GTR#13: towards inherently safer hydrogen-powered vehicles

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Recent advances by Hydrogen Safety Engineering and Research Centre (HySAFER)

Outline of presentation

- Fire test (improved reproducibility)
- Pressure peaking phenomenon (new phenomenon)
- System storage container-TPRD (“coupled” approach)
- Concluding remarks
- List of relevant urgent PNR topics

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Fire test reproducibility

Definitions

Bare container	-	ordinary (unprotected) container
Protected container	-	container with thermal protection, e.g. intumescent paint, Ulster IP, etc.
Heat release rate (HRR)	-	heat release rate in a fire [kW]
Fire resistance rating (FRR)	-	time from burner ignition until container rupture in a fire (without TPRD)

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Issues of GTR#13 fire test

- Poor reproducibility of the fire test in different laboratories.
- No test without TPRD (a serious first responders' concern, EU HyResponse). EU FireCOMP: there is a non-zero probability of TPRD failure.
- No test procedure for novel thermally protected storage containers, e.g. explosion-free in a fire containers.

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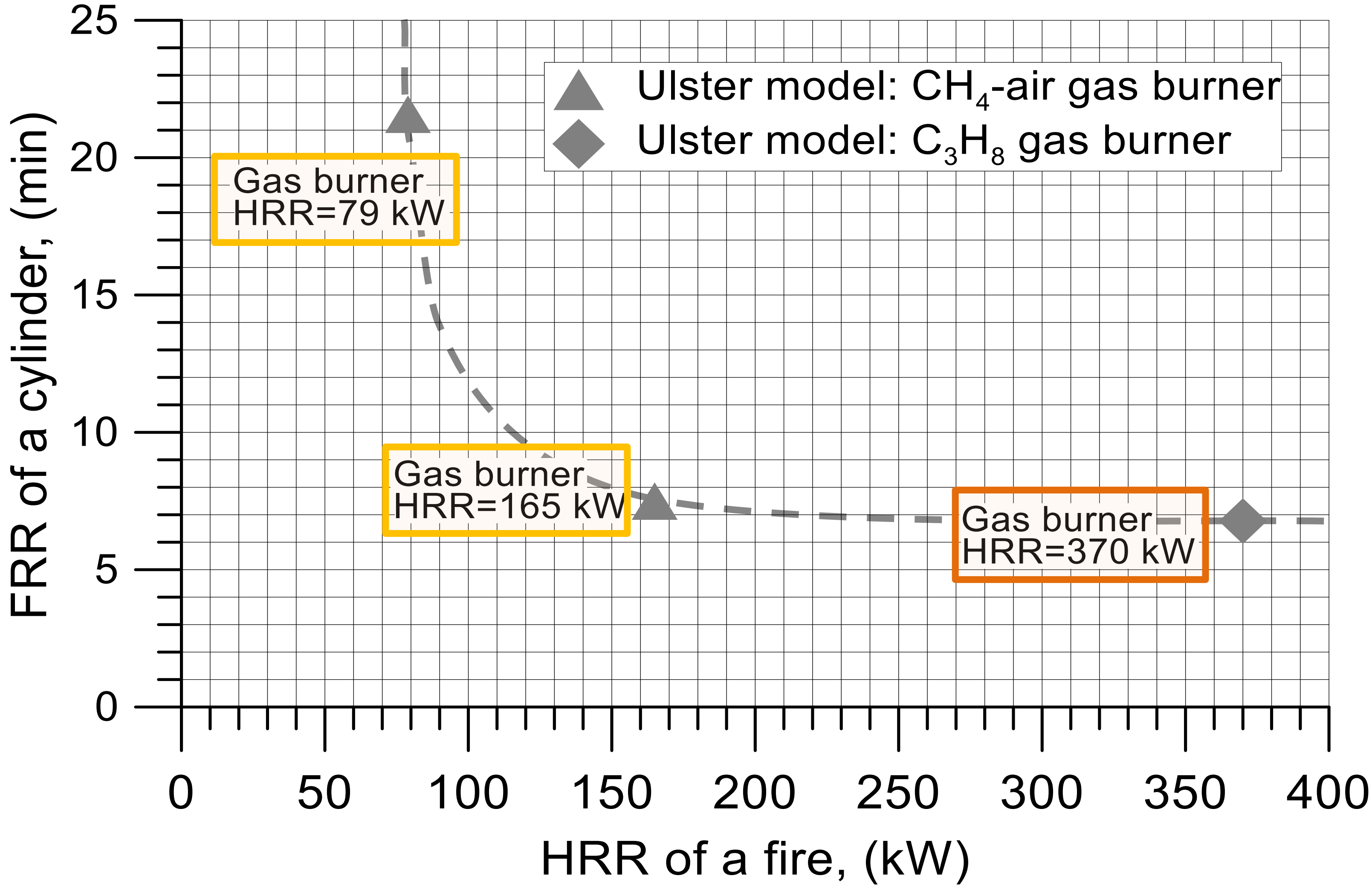
Poor reproducibility

CFD: revealed dependence of FRR on HRR



Poor reproducibility

Experimental validation of numerical study

Heat release rate	Fire source	Fire resistance rating
79 kW [1]	Premixed CH4-air burner	16 min
170 kW [1]	Premixed CH4-air burner	9 min
370 kW [2, 3]	Diffusion C3H8 burner	6.5 min
4100 kW [4]	n-C7H16, pool fire	6 min

[1] D. Makarov, Y. Kim, S. Kashkarov, V. Molkov, Thermal protection and fire resistance of high-pressure hydrogen storage, in *Proceedings 8th ISFEH*, Hefei, China, 2016.

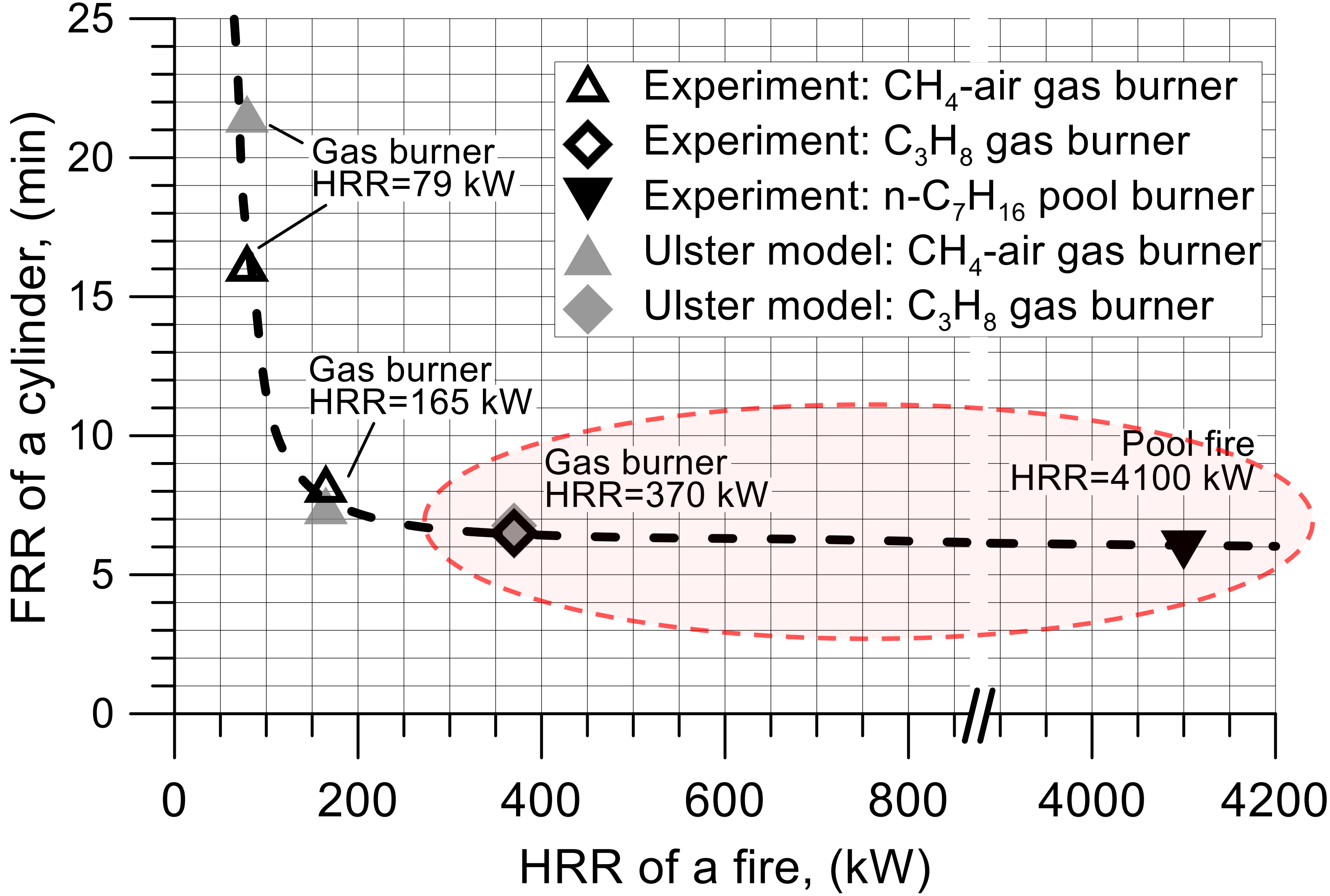
[2] N. Weyandt, Analysis of Induced Catastrophic Failure Of A 5000 psig Type IV Hydrogen Cylinder, Southwest Research Institute report for the MVFRI, 01.06939.01.001, 2005.

[3] R. Zalosh, Blast waves and fireballs generated by hydrogen fuel tank rupture during fire exposure', in *Proceedings 5th ISFEH*, Edinburgh, UK, 2007.

[4] L. Bustamante Valencia, P. Blanc-Vannet, L. Heudier, D. Jamois, 'Thermal history resulting in the failure of lightweight fully-wrapped composite pressure vessel for hydrogen in a fire experimental facility', Fire Technology, no. 52, pp. 421–442, 2016.

Poor reproducibility: way out

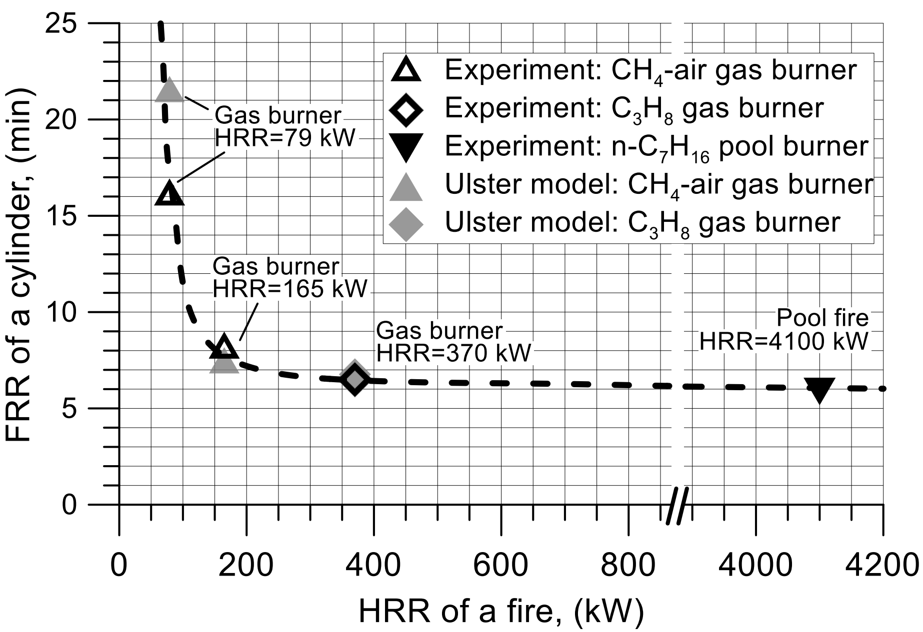
Saturation of FRR at HRR>350 kW



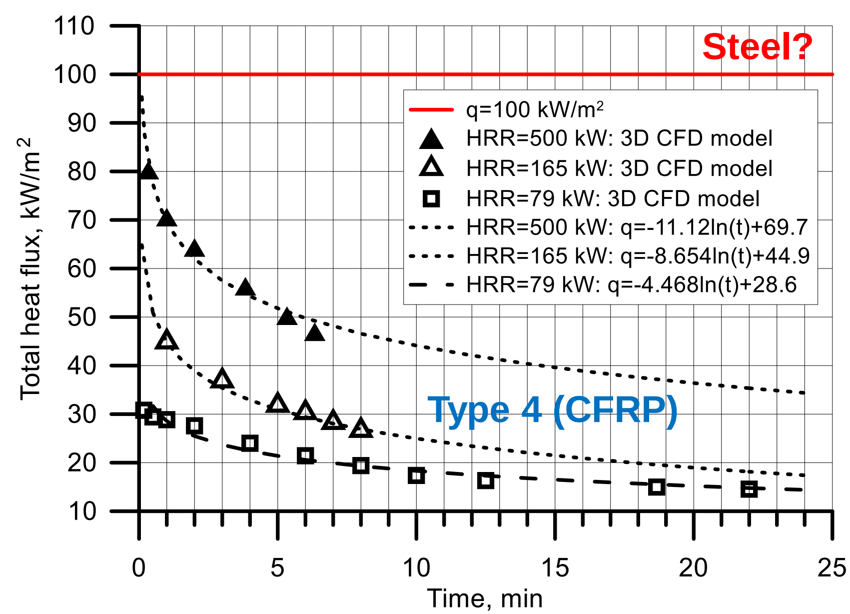
Two ways to ensure reproducibility:

- Constant HRR above 350 kW
- Heat flux (input) of minimum 100 kW/m²

HRR: saturation above 350 kW



Heat flux: continuous decrease



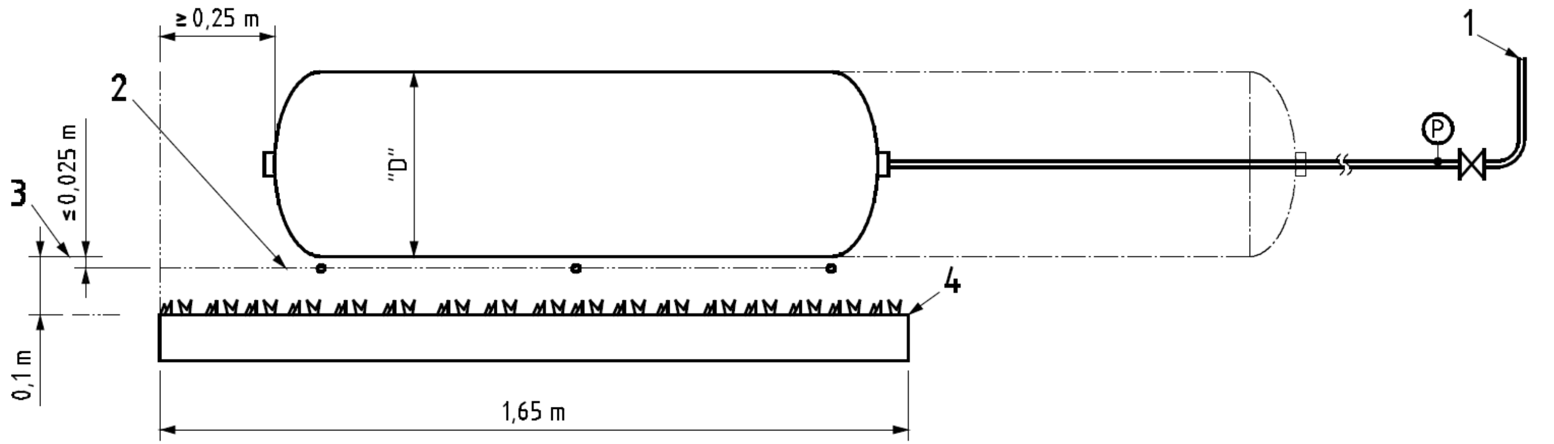
Two ways to ensure reproducibility:

- **Constant HRR above 350 kW**
- **Heat flux (input) of minimum 100 kW/m^2**

Parameter	HRR (burner + LPG flow rate)	Heat flux (input)
Technical realisation	Easy (as now)	Complicated and questionable (suggested minimum is too high)
Additional cost per test	No	$600 per sensor in a destructive test
Location and number of sensors	Easy (as now)	Where and how? How many?
Provision of required control parameter level	Easy (as now)	Is it possible to provide minimum of 100 kW/m2 for type 4
Steadiness of parameter in steady-state fire	Yes	No (decreases during the test)

ISO TC58: fire test without TPRD

Right move: "Fire test until rupture"



Key

1 Vent stack 2 Thermocouples 3 Tank surface 4 Fire source

Right approach of ISO TC58 ('Gas Cylinders — Guidance for design of composite cylinders — Part 2: Bonfire test issues', ISO/TC 58/SC 3 N 1714, 2017):

- **"For cylinders tested under option B – fire test until rupture"**

Engulfing fire test update

Need in thermally protected tank test

Current Engulfing fire test

- **Method 1E**: Bare tank
- **Method 2E**: Thermally protected tank

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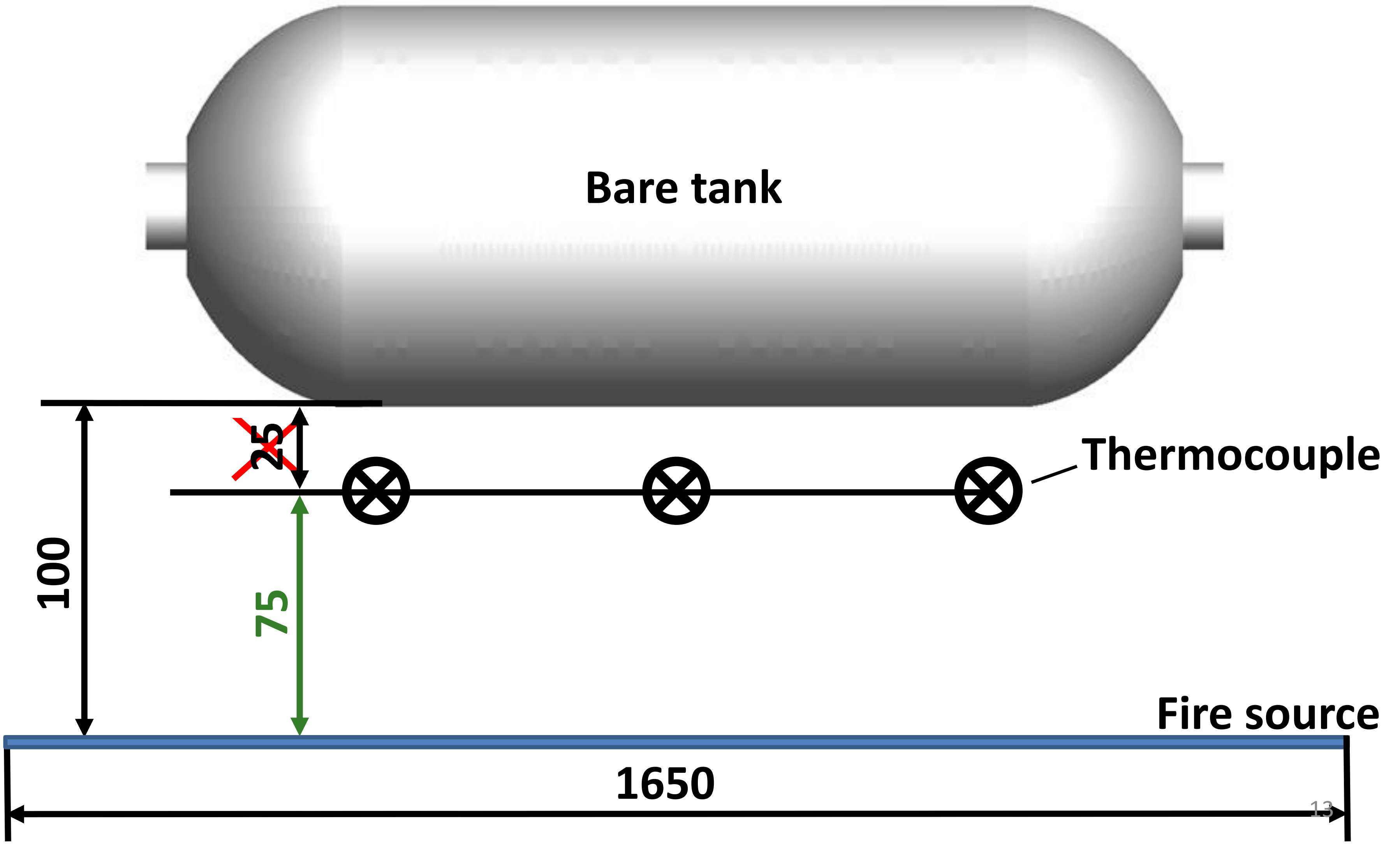
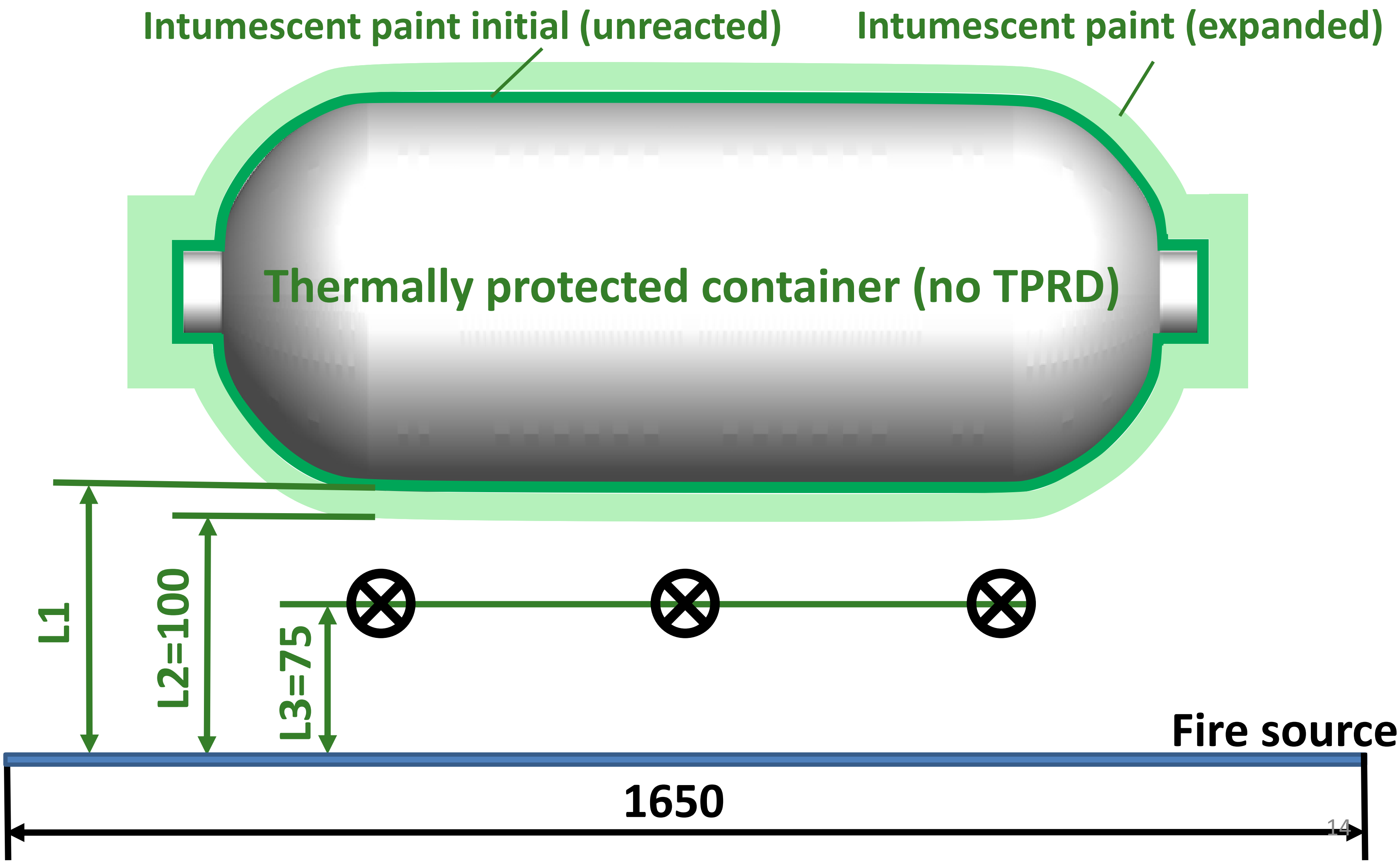
Method 1E: Bare tank (minor changes)

New requirements: HRR ≥ 350 kW, TC location

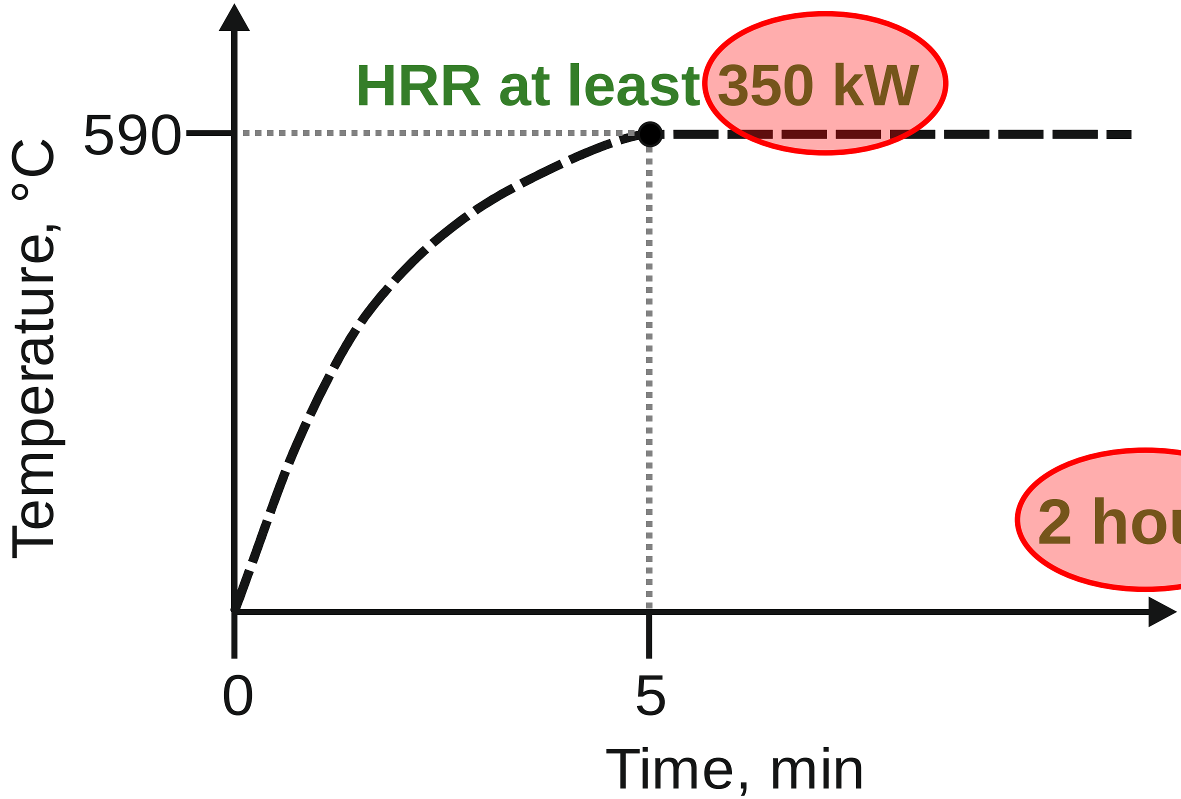


Method 2E: Thermally protected tank

Provide functioning of thermocouples



Method 2E: Thermally protected tank

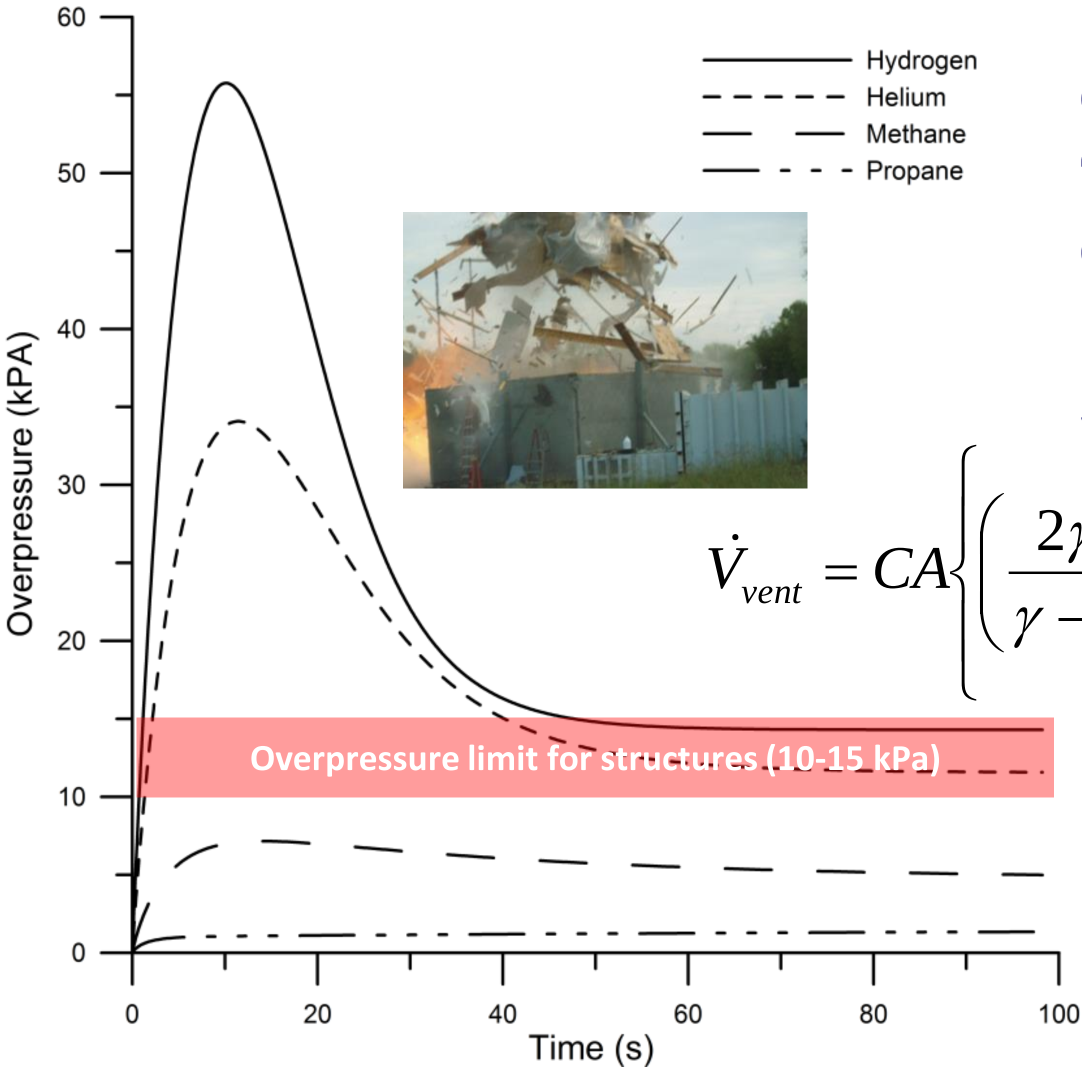


Maximum recorded duration of car fire is 2 hours (e.g. *K. Okamoto, et al., 'Burning behaviour of minivan passenger cars', Fire Safety Journal, vol. 62, pp. 272–280, 2013*).

Pressure peaking phenomenon

Pressure peaking phenomenon

Physics



Example

Garage 4.5x2.6x2.6 m, "brick" vent.

Car (350 bar, D=5.08 mm)**:** mass flow rate from TPRD 390 g/s.

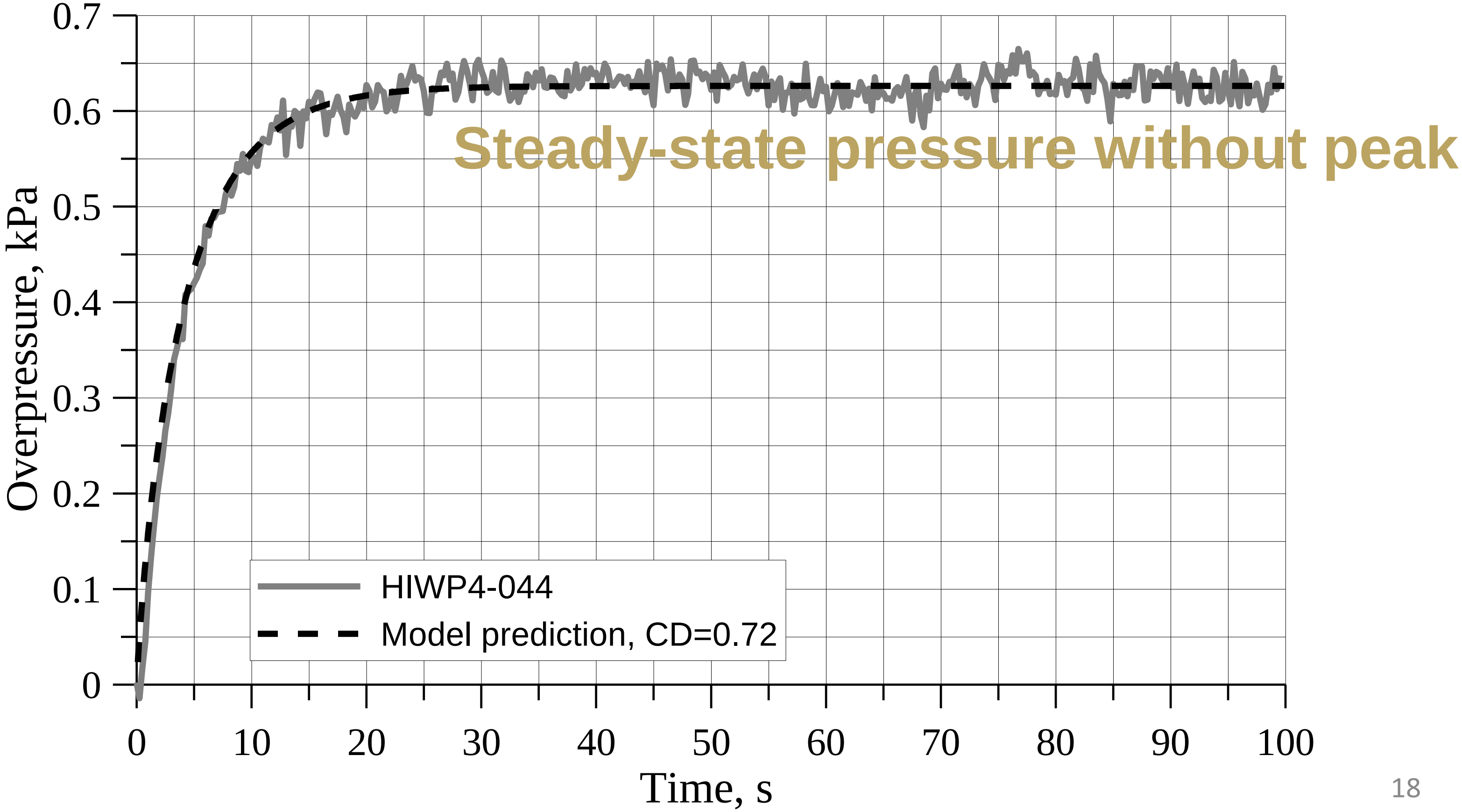
$$\dot{V}_{vent} = CA\left\{\left(\frac{2\gamma}{\gamma-1}\right)\frac{P_S}{\rho_{encl}}\left[\left(\frac{P_S}{P_{encl}}\right)^{\frac{2}{\gamma}} - \left(\frac{P_S}{P_{encl}}\right)^{\frac{\gamma+1}{\gamma}}\right]\right\}^{\frac{1}{2}}$$

Solution: decrease TPRD diameter + increase fire resistance rating of onboard storage tank!

Pressure peaking phenomenon

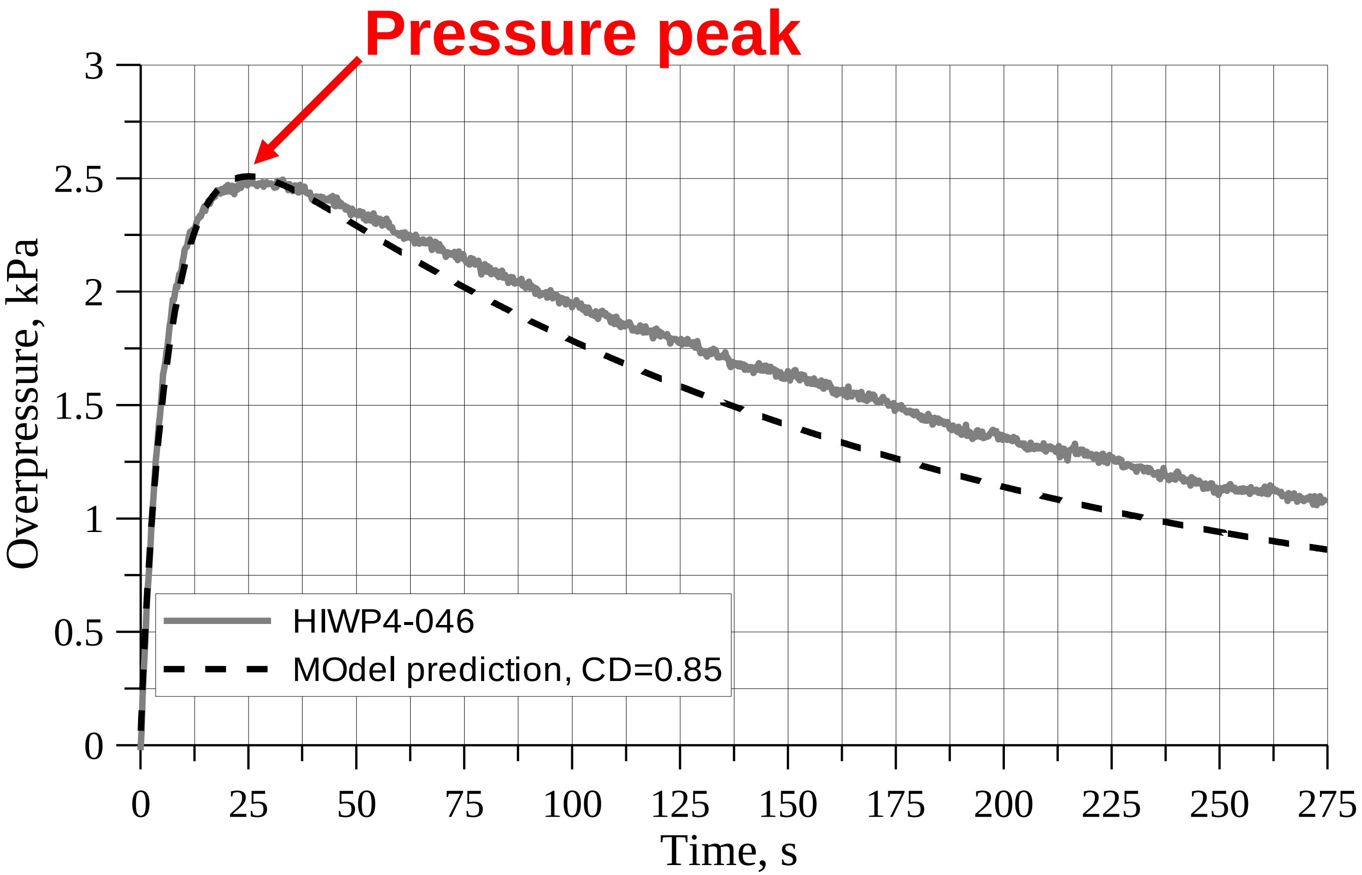
Validation: air (no pressure peaking)

Air release 2.8 g/s (enclosure 1 m^3, vent D=11 mm). Only gases lighter than air can generate pressure peaking.



Pressure peaking phenomenon
Validation: helium

Helium release 0.99 g/s (enclosure 1 m^3, vent D=11 mm)

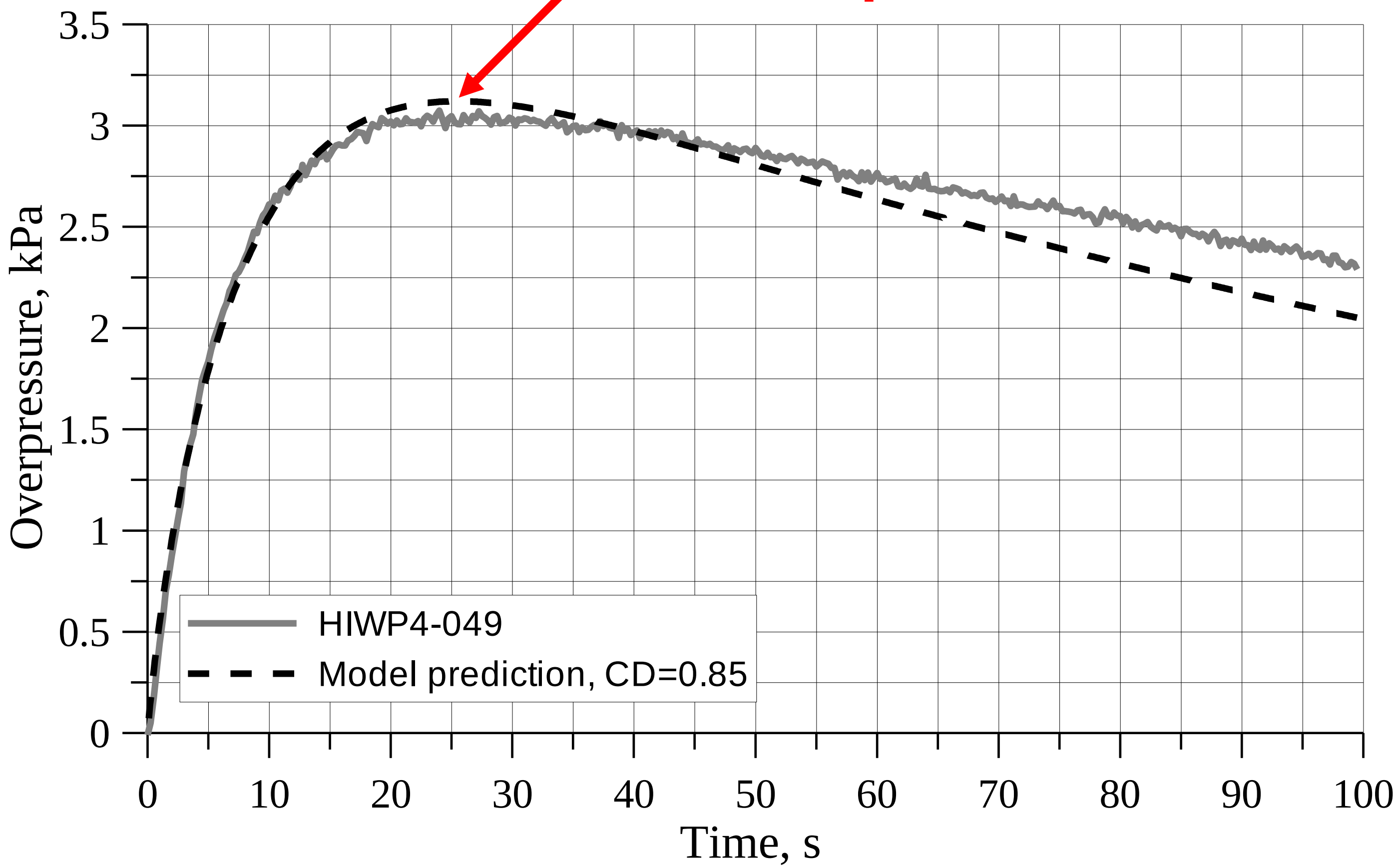


Pressure peaking phenomenon

Validation: hydrogen

Hydrogen release 0.55 g/s (enclosure 1 m^3, vent D=11 mm)

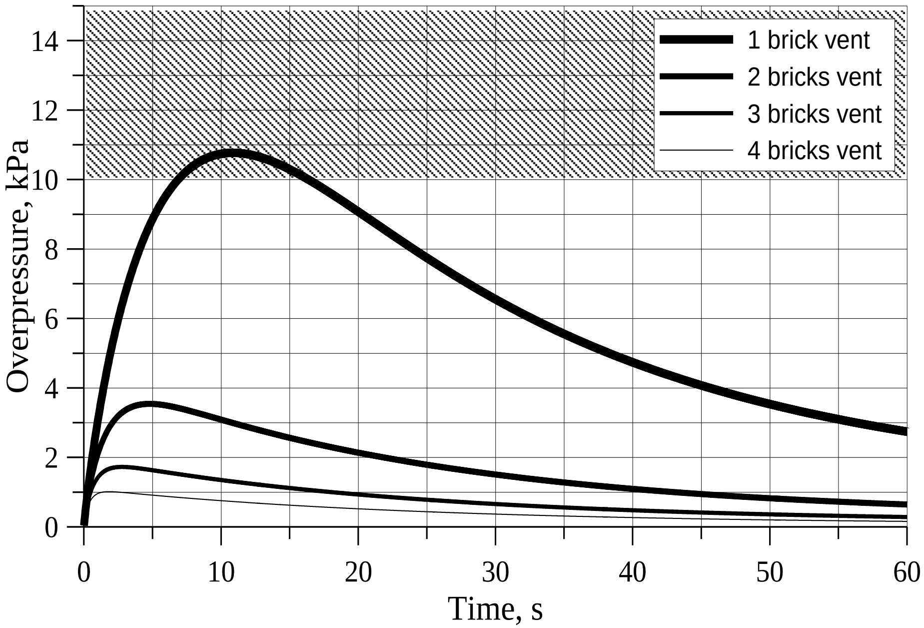
Pressure peak



Pressure peaking phenomenon

Case 1

Unignited release in the garage: TPRD D=2.0 mm, P=70 MPa (107 g/s).



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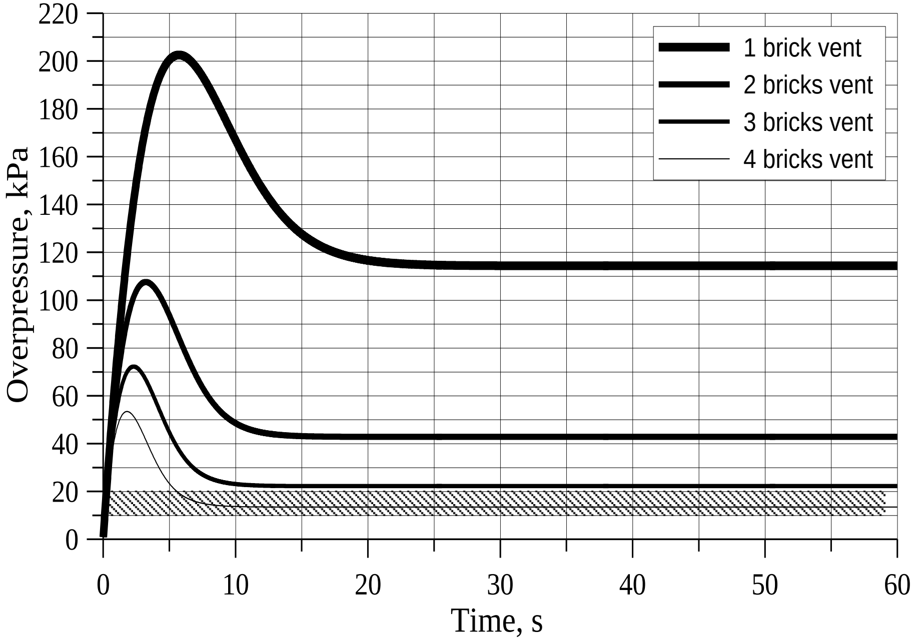
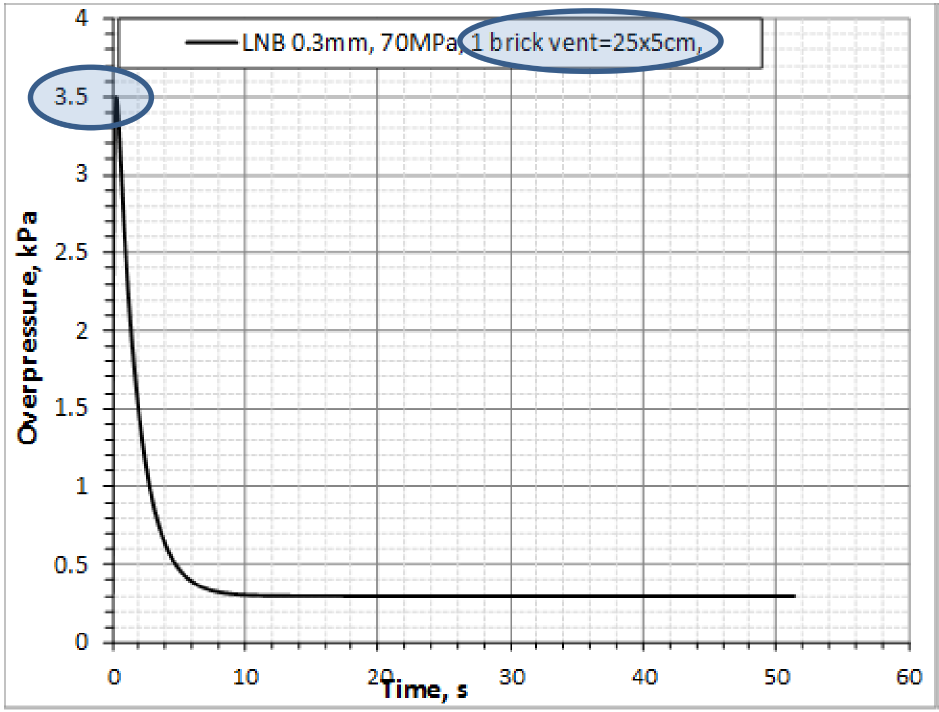
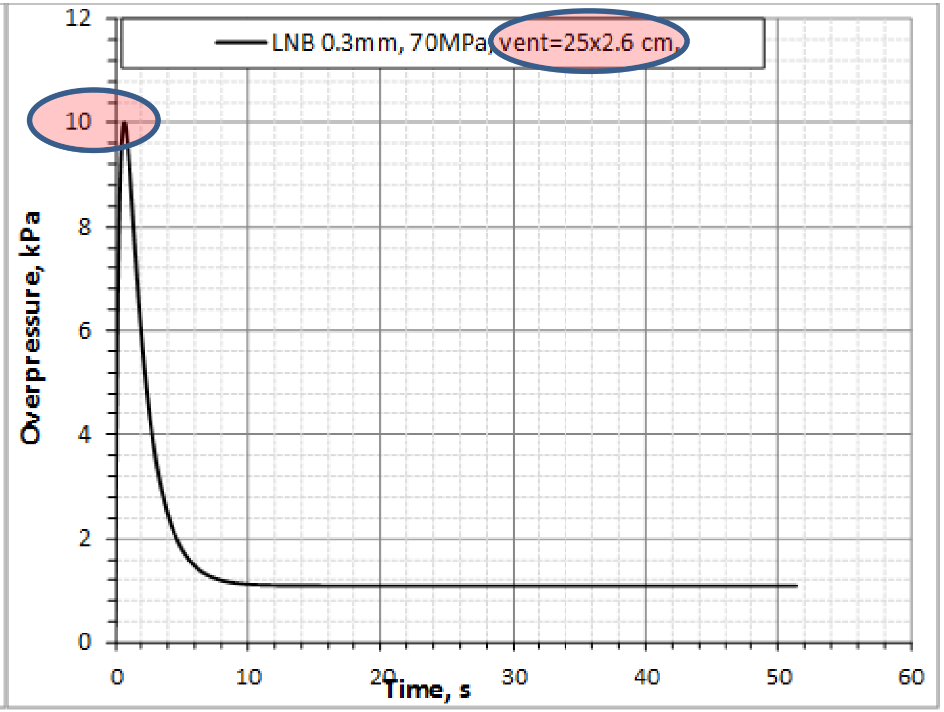


Pressure peaking phenomenon

Case 2

- **Ignited** release from TPRD with D=0.3 mm in a garage 2.6x2.6x4.5 m with vent 1 brick (left) or 0.5 brick (right).
- Onboard tank storage pressure 700 bar.
- Garage can withstand overpressure 10 kPa.

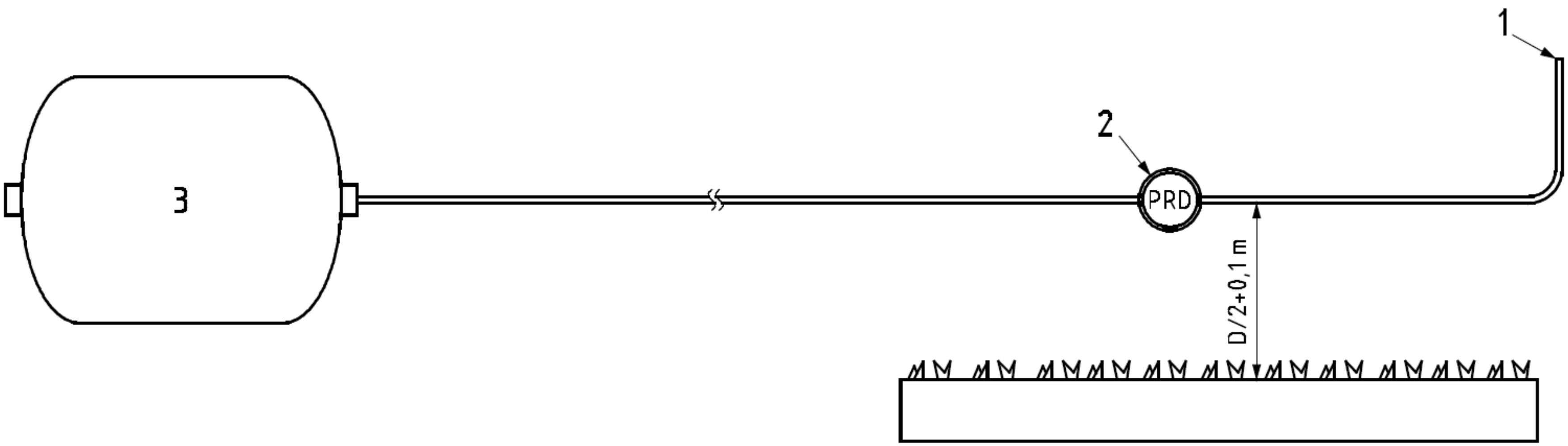




System tank-TPRD

ISO/TC 58: decoupled tank-TPRD test

Could we model coupled functioning (reality)?



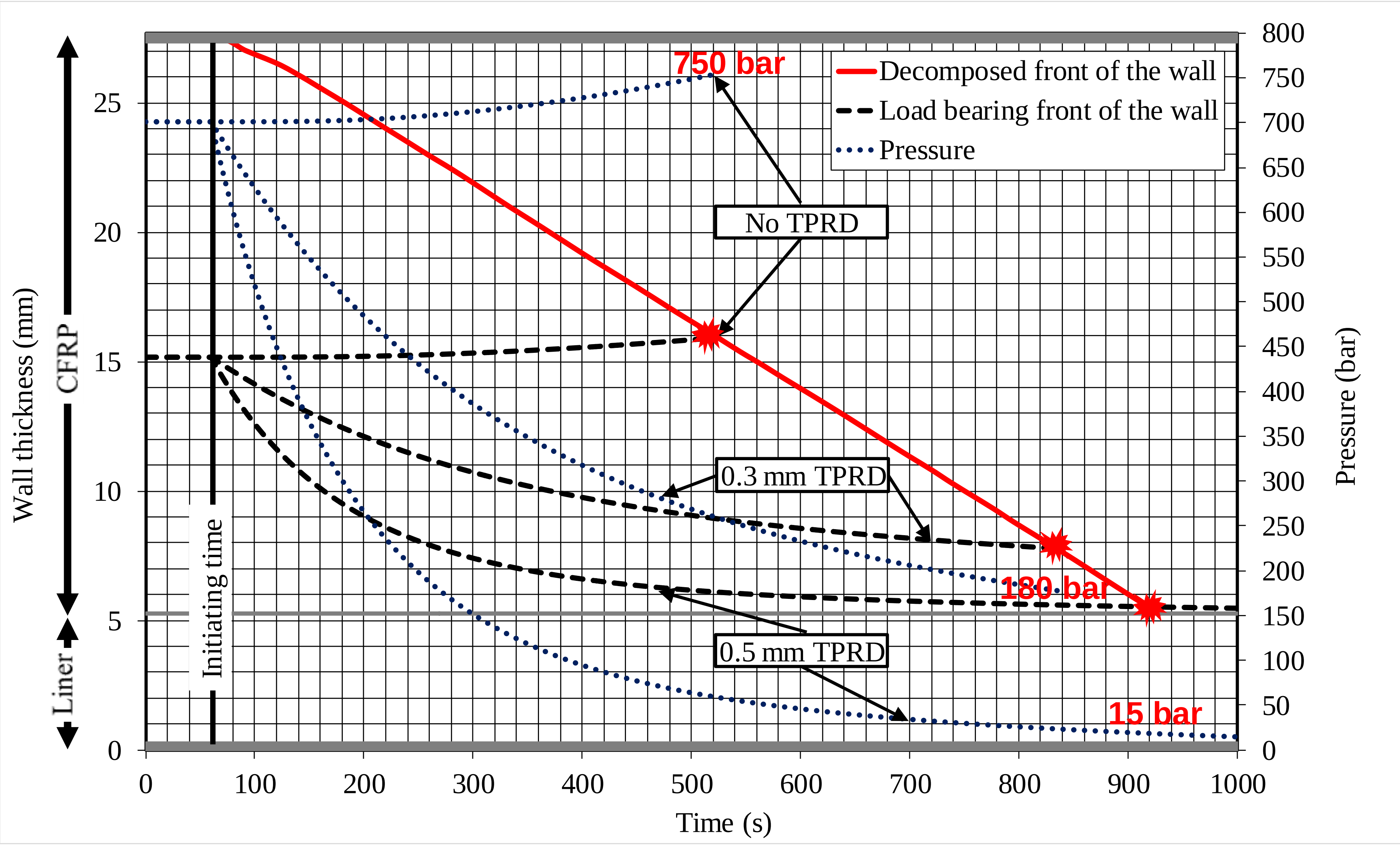
Key

1 Vent stack 2 Temperature activated pressure relief devise 3 Gas source

ISO, 'Gas Cylinders — Guidance for design of composite cylinders — Part 2: Bonfire test issues', ISO/TC 58/SC 3 N 1714, 2017

Simulation of tank-TPRD system

Initial model development



Concluding remarks

- Improvement of GTR#13 fire test reproducibility is suggested through requirements of a burner to have heat release rate above 350 kW. Development of a burner requires additional PNR.
- Pressure peaking phenomenon could be practically eliminated using TPRD diameter of 0.3-0.5 mm. This would require increase of fire resistance rating (time to rupture in test without TPRD).
- The use of TPRD diameter 0.3-0.5 mm increases fire resistance (to let first responders more time to control and eliminate “hazards”) yet doesn’t exclude the tank rupture (preliminary result).
- Explosion-free in a fire tanks could be a solution.

List of relevant urgent PNR topics

- Burner design to provide GTR#13 fire test reproducibility, including effects of wind
- Testing pressure peaking phenomenon at realistic garage-like enclosures.
- Inherently safer tank-TPRD system with minimised TPRD diameter (to exclude pressure peaking phenomenon and yet to avoid tank rupture)
- TPRD reliability data for risk assessment
- Development of explosion-free in a fire tanks
- Vehicles in tunnels, underground parking
- In-situ dumping of compressed gas potential energy
- …

Thank you