Clean Hydrogen Partnership

European Hydrogen Safety Panel (EHSP)
Clean Hydrogen JU Webinar "Computational Fluid Dynamics (CFD) for hydrogen safety analysis ", 07 December 2022

CFD analysis of hazards and associated risks

Example of joint theoretical, numerical, experimental studies for assessment of consequences for QRA of onboard hydrogen tank rupture in a tunnel fire (HyTunnel-CS project, www.hytunnel.net)

Vladimir Molkov
Member of European Hydrogen Safety Panel (EHSP)

Acknowledgements to researchers contributed to this study and relevant papers:

- Molkov VV, Cirrone DMC, Shentsov VV, Dery W, Kim W, Makarov DV. Dynamics of blast wave and fire-ball after hydrogen tank rupture in a fire in the open atmosphere. ***International Journal of Hydrogen Energy***, 46 (2021) 4644-4665. https://doi.org/10.1016/j.ijhydene.2020.10.211
- Molkov V, Dery W. The blast wave decay correlation for hydrogen tank rupture in a tunnel fire. ***International Journal of Hydrogen Energy***, 2020;45:31289-31302. https://doi.org/10.1016/j.ijhydene.2020.08.062
- Kudriakov S, Studer E, Bernard-Michel G, Bouix D, Domergue L, Forero D, Gueguen H, Ledier C, Manicardi P, Martin M, Sauzedde F. Full-scale tunnel experiments: Blast wave andfireball evolution following hydrogen tank rupture. ***International Journal of Hydrogen Energy***, 47 (2022) 18911-18933. https://doi.org/10.1016/j.ijhydene.2022.04.037
- Kashkarov S, Dadashzadeh M, Sivaraman S, Molkov V. QRA methodology for hydrogen tank rupture in a tunnel fire. ***Hydrogen***, 2022 (submitted for publication)

EUROPEAN PARTNERSHIP

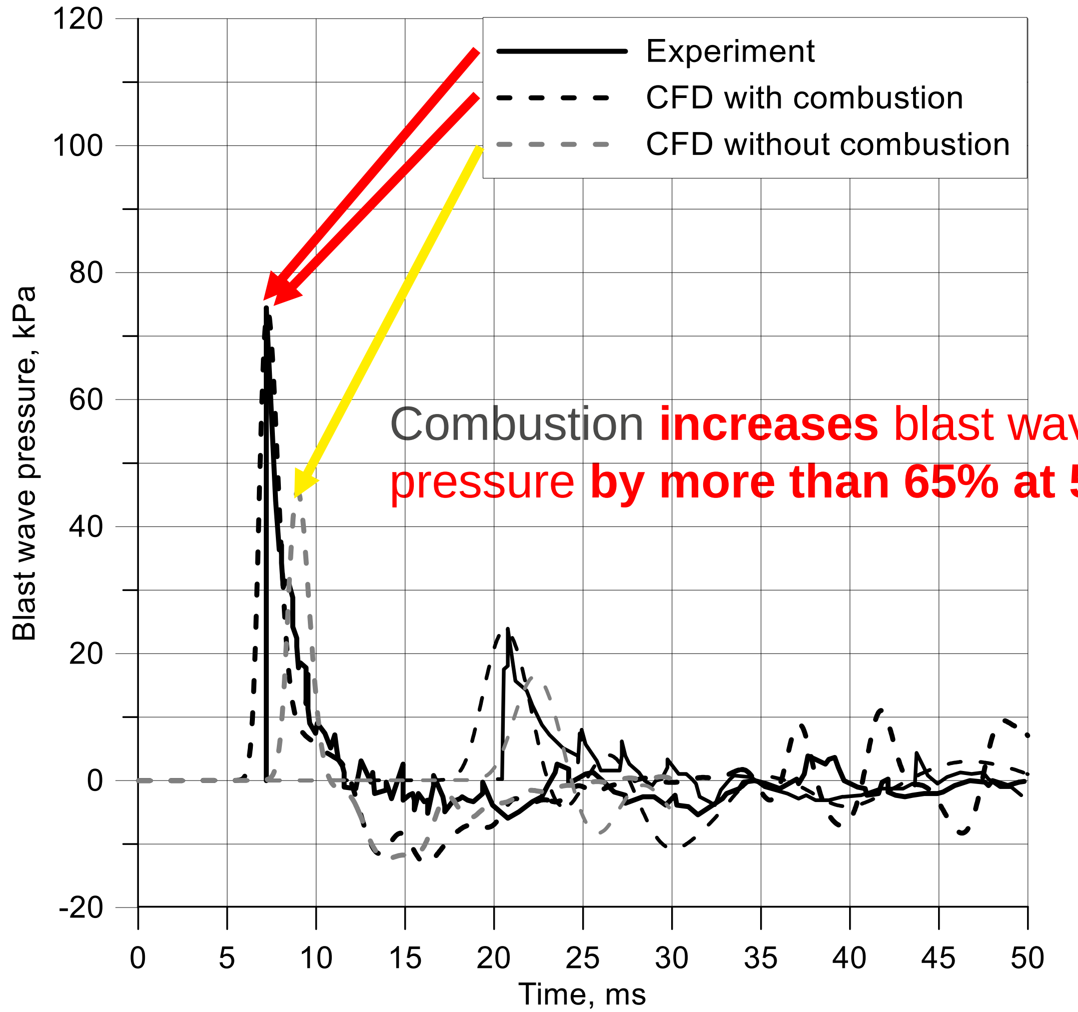
Presentation outline

- Example of joint theoretical, numerical, experimental studies to underpin the QRA in HyTunnel-CS project (www.hytunnel.net). Research structure applied:
  - Development and validation of CFD model accounting for all physical phenomena and reproducing experimental data on **tank rupture in a fire**.
  - CFD analysis of hazards: **numerical experiments** on different tanks rupture **in tunnels** with different length, cross-section area, aspect ratio, etc.
  - Theoretical **similitude analysis** of numerical experiments **to build the universal correlation** for blast wave decay after tank rupture in a tunnel fire.
  - **Validation of the universal correlation** for blast wave decay after tank rupture in a tunnel fire against **experiments in real tunnel**.
  - Use of the correlation for **assessment of hazards (consequences) and QRA** of incidents with hydrogen-powered vehicles in tunnels.

Co-funded by the European Union

CFD model of tank rupture in a fire

Combustion contributes to the blast wave strength



Combustion **increases** blast wave pressure **by more than 65% at 5 m!**

Japanese Test No.2 (open atmosphere)

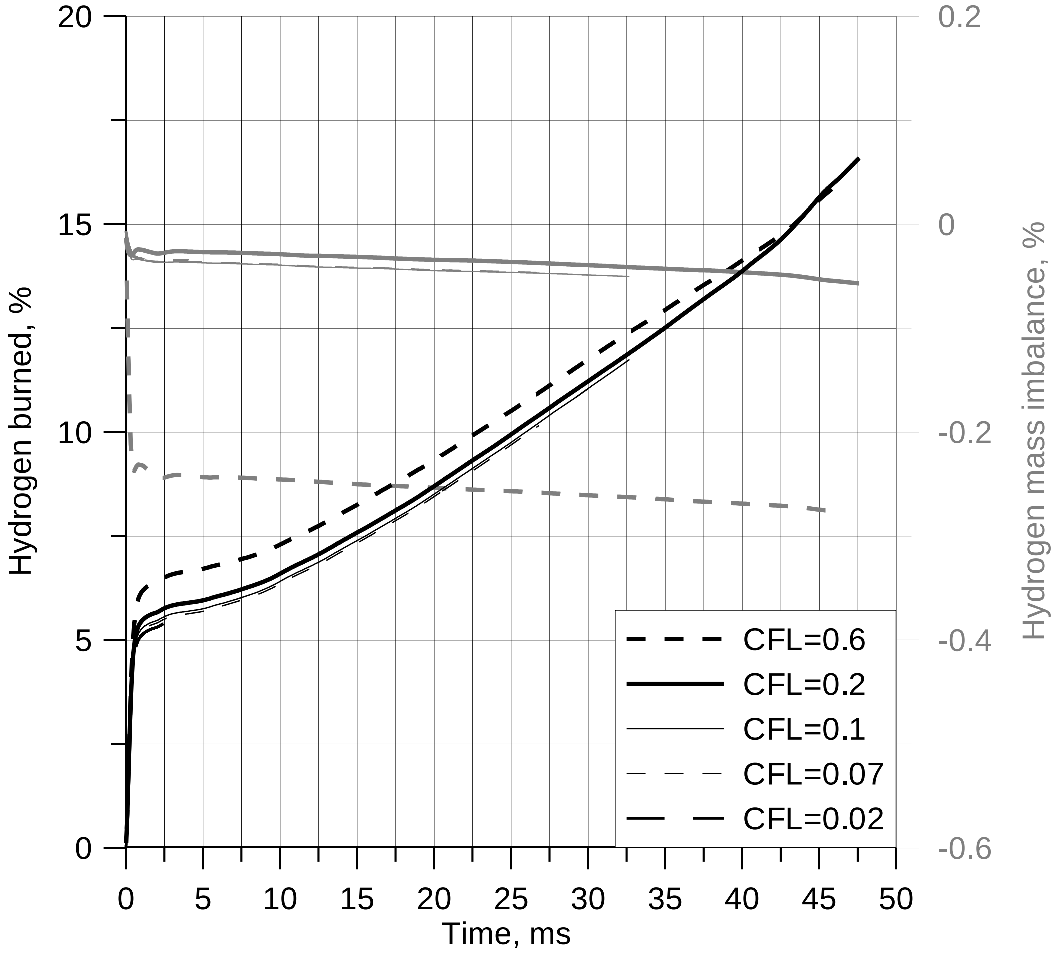
Conclusion: tank rupture models without combustion cannot be used for hydrogen safety engineering.

Clean Hydrogen Partnership

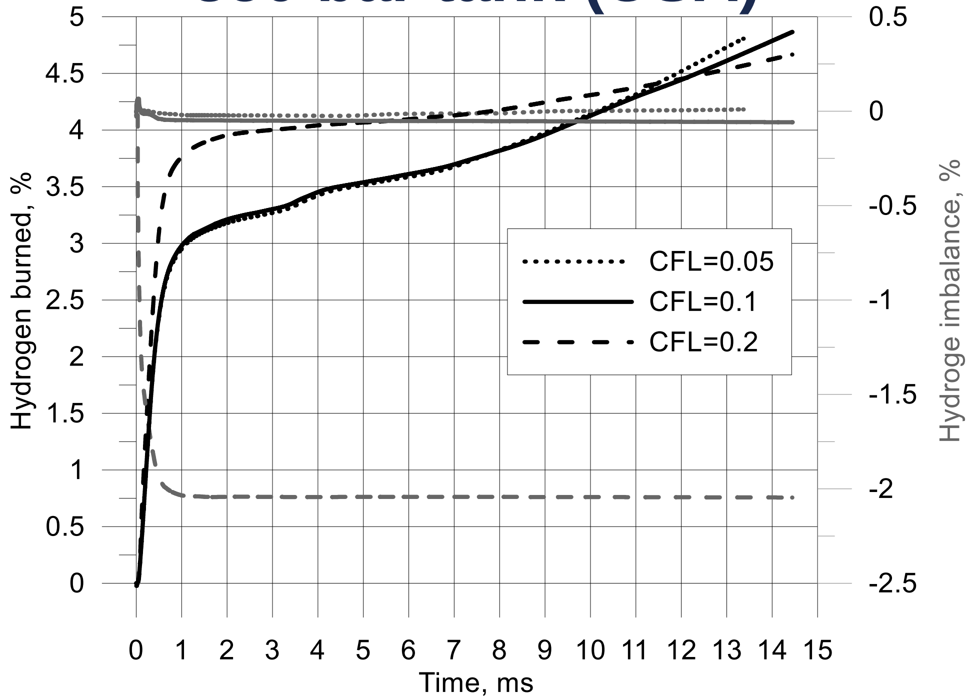
CFD model of tank rupture in a fire

Why combustion rate decreases after about 1 ms?

700 bar tank (Japan)



350 bar tank (USA)



Hydrogen mass burnt during fast combustion:

- **3%** for storage tank with NWP=**350 bar**
- **6%** for tank with NWP=**700 bar**

Conclusion: hydrogen mass contributing to the blast wave strength depends on storage pressure.

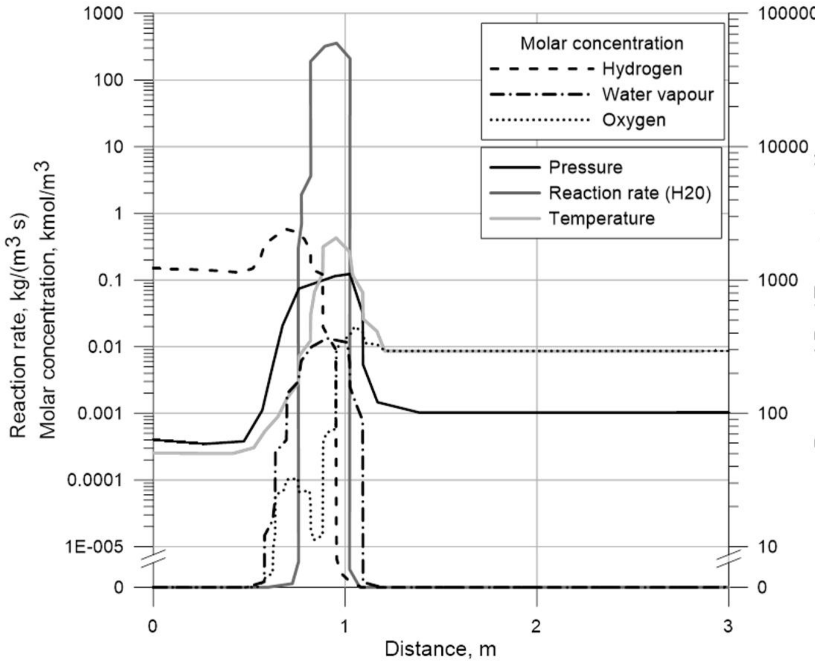
Clean Hydrogen Partnership

CFD model of tank rupture in a fire

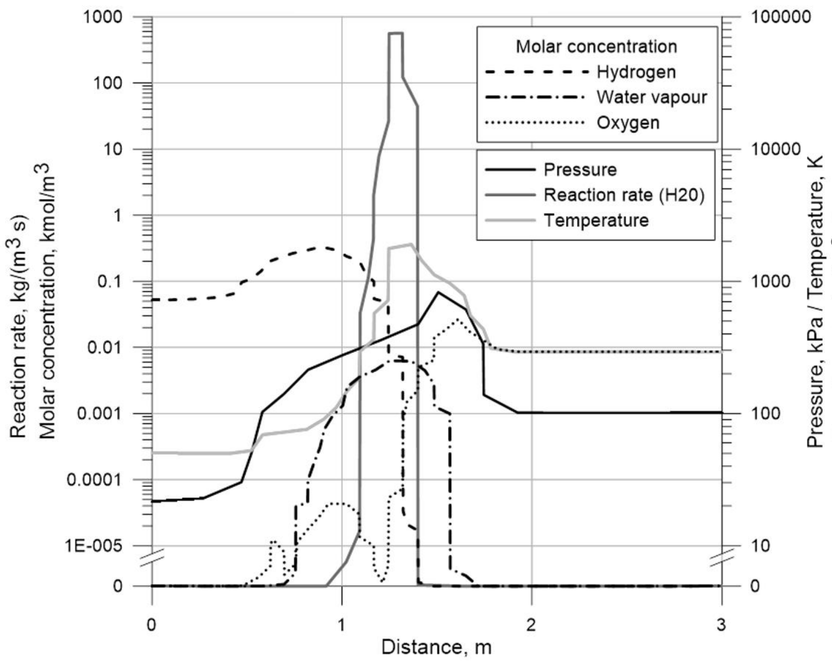
Why combustion rate decreases after about 1 ms?

Dynamics of H2, O2, H2O, temperature, reaction rate (H2O), and pressure in time.

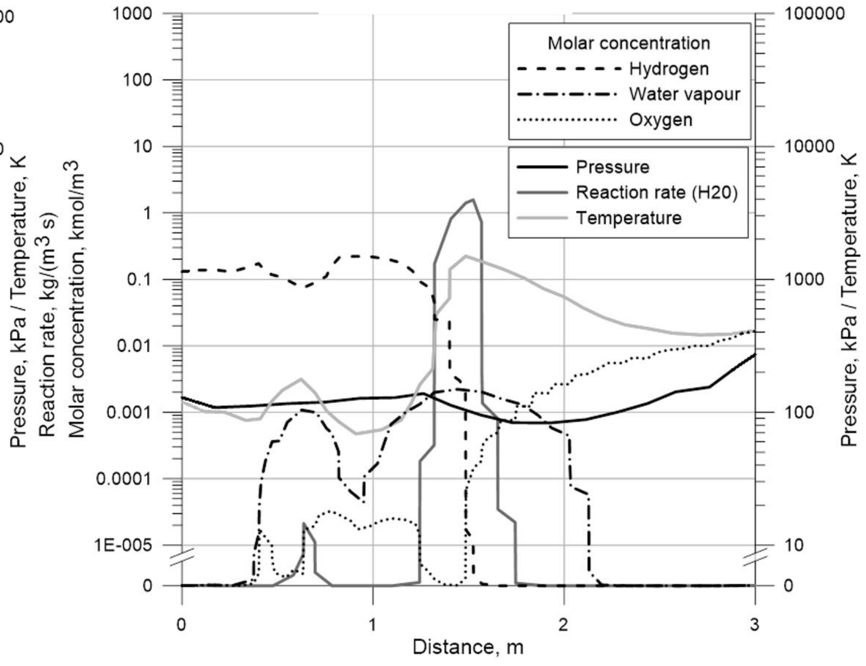
0.5 ms



1 ms



3 ms



Conclusion: reaction rate decrease with decrease of pressure at the contact surface.

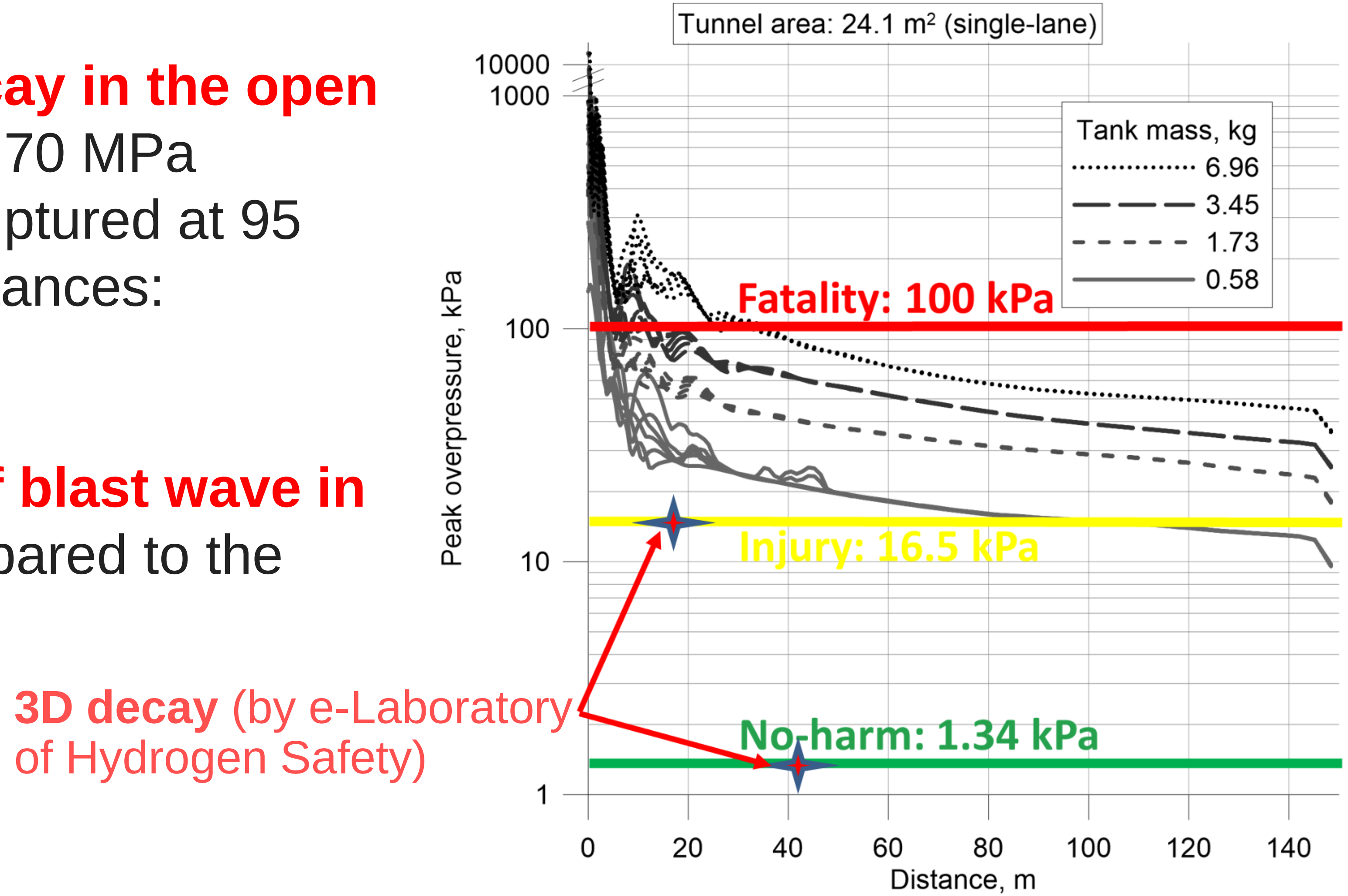
Co-funded by the European Union

Clean Hydrogen Partnership

Numerical experiments with validated model

Blast wave decay: atmosphere versus tunnel

- **Diamonds – fast 3D decay in the open atmosphere** for 171.5 L, 70 MPa (6.96 kg at 288 K) tank ruptured at 95 MPa (390 K). Hazard distances:
  - Serious injury: <18 m
  - No-harm: >41 m
- Extremely **slow decay of blast wave in a tunnel** (quasi-1D) compared to the open atmosphere (3D).

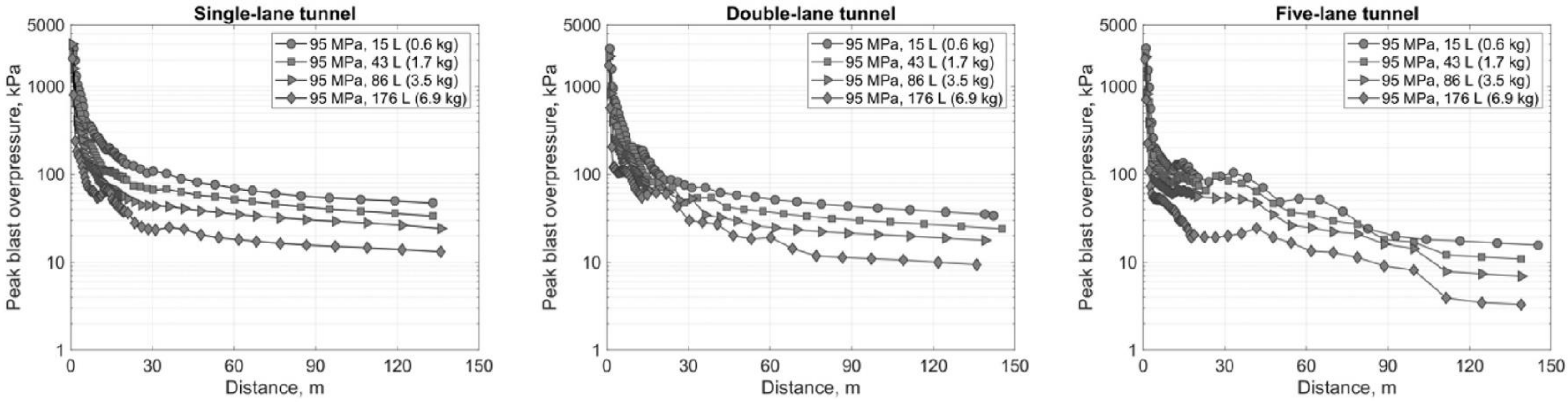


Conclusion: tank rupture in a tunnel (confined space) must be excluded by all means.

Numerical experiments with validated model

Series of storage tanks rupturing in different tunnels

Numerical experiments in tunnels of cross-section area 24-139 m^2, aspect ratio width-height 1.2-2.7, tunnel length 150-1500 m with tanks of volume 15-176 L, and pressure 35-95 MPa (mass 0.6-6.9 kg).



Conclusion: numerical tests with validated CFD model are efficient for consequences analysis.

Co-funded by the European Union

Clean Hydrogen Partnership

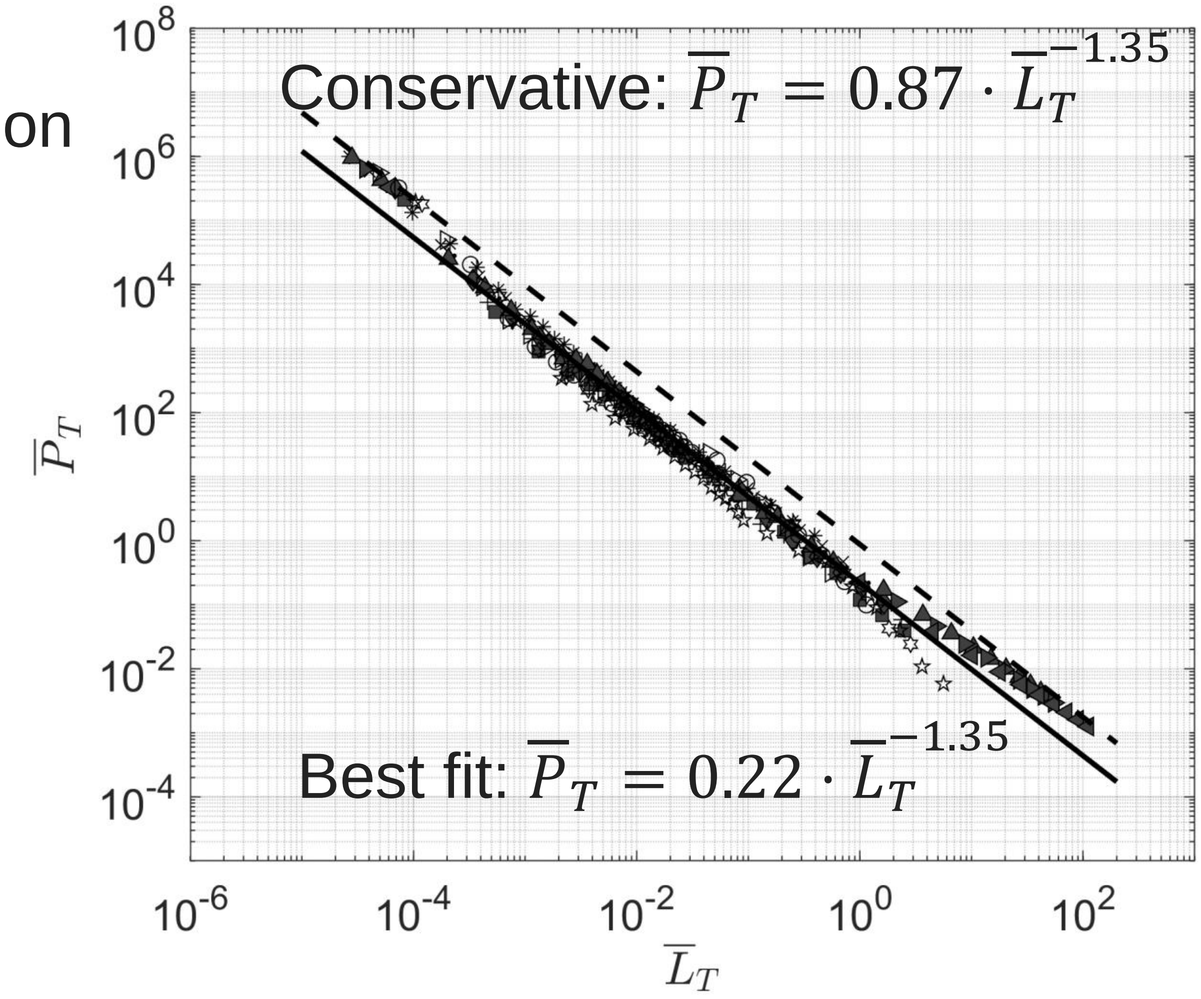
The correlation for blast decay in tunnel

Similitude analysis of numerical experiments

Rupture of tank of arbitrary volume and pressure in a tunnel of different cross-section area, aspect ratio and length.

Dimensionless distance: $\overline{L}_T = \frac{P_0 LA}{E \cdot AR^{0.5}} \left(\frac{fL}{D_T}\right)$

Dimensionless pressure : $\overline{P}_T = \frac{\Delta P}{P_0} \cdot \frac{1}{\overline{L}_T}$



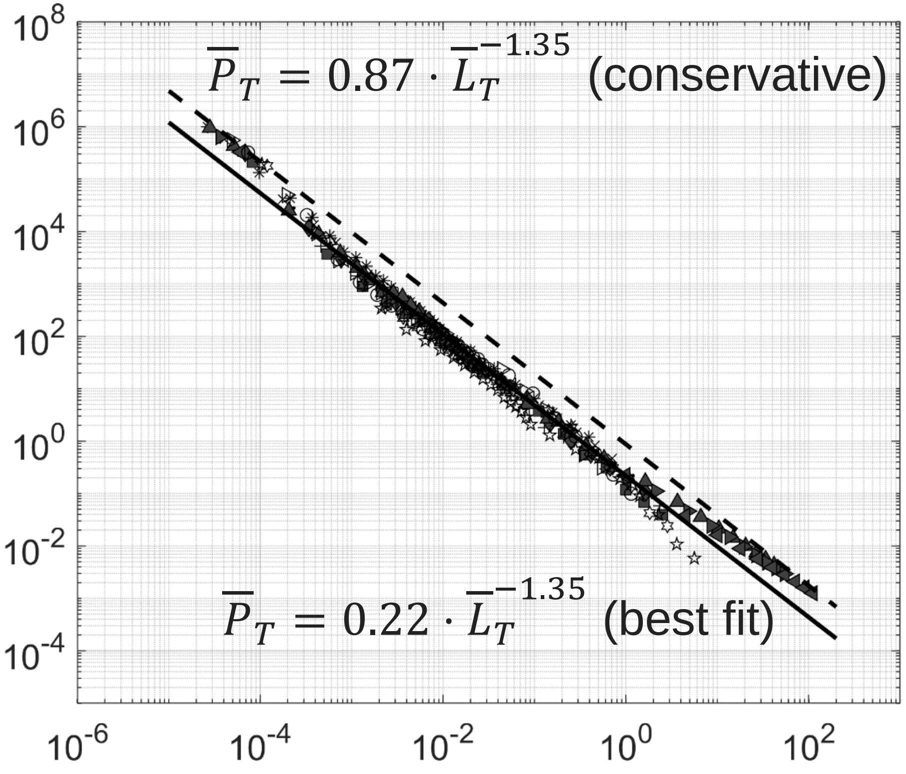
Conclusion: use complementarities and synergies of theoretical and numerical methods to develop tools for hydrogen safety engineering.

The correlation for blast decay in tunnel

Validation of the correlation against real tunnel tests

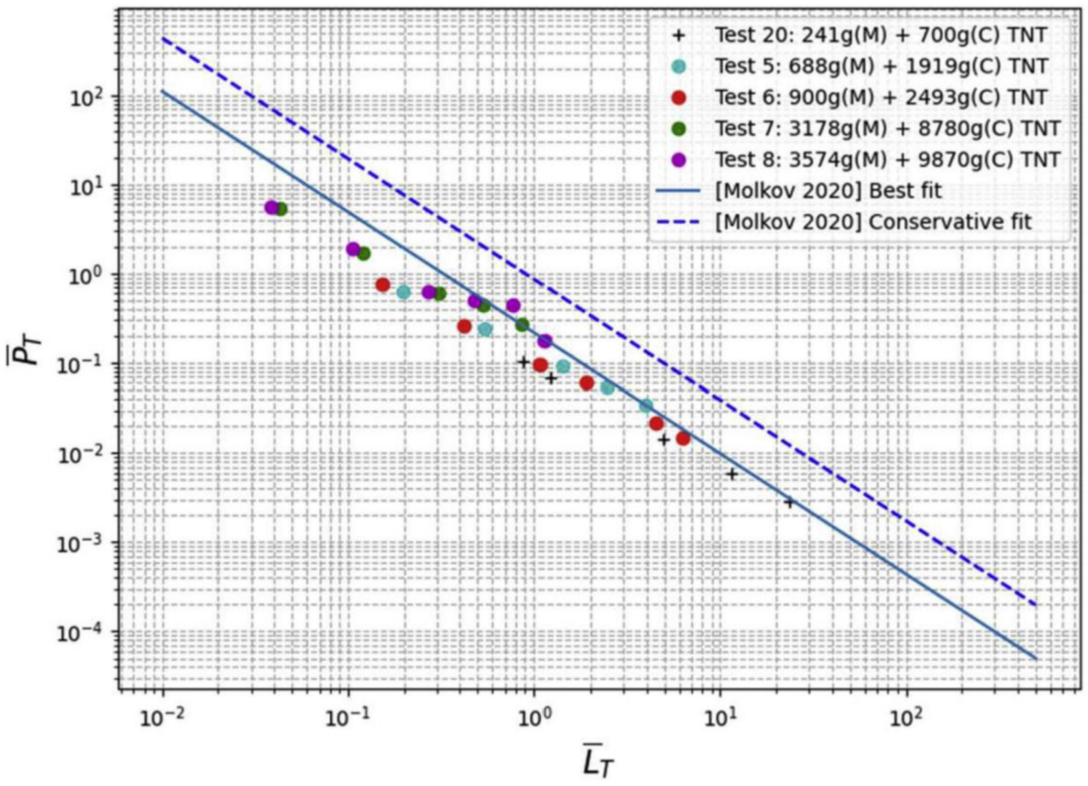
Correlation by Ulster

$$\overline{P}_T = \frac{\Delta P}{P_0} \cdot \frac{1}{\overline{L}_T}$$



$$\overline{L}_T = \frac{P_0 LA}{E \cdot AR^{0.5}} \left(\frac{fL}{D_T} \right)$$

Validation by CEA



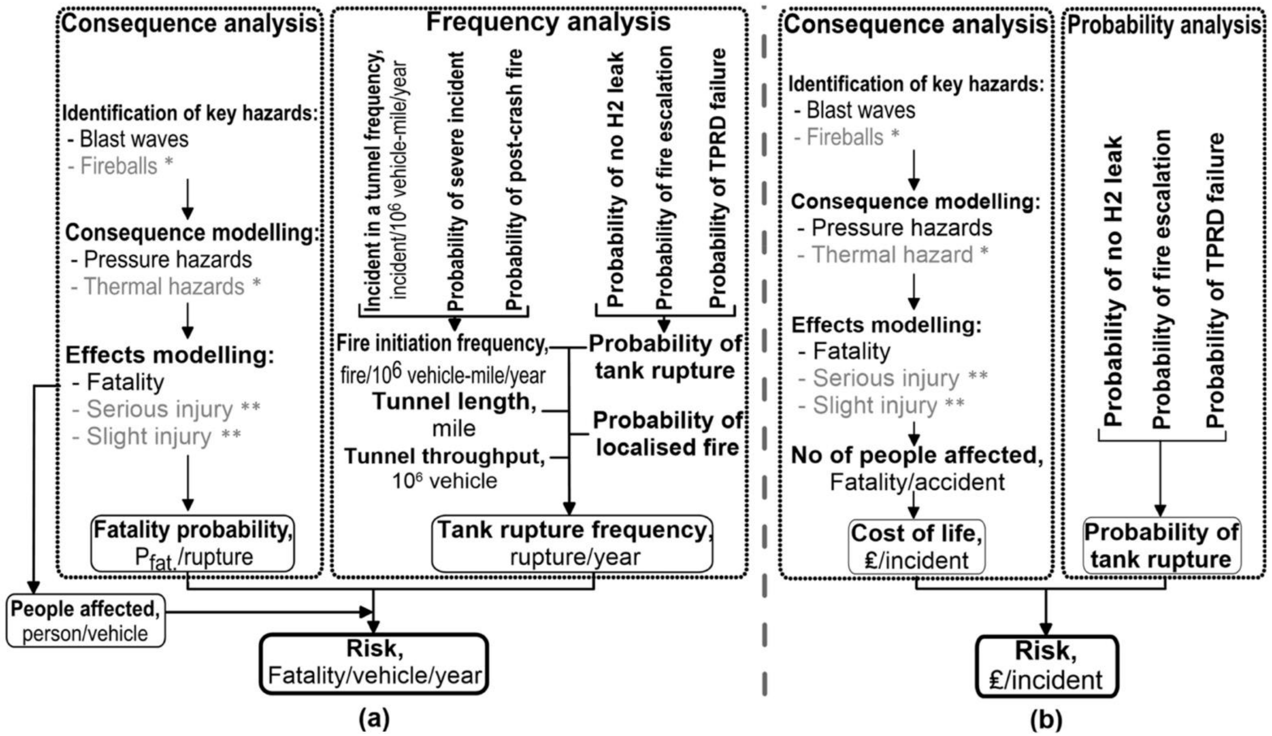
Best fit correlation is demonstrated

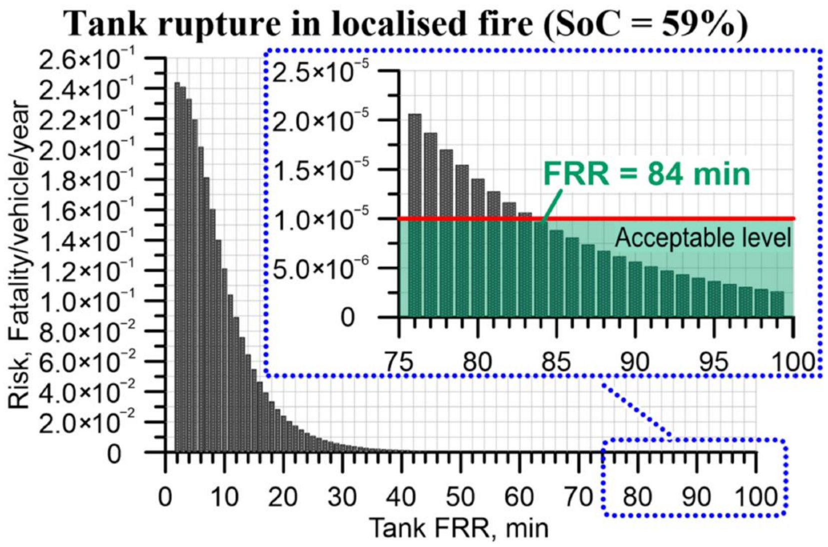
Conclusion: joint theoretical-numerical-experimental study generated a new tool for QRA.

Assessment of consequences for QRA

Scenario: hydrogen vehicle incident in Dublin tunnel

- Risk = (Probability of an event) X (**Consequences**)
- The developed correlation for blast wave decay is applied to **assess consequences** of incident with hydrogen vehicle in Dublin tunnel fire as a part of **QRA methodology**.





Risk is acceptable if FRR of tank-TPRD system is more than 84 min or explosion free in a fire self-venting (TPRD-less) tanks are used.

Conclusion: QRA is preferable to "coloured" risk but requires validated tools as in this study.

Clean Hydrogen Partnership

Thank you

Vladimir MOLKOV
European Hydrogen Safety Panel
EHSP@clean-hydrogen.europa.eu

For further information
v.molkov@ulster.ac.uk

Co-funded by the European Union