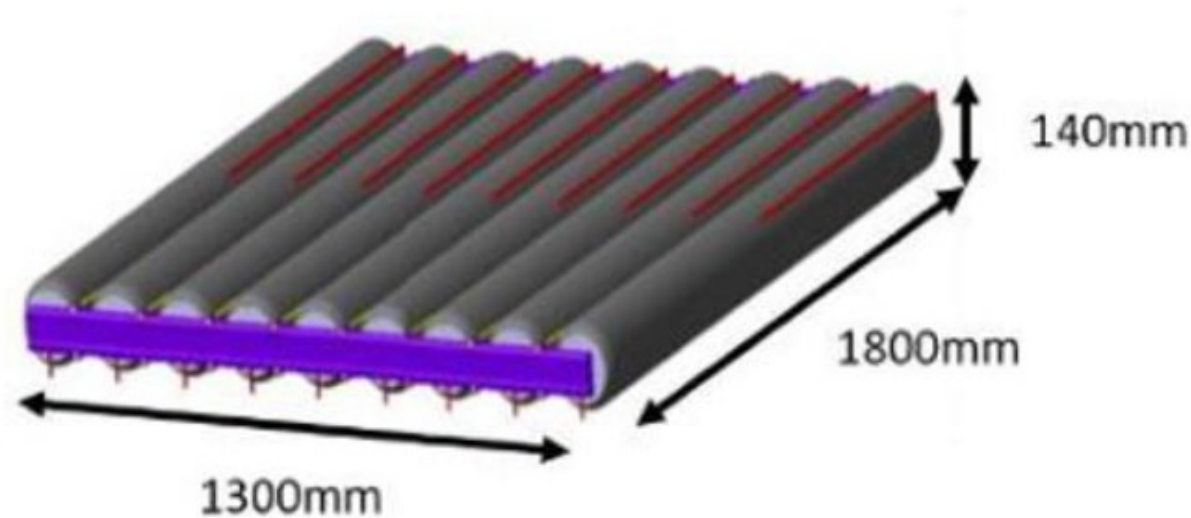


# Agenda of workshop

- Design Space evolutions
- Configurations Analyzed
- Results
- Conclusion

# Initial Design Space at Project Filing

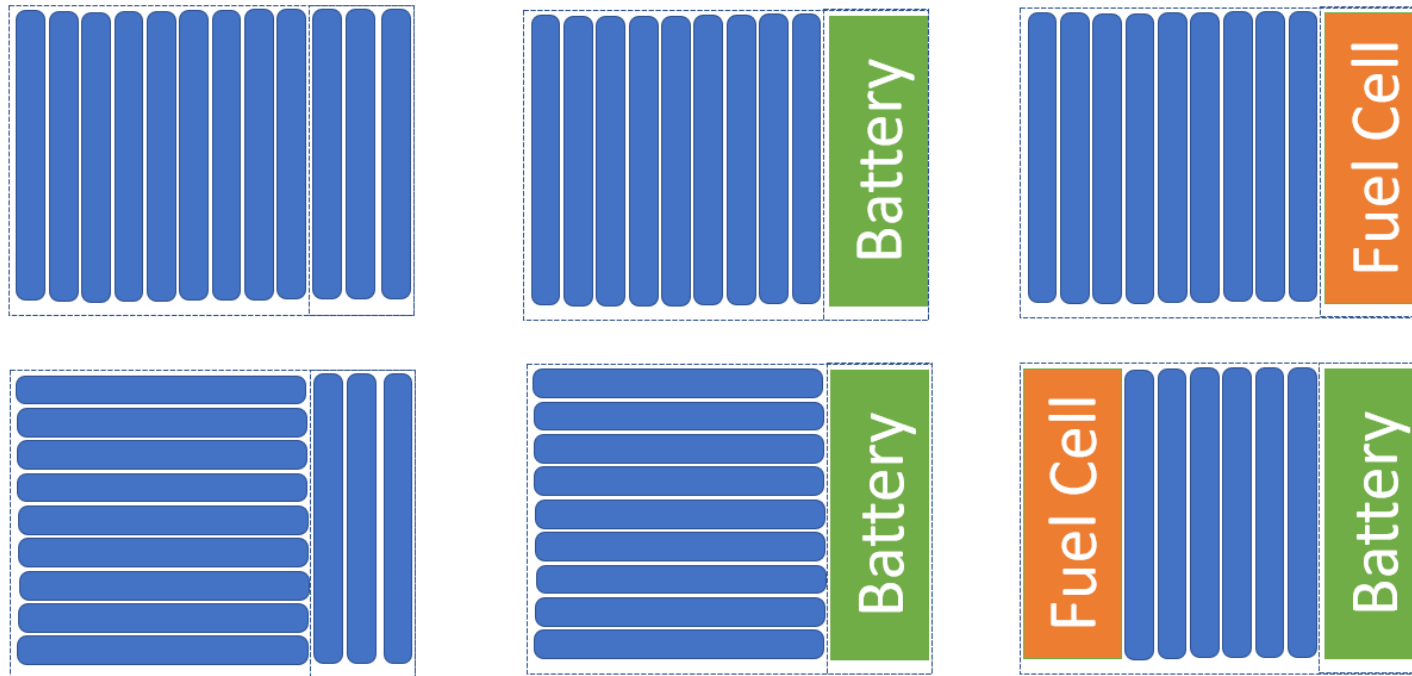
- Design Space : 1800mm x 1300mm x 140mm (9 vessels)





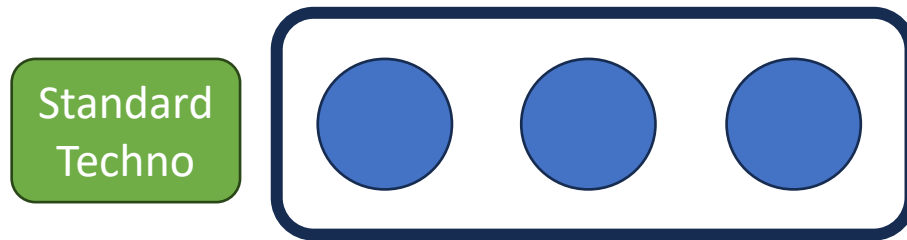
# First Design Space evolution

- Vessel length adaptation to more mainstream OEM vessel lengths during start of SH2APED Project : 1680mm x 1400mm x 140mm (12 vessels)
- Flexibility to various option to integrate the Fuel Cell and Battery

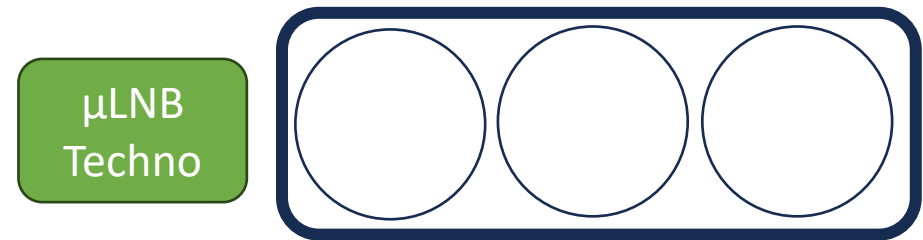


# Second Design Space evolution

- Compatibility with  $\mu$ LNB vessels  
1740mm x 1470mm x 170mm (9 vessels)



Vessel diameter : 138mm



Vessel diameter : 160 mm

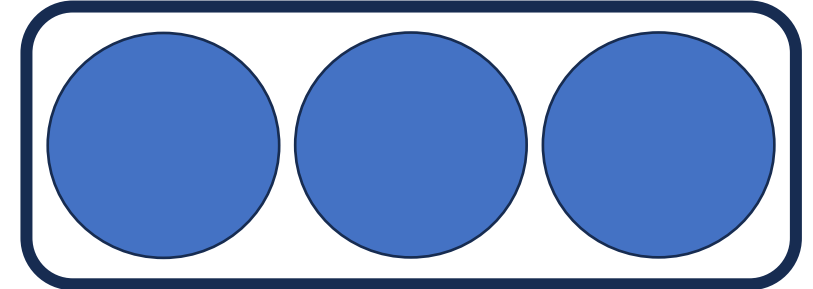
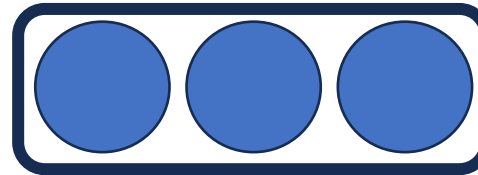
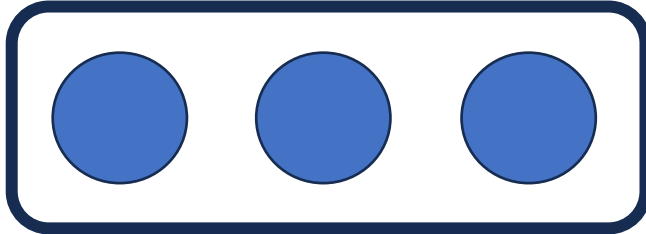
# System Configurations Analyzed

Configuration A

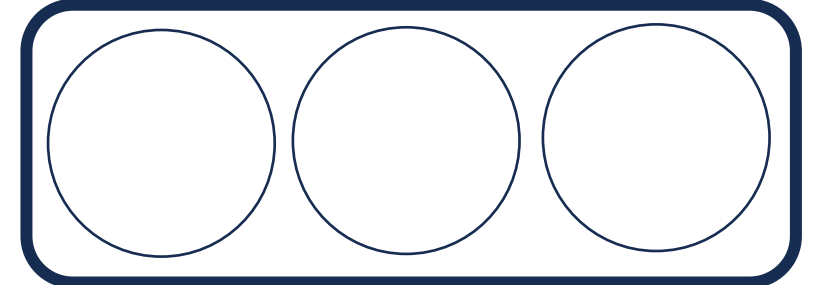
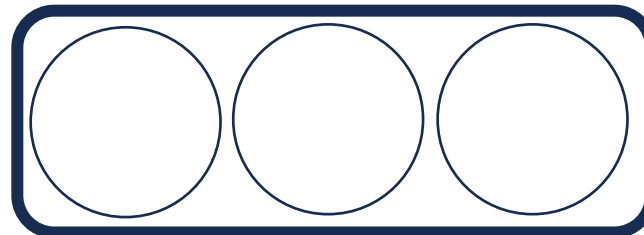
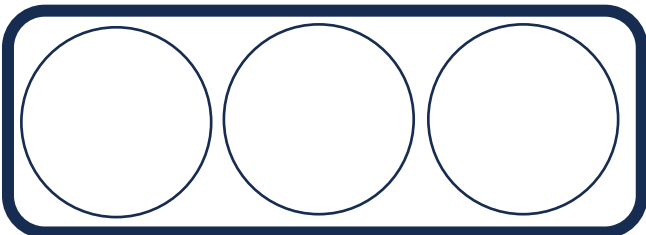
Configuration B

Configuration C

Standard  
Techno

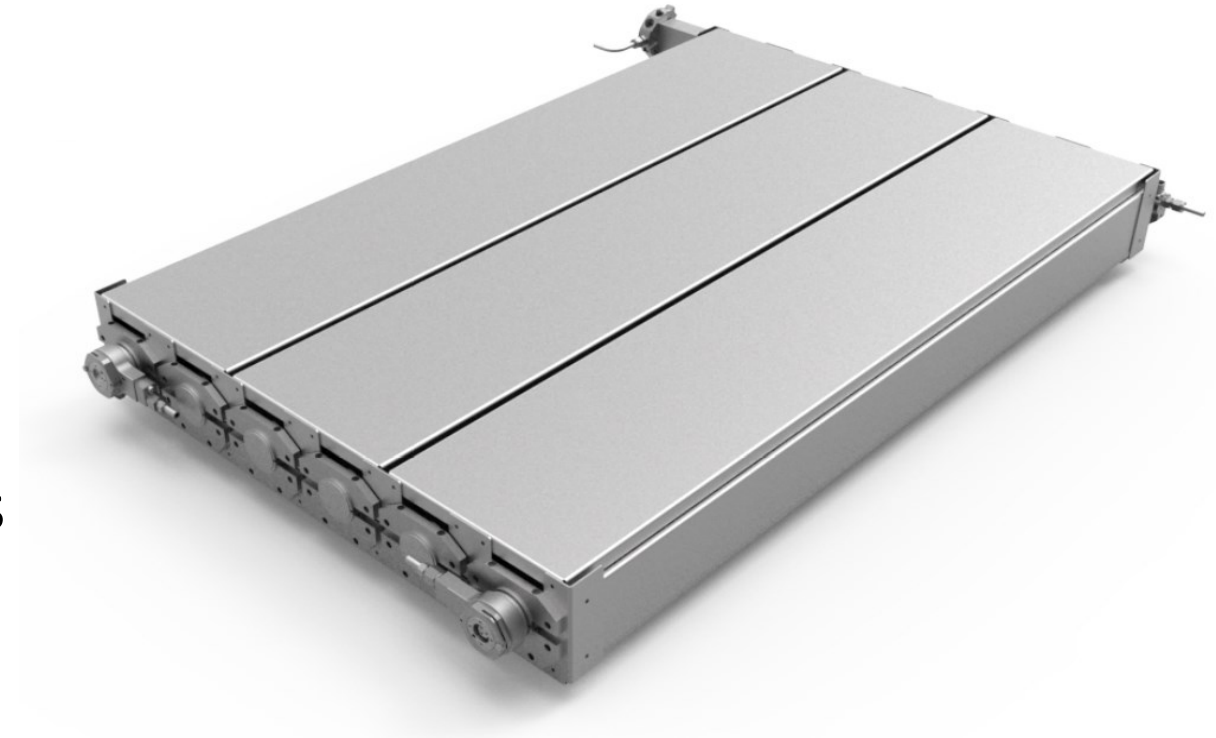


μLNB  
Techno



# System components considered

- Frame
- Vessels
- Standard system : TPRD Components
- $\mu$ LNB system: no TPRD Components
- Manifolds with integrated valves



# Configuration A - Results

| SH2APED SYSTEM FOR TECHNOBRICKS VALIDATION |                                           |                                 |         | SH2APED - proto           |       |                               |       |  |
|--------------------------------------------|-------------------------------------------|---------------------------------|---------|---------------------------|-------|-------------------------------|-------|--|
|                                            |                                           |                                 |         | Design with Std vessels   |       | Design including μLNB vessels |       |  |
|                                            |                                           |                                 |         | As realized on prototypes |       |                               |       |  |
|                                            |                                           |                                 |         | 9/25/2023                 | Owner | 9/25/2023                     | Owner |  |
| Dimensions                                 | Sh2aped vessel size<br>(flange to flange) | Diam                            | mm      | 138,5 +/- 1               | PO    | 158,5 +/- 1,2                 | PO    |  |
|                                            |                                           | Length                          | mm      | 1274                      | PO    | 1274                          | PO    |  |
|                                            | SH2APED system<br>outer dimensions        | Length (direction of vessel)    | mm      | 1560                      | OMB   | 1560                          | OMB   |  |
|                                            |                                           | width (perpendicular of vessel) | mm      | 1690                      | OMB   | 1690                          | OMB   |  |
|                                            |                                           | Height                          | mm      | 176                       | OMB   | 176                           | OMB   |  |
| H2 CONTENT AND<br>SYSTEM VOLUME            | Inner volume of 1 vessel                  | H2Vol NWP                       | dm3     | 10.9                      | PO    | 11.4                          | PO    |  |
|                                            | # of vessel in one system                 |                                 | #       | 9                         | OMB   | 9                             | OMB   |  |
|                                            | inner volume for all vessels at NWP       |                                 | dm3     | 98.1                      | PO    | 102.6                         | PO    |  |
|                                            | External volume of one system             |                                 | dm3     | 464                       |       | 464                           |       |  |
| reminder                                   | H2 density at NWP , 15°C                  |                                 | g/dm3   | 40.173                    |       | 40.173                        |       |  |
| SH2APED<br>PROJECT<br>KPIs                 |                                           | TARGET                          |         |                           |       |                               |       |  |
|                                            | Volumetric Efficiency                     | >45% of design space            |         | 21%                       |       | 22%                           |       |  |
|                                            | Gravimetric Efficiency ( vessel level)    | >5,7%                           |         | 4.25%                     |       | 2.16%                         |       |  |
|                                            | Gravimetric efficiency ( System Level)    | NO TARGET                       |         | 2.25%                     |       | 1.51%                         |       |  |
|                                            | Cost for the tank system                  | <400€/kg_H2                     | €/kh H2 | 1121                      |       | 1177                          |       |  |
|                                            |                                           | Pitch                           | mm      | 175                       |       | 175                           |       |  |



# Configuration B - Results

| SH2APED SYSTEM FOR TECHNOBRICKS VALIDATION |                                           |                           |         | SH2APED optimized (e.g. good pitch & box dimensions)  |       |  |                               |       |  |
|--------------------------------------------|-------------------------------------------|---------------------------|---------|-------------------------------------------------------|-------|--|-------------------------------|-------|--|
|                                            |                                           |                           |         | Design with Std vessels but thin liner                |       |  | Design including μLNB vessels |       |  |
|                                            |                                           |                           |         | approach: SH2APED with correct pitch & correct height |       |  |                               |       |  |
|                                            |                                           |                           |         | 9/25/2023                                             | Owner |  | 9/25/2023                     | Owner |  |
| Dimensions                                 | Sh2aped vessel size<br>(flange to flange) | Diam                      | mm      | 138,5 +/- 1                                           | PO    |  | 158,5 +/- 1,2                 | PO    |  |
|                                            |                                           | Length                    | mm      | 1274                                                  | PO    |  | 1274                          | PO    |  |
|                                            | SH2APED system<br>outer dimensions        | Length (direction of vess | mm      | 1560                                                  | OMB   |  | 1560                          | OMB   |  |
|                                            |                                           | width (perpendicular of   | mm      | 1925                                                  | OMB   |  | 2200                          | OMB   |  |
|                                            |                                           | Height                    | mm      | 155                                                   | OMB   |  | 176                           | OMB   |  |
| H2 CONTENT AND<br>SYSTEM VOLUME            | Inner volume of 1 vessel                  | H2Vol NWP                 | dm3     | 11.4                                                  | PO    |  | 11.4                          | PO    |  |
|                                            | # of vessel in one system                 |                           | #       | 12                                                    | OMB   |  | 12                            | OMB   |  |
|                                            | inner volume for all vessels at NWP       |                           | dm3     | 136.8                                                 | PO    |  | 136.8                         | PO    |  |
|                                            | External volume of one system             |                           | dm3     | 465                                                   |       |  | 604                           |       |  |
| reminder                                   | H2 density at NWP , 15°C                  |                           | g/dm3   | 40.173                                                |       |  | 40.173                        |       |  |
| SH2APED<br>PROJECT<br>KPIs                 |                                           | TARGET                    |         |                                                       |       |  |                               |       |  |
|                                            | Volumetric Efficiency                     | >45% of design space      |         | 29%                                                   |       |  | 23%                           |       |  |
|                                            | Gravimetric Efficiency ( vessel level)    | >5,7%                     |         | 4.45%                                                 |       |  | 2.16%                         |       |  |
|                                            | Gravimetric efficiency ( System Level)    | NO TARGET                 |         | 2.66%                                                 |       |  | 1.61%                         |       |  |
|                                            | Cost for the tank system                  | <400€/kg_H2               | €/kh H2 | 968                                                   |       |  | 1099                          |       |  |
|                                            |                                           | Pitch                     | mm      | 145                                                   |       |  | 165                           |       |  |

# Configuration C - Results

| SH2APED SYSTEM FOR TECHNOBRICKS VALIDATION |                                           |                                 |         | SH2APED customer environment                               |  |                           |  |
|--------------------------------------------|-------------------------------------------|---------------------------------|---------|------------------------------------------------------------|--|---------------------------|--|
|                                            |                                           |                                 |         | Customer environment                                       |  | Customer environment μLNB |  |
|                                            |                                           |                                 |         | approach: integrate customer vessel into OMB SH2APED frame |  |                           |  |
|                                            |                                           |                                 |         | CONFIDENTIAL                                               |  |                           |  |
| Dimensions                                 | Sh2aped vessel size<br>(flange to flange) | Diam                            | mm      |                                                            |  |                           |  |
|                                            |                                           | Length                          | mm      |                                                            |  |                           |  |
|                                            | SH2APED system<br>outer dimensions        | Length (direction of vessel)    | mm      |                                                            |  |                           |  |
|                                            |                                           | width (perpendicular of vessel) | mm      |                                                            |  |                           |  |
| Height                                     |                                           | mm                              |         |                                                            |  |                           |  |
| H2 CONTENT AND<br>SYSTEM VOLUME            | Inner volume of 1 vessel                  | H2Vol NWP                       | dm3     |                                                            |  |                           |  |
|                                            | # of vessel in one system                 |                                 | #       |                                                            |  |                           |  |
|                                            | inner volume for all vessels at NWP       |                                 | dm3     |                                                            |  |                           |  |
|                                            | External volume of one system             |                                 | dm3     |                                                            |  |                           |  |
| reminder                                   | H2 density at NWP , 15°C                  |                                 | g/dm3   | 431                                                        |  | 431                       |  |
| SH2APED<br>PROJECT<br>KPIs                 |                                           | TARGET                          |         |                                                            |  |                           |  |
|                                            | Volumetric Efficiency                     | >45% of design space            |         | 42%                                                        |  | 32%                       |  |
|                                            | Gravimetric Efficiency ( vessel level)    | >5,7%                           |         | 6.10%                                                      |  | 2.24%                     |  |
|                                            | Gravimetric efficiency ( System Level)    | NO TARGET                       |         | 2.81%                                                      |  | 2.07%                     |  |
|                                            | Cost for the tank system                  | <400€/kg_H2                     | €/kh H2 | 854                                                        |  | 1361                      |  |
|                                            |                                           | Pitch                           | mm      | CONFIDENTIAL                                               |  |                           |  |

- The higher the hydrogen storage space, the better the gravimetric and volumetric efficiency becomes
- $\mu$ LNB technology is decreasing the gravimetric and volumetric efficiency of a hydrogen storage system
- More efforts are needed to increase competitiveness of the hydrogen storage system (standard and  $\mu$ LNB)

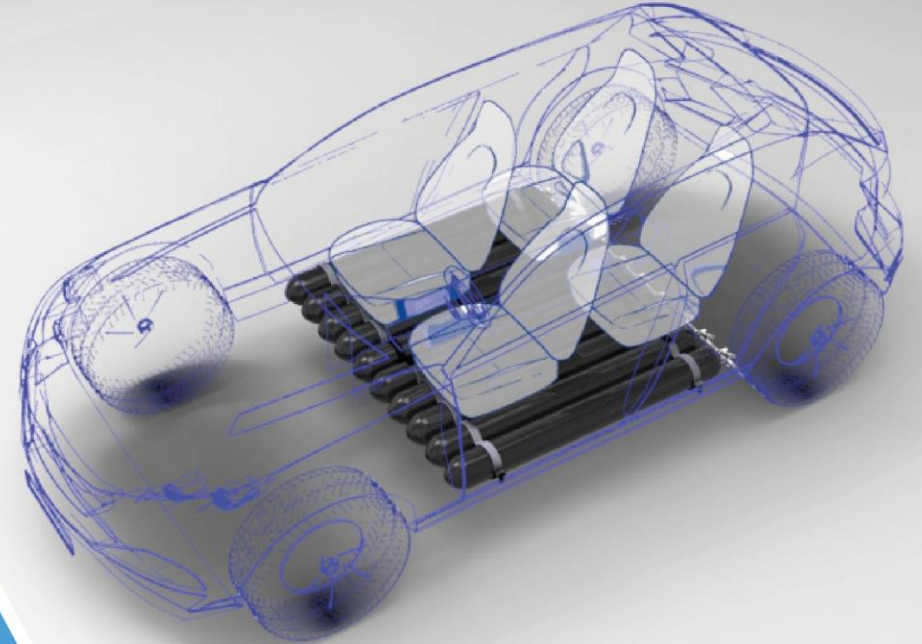


This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 101007182. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and Hydrogen Europe Research.

# Recommendations for update of Regulations, Codes, and Standards (RCS)

Stakeholder's workshop of SH2APED project  
26-27 September 2024, Brussels, Belgium

V. Shentsov, S. Kashkarov, H. Xie, D. Makarov, V. Molkov





# Abbreviations

- FRR** - Fire resistance rating
- HDPE** - High density polyethylene
- HRR** - Heat release rate
- HRR/A** - Specific heat release rate (HRR divided by fire source area A)
- μLNB** - Microleaks-no-burst
- PA** - Polyamide (Nylon)
- SoC** - State of charge
- TPRD** - Thermally-activated pressure relief device



# Recommendation 1: statement

**Hydrogen storage tanks and CHSS should not rupture in any fire.**



# Recommendation 1: rationale

**Hydrogen storage tanks and CHSS should not rupture in any fire.**

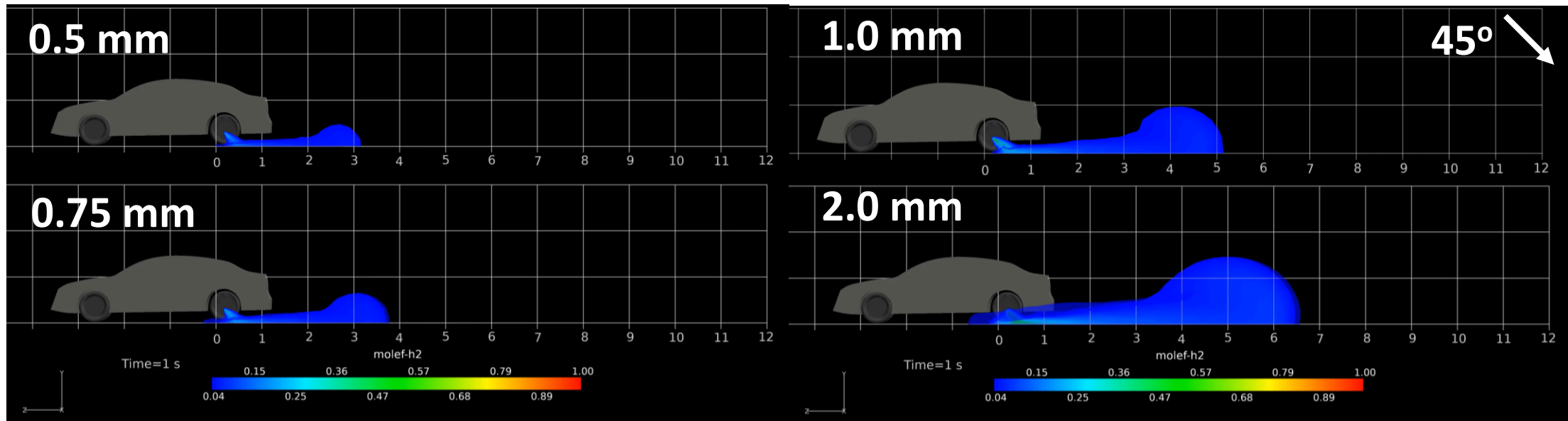
Hydrogen must be safely released from the storage system to exclude its rupture.

The release should be arranged in a way that the following conditions are met:

- *No tank rupture before, during and after release.*
- *No long jet fire to exclude the domino effect on the incident scene.*
- *No pressure peaking phenomenon in the confined space.*
- *No hydrogen accumulation in naturally ventilated enclosures, e.g. to allow the use of CHSS under the deck of a maritime vessel or onboard other means of transportation.*

# Recommendation 2: statement

Use contemporary validated tools like CFD to assess an inherently safer TPRD orifice size for minimising hazards from long flame and the pressure peaking phenomenon.



# Recommendation 2: rationale

**Use contemporary validated tools like CFD to assess an inherently safer TPRD orifice size for minimising hazards from long flame and the pressure peaking phenomenon.**

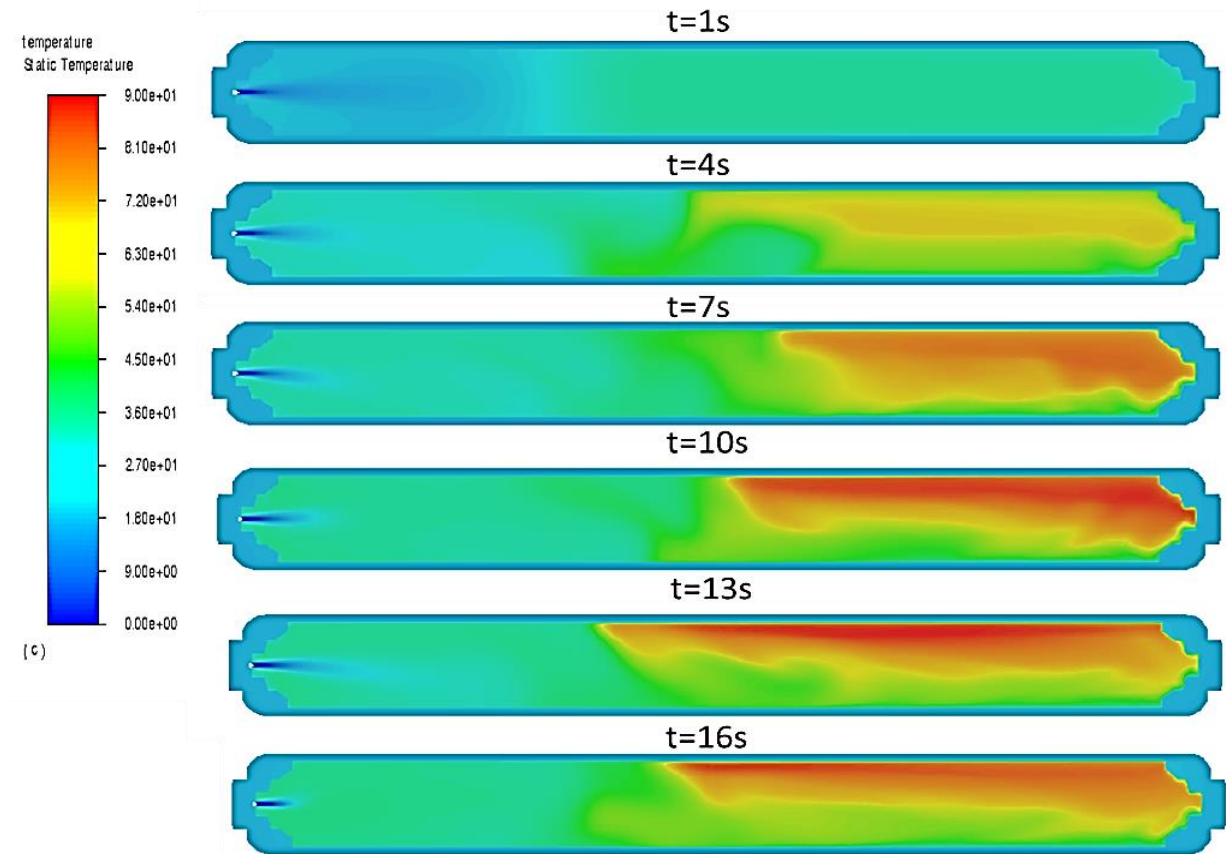
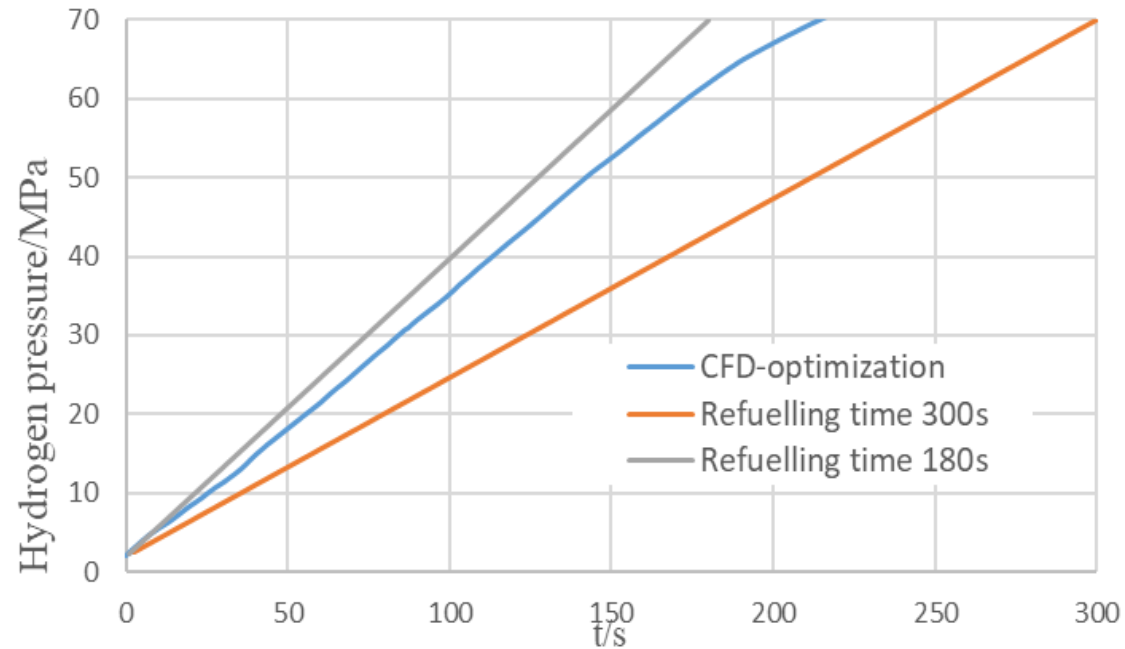
To minimize hazards in confined spaces and ensure safer evacuation during hydrogen release:

- Optimize TPRD orifice size using validated CFD models to avoid pressure peaking and long flames.
- TPRD release angle of 45° and orifice size  $\leq 0.75$  mm for ceiling heights of 2.1-3.0 m and up to 10 ACH.
- Avoid positioning TPRD discharge towards walls to prevent gas accumulation.
- Ensure hot gases don't exceed 300°C at the ceiling.



# Recommendation 3: statement

**Use scientifically based fuelling protocols to minimise hydrogen temperature non-uniformity inside the tank.**



# Recommendation 3: rationale

**Use scientifically based fuelling protocols to minimise hydrogen temperature non-uniformity inside the tank.**

- Ulster University's 3D CFD simulations of fuelling of conformable tanks showed formation of hydrogen temperature non-uniformity and stratification (hot spots) inside the tank .
- The difference between bulk and the maximum hydrogen temperatures was observed to reach 35 degrees. This significant non-uniformity makes it a challenge not to exceed the maximum allowed temperature of 85°C in the tank.
- An increase in initial pressure from 2 MPa to 3 MPa reduced the maximum temperature and decreased overall temperature non-uniformity to 27 degrees.
- The SH2APED project considers bulk temperature control insufficient, and control over the maximum temperature must be addressed by the relevant RCS.

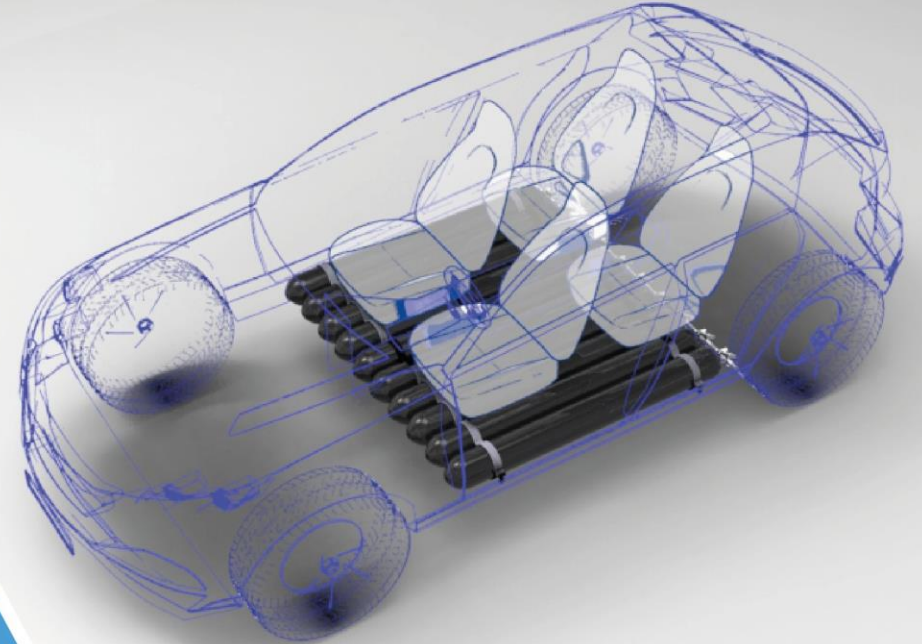
# THANK YOU



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# Industrial perspective for future technology exploitation

Stakeholder's workshop of SH2APED project  
26-27 September 2024  
HySAFER, Ulster University





# Safety technology of self-venting (TPRD-less) tanks

The breakthrough safety technology of CGH2 storage is adaptable and **will be exploited in road, rail, aviation, maritime sectors**. It provides:

- **Exclusion of tank rupture in any fire**, including elimination of catastrophic consequences in a form of blast wave, fireball, projectiles, etc. This is essential reduction of hazards and associated risks, especially for high intensity fires.
- **The industrial impact** is in that the technology opens the way to new generation of inherently safer hydrogen storage tanks on a market.
- **The societal impact** is through provision of information for relevant **RCS** to implement the developed and validated technology.





**The target groups of our collaborators in Europe, America, Asia and Oceania which can exploit this innovative technology include but are not limited to:**

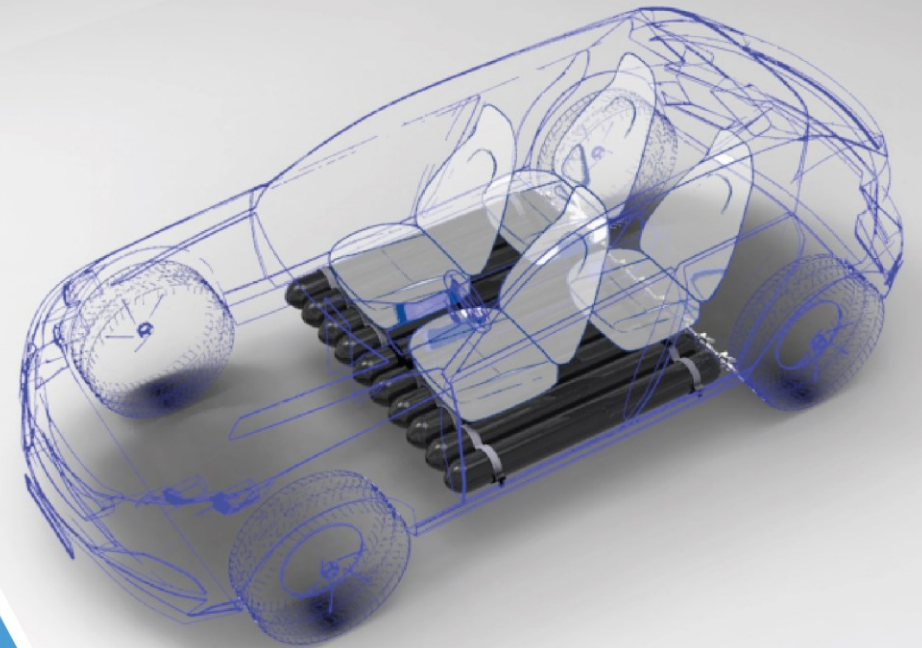
- Compressed hydrogen tank manufacturers (Type IV).
- Automotive sector, including manufacturers/OEMs, etc.
- Rail sector, including rolling stock manufacturers, etc.
- Maritime sector, including ship owners, designers, etc.
- Aviation sector, including helicopters, other flying objects, etc.
- The main beneficiary is the public and passengers of hydrogen vehicles.
- Regulators (GTR#13P3) and classification societies (Lloyds, DNV).

#### References:

- Molkov V, Makarov D, Kashkarov S. Composite Pressure Vessel for Hydrogen Storage. European (EPO) Patent Application No. 18706224.5. PCT No: PCT/EP2018/053384. WO 2018/149772 A1, 2019.
- Molkov V, Kashkarov S, Makarov D. Breakthrough safety technology of explosion free in fire self-venting (TPRD-less) tanks: The concept and validation of the microleaks-no-burst technology for carbon-carbon and carbon-glass double-composite wall hydrogen storage systems. *Int J Hydrog Energy* 2023.
- Molkov V, Kashkarov S, Makarov D. Explosion free in fire self-venting (TPRD-less) composite tanks: Performance during fire intervention. *Int J Hydrog Energy* 2023.
- Molkov V, Kashkarov S, Makarov D, Fletcher J, Rattigan W. Explosion free in fire self-venting (TPRD-less) Type IV tanks: Validation under extreme impinging 70 MPa hydrogen jet fire conditions. *Int J Hydrog Energy* 2023.

# Industrial Perspective by OP Mobility

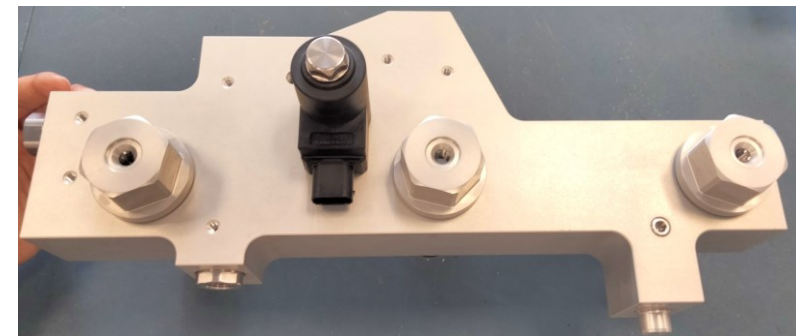
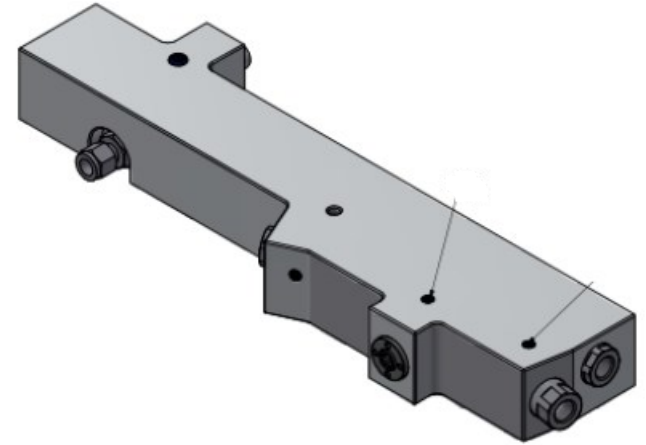
STAKEHOLDER's Workshop Brussel  
September 26<sup>th</sup> – 27<sup>th</sup>, 2024



- The collaboration allows to research and build a prototype for an H<sub>2</sub> storage system more efficient, safer and optimized.
- A TRL4 prototype with developments will become a competitive product which makes H<sub>2</sub> mobility closer.



- A system of manifold has been designed for the 9-tank system, to replace the more common singular hydrogen tank valve. With this manifold design, the goal is to improve the performance, optimising the overall and the weight of the system.
- *Reducing system complexity*
- *Reducing the number of possible points of leakage*
- The entire system including the piping system and the whole valve system is protected and covered by a dedicated frame.
- The system has been designed to replace the electric batteries, maintaining the same car layout and space.



# Target Market

- The target market is the entire market for H<sub>2</sub>
  - in automotive for road, rail, marine, aviation and hydrogen refueling stations.
- List of early adopters
  - **Automotive Manufacturers:**
  - **Hydrogen Suppliers:**
  - **Government Agencies:**
    - Provide funding, regulations, and incentives for H<sub>2</sub> projects.
    - Promote clean energy and reduce carbon emissions.
  - **Safety Experts:** Ensure the safe handling and storage of hydrogen.
  - **Research Institutions:**
  - **Infrastructure Providers:**
  - **Environmental Organizations:**
    - Support clean energy initiatives.
    - Advocate for sustainable transportation.
  - **Public:**
    - Potential consumers of hydrogen-powered vehicles.
    - Influence public opinion and market adoption.
  - **Materials Suppliers:** Provide materials for H<sub>2</sub> storage tanks and components.



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## ■ Vehicle integration : variety of approach



« BEV platforms » → fit battery volume  
→ Floor module (Long & Thin)  
→ ~5-7kgH<sub>2</sub>



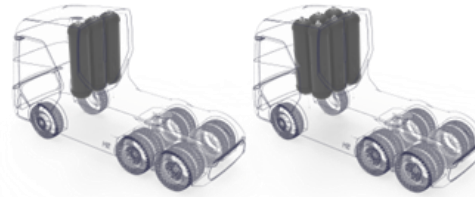
« ICE platforms » → fit fuel tank volume  
→ « traditionnal HPV » or conformable  
→ ~5-7kgH<sub>2</sub>



« in-chassis » → longitudinal tanks  
3 LDT/MDT HPV ~8-9kgH<sub>2</sub>



« behind the cabin » → transversal tanks  
3 MDT HPV ~15-20kgH<sub>2</sub>



« behind the cabin » → single or dual module  
HDT HPV in vertical or horizontal position  
~60kgH<sub>2</sub> single / 120kgH<sub>2</sub> dual



« in-chassis / diesel like » → side tanks  
2 HDT HPV in longitudinal position ~28kgH<sub>2</sub>  
if large HPV – 600L ~ 48kg



« in-chassis + behind the cabin »  
→ 2 side tanks + single  
~88kgH<sub>2</sub>

LDT = Light Duty Truck  
MDT = Medium Duty Truck  
HDT = Heavy Duty Truck

« Floor module » approach fits perfectly Passenger Cars, and Light Commerical Vehicles

- **Commercial vehicles as front runners for H2 mobility**
  - **H2 mobility market evolution**
    - **Market ramp-up slightly delayed ...**
      - H2 production & distribution are progressing too slowly
      - Major customers confirmed their programs, with lower volumes or some delay in SoP
      - Uncertainties on regulations (Worldwide)

but

- **Confirmation of the first industrial perspectives**
  - Light Commercial Vehicles
  - Heavy-Duty trucks with both H<sub>2</sub>-ICE & FCEV (trends from IAA Transportation 2024)



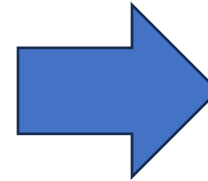
# Industrial perspective / H2 market



OPmobility to deliver >20.000 Hydrogen Storage System per year for LCVs



- A first approach of floor module already in development !



Tomorrow



OPmobility is leading the way to support LCV front runners like Hyvia & Stellantis  
Flexibility to produce « Floor module » in our Plants / Pilot Lines

Contact: [bjorn.criel@opmobility.com](mailto:bjorn.criel@opmobility.com)



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