Hydrogen safety research
– the achievements and the challenges

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Low carbon hydrogen will be essential for achieving net zero

Figure 1.2: Hydrogen demand and proportion of final energy consumption in 2050

% = hydrogen as proportion of total energy consumption in 2050

Source: Central range – illustrative net zero consistent scenarios in CB6 Impact Assessment. Full range – based on whole range from UK Hydrogen Strategy Analytical Annex. Final energy consumption from ECUK (2019).

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The Hydrogen Value Chain

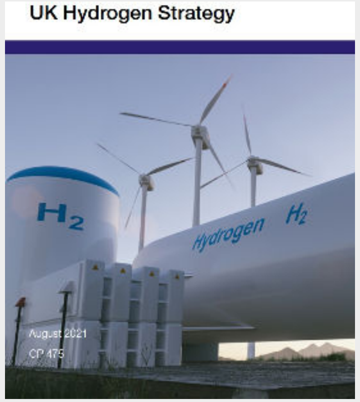
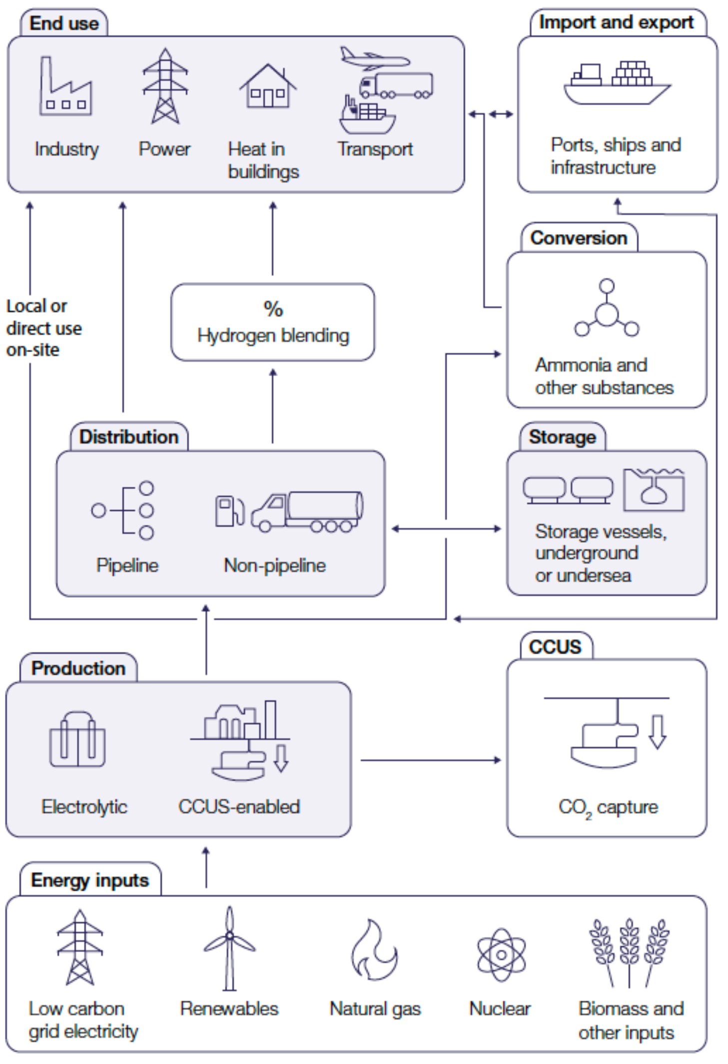


Figure 2: The hydrogen value chain

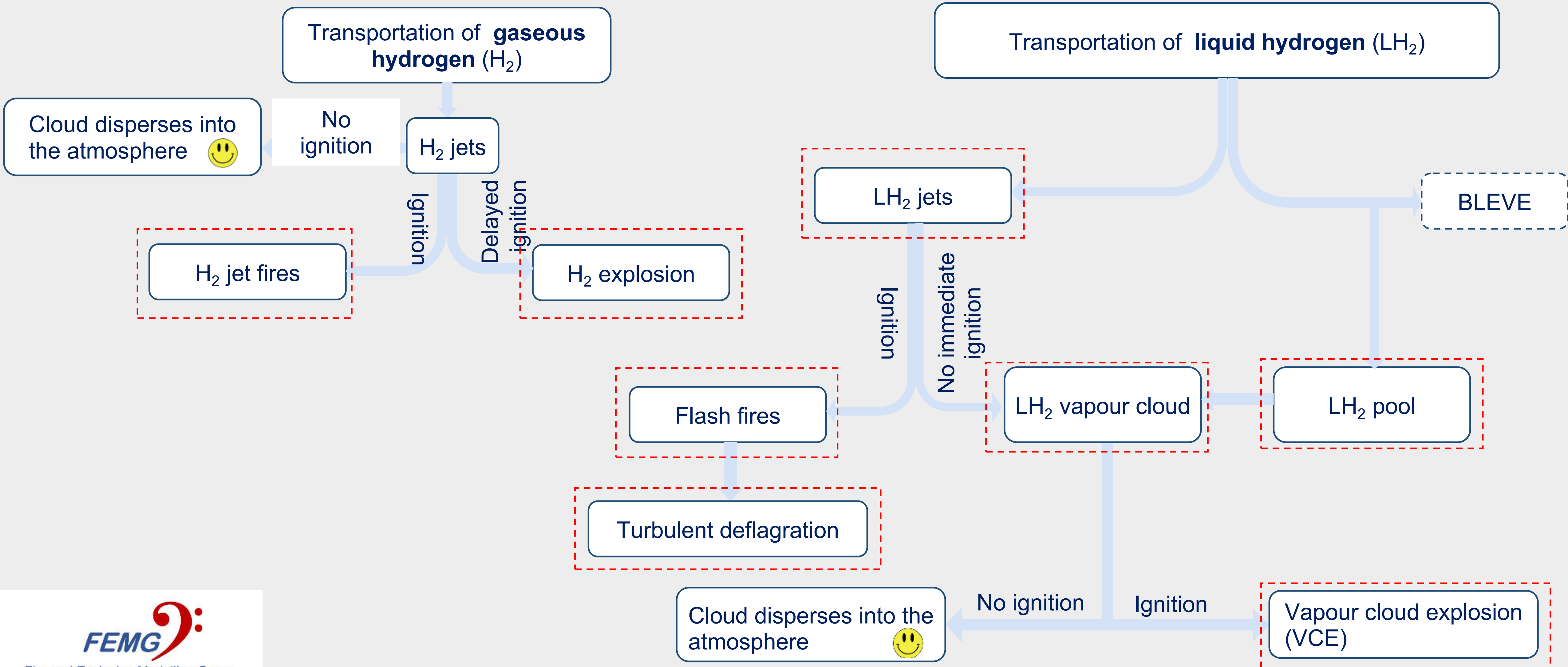


Gaseous (H2)

Liquid hydrogen (LH2)

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf

Potential accidental scenarios



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Outline

- Releases
- Ignition
- Hydrogen jet fires
- Hydrogen deflagrations
- Flame acceleration (FA) and deflagration to detonation transition (DDT)

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Releases – Gaseous Hydrogen

Knowledge gaps: the environment impact of anthropogenic hydrogen*(both gaseous and liquid hydrogen)* leaking into the atmosphere

» Significant experimental and numerical studies have been conducted

» The behavior of gaseous hydrogen in the air is well understood

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Releases – Liquid Hydrogen (1/2)

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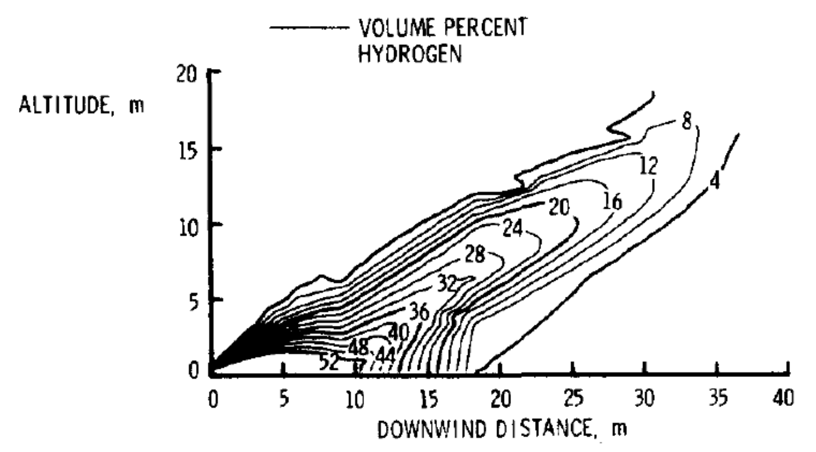
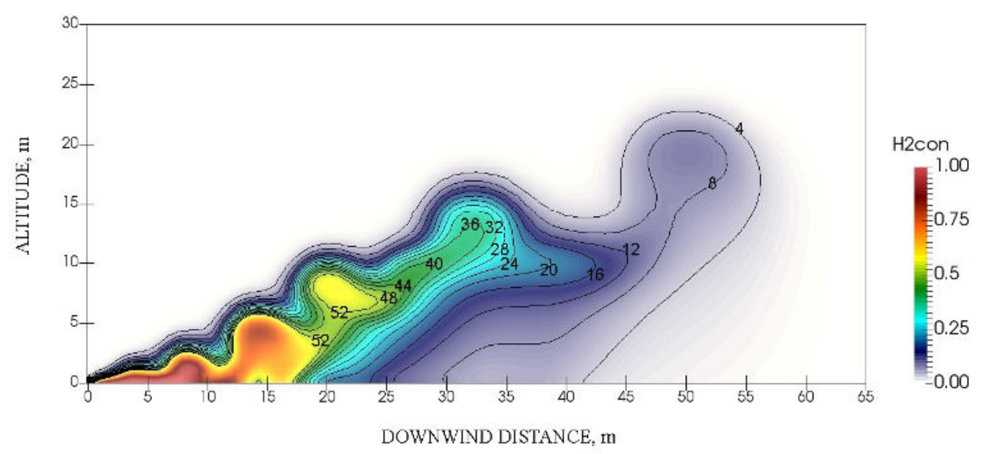
Earlier NASA tests and some validation



Witcofski RD, Chirivella JE. Experimental and analytical analyses of the mechanisms governing the dispersion of flammable clouds formed by liquid hydrogen spills. Int J Hydrogen Energy 1984; 9(5).



BP Xu, S Jallais, D Houssin, E Vyazmina, L Bernard, JX Wen, Numerical simulations of atmospheric dispersion of large-scale liquid hydrogen releases, Ebook - ICHS 2021 – Sep.2021

	Experiment	Prediction
Horizontal extent of visible cloud	160	173
Vertical extent of visible cloud	65	69
Duration of visible cloud	90	88

Comparison between measured (left) and predicted (right) H_2 molar concentration at = 20.9 s

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Releases – Liquid Hydrogen (2/2)

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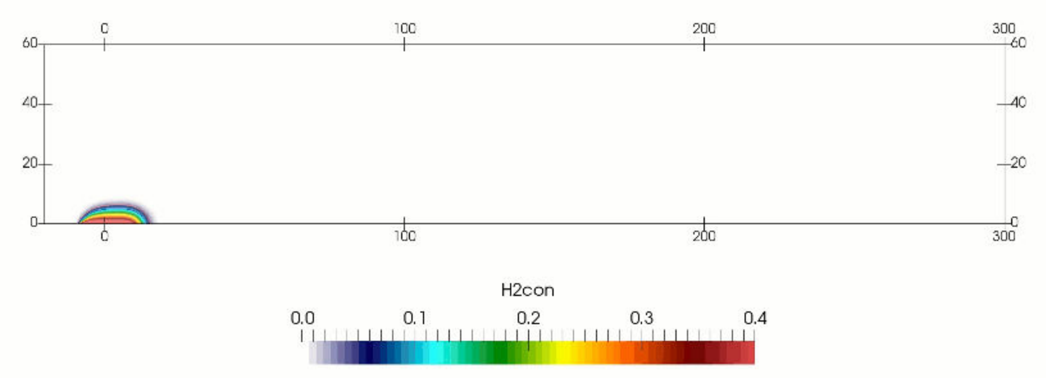
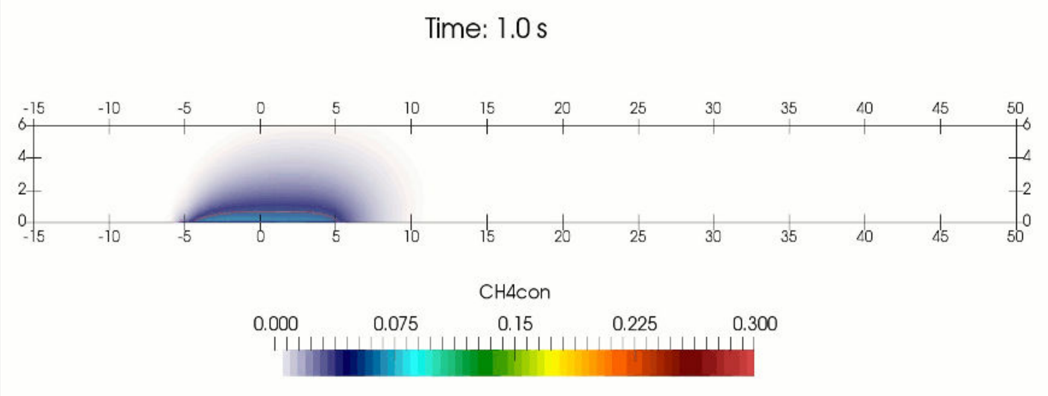
Knowledge gasps: Quantitative validation is needed.

Vapour cloud from 1 ton release of LH_2 and LNG





Ambient temperature: 293K
5 m/s neutral condition

LH_2

Ambient temperature: 293K

Without retention pit (**5D**) : 0 – 100 s

Red line: 4% H_2 molar concentration

LNG

Without retention pit (**5D**) : 0 – 150 s
Red line: 5% CH_4 molar concentration.

BP Xu, S Jallais, D Houssin, E Vyazmina, L Bernard, JX Wen, Numerical simulations of atmospheric dispersion of large-scale liquid hydrogen releases, Ebook - ICHS 2021 – Sep.2021

Air Liquide

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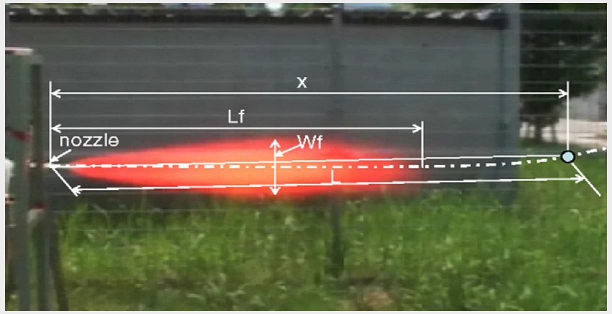
Ignition

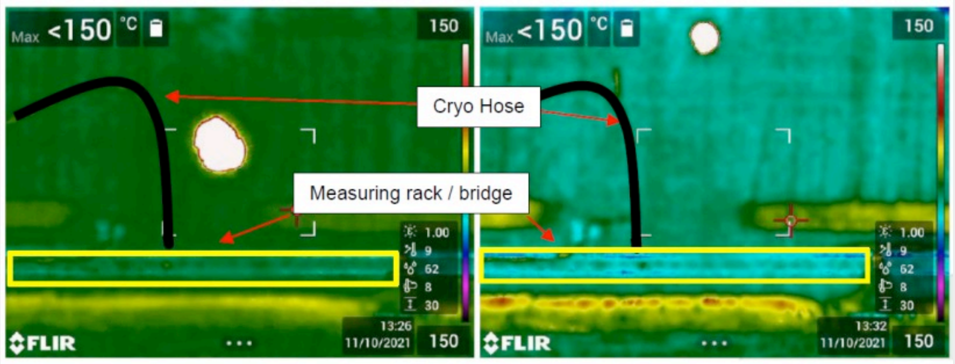
Knowledge gaps: ignition of ultra lean H2-air mixtures
ignition mechanism H2 vapour cloud from cryogenic release

- **Spontaneous (diffusion) ignition**
- **Hot surface ignition**
- **Static electricity**
- **Mechanical friction and impact**

Releases of compressed H_2 into the air



Tomohiko Imamura, Shota Hamada, Toshio Mogi, Yuji Wada, Sadashige Horiguchi, Atsumi Miyake, Terushige Ogawa, Int J of Hyd Energy, 33,(13),2008.



Releases of LH_2 onto and under water

1. *M. Kluge, A.K. Habib and K. van Wingerden, Experimental investigation into the consequences of release of liquified hydrogen onto and under water, Proc. 14th Int. Symp on Hazards, Prevention, and Mitigation of Industrial Explosions (ISPMIE), July 2022, Germany.*
2. *K. van Wingerden, M. Kluge, A.K. Habib, F. Ustolin, N. Paltrinieri, Experimental investigation into the consequences of release of liquified hydrogen onto and under water, CHEMICAL ENGINEERING TRANSACTIONS, VOL. 90, 2022.*

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Gaseous hydrogen jet fires

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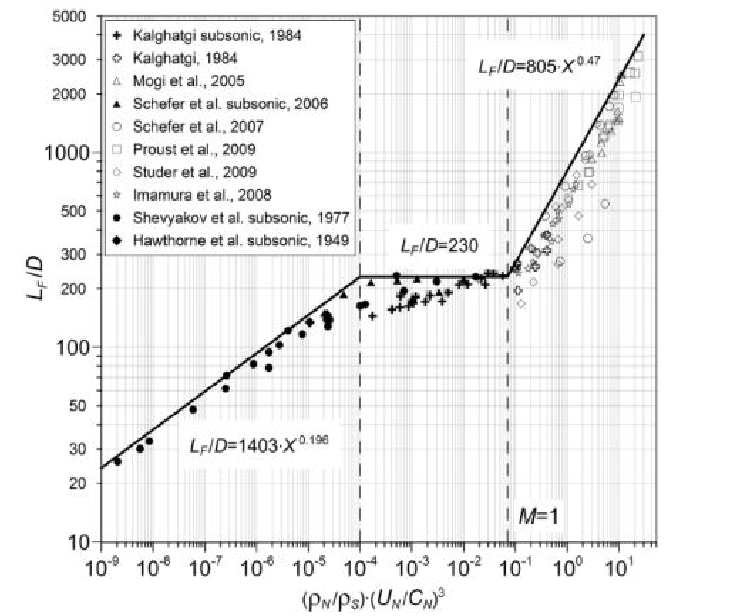
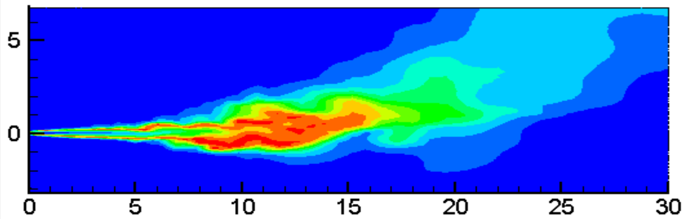
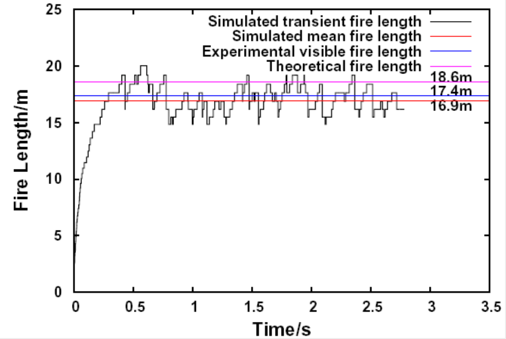


The dimensionless correlation for hydrogen jet flames (in formulas "X" denotes the similarity group shown in the horizontal axis)

Molkov VV, Saffers JB. Hydrogen jet flames. Int J Hyd Energy 2013; 38(19).





Comparison between jet fire predictions and measurements.

Ekoto, I.W., Houf, W.G., Ruggles A.J., Creitz, L.W. and Li, J.X., Large-scale Hydrogen Jet Flame Radiant Fraction Measurements and Modelling, Proceedings of the 2012 9th the International Pipeline Conference, Calgary, Alberta, Canada, 2012, Paper IPC2012-90535, 2012.

Wang, C. J., Wen, Jennifer X., Chen, Z. B. and Dembele, S. (2014) Predicting radiative characteristics of hydrogen and hydrogen/methane jet fires using FireFOAM. International Journal of Hydrogen Energy, 39 (35).

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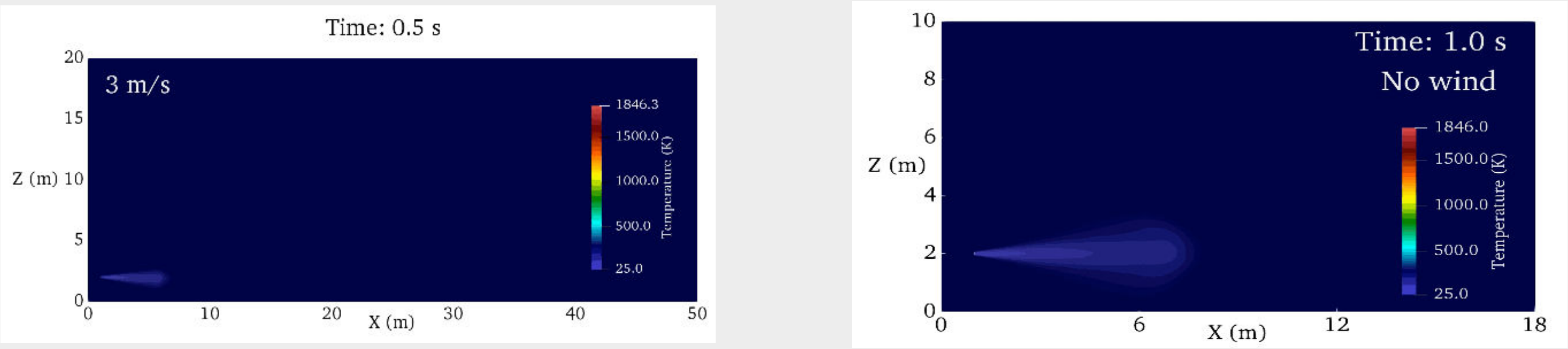
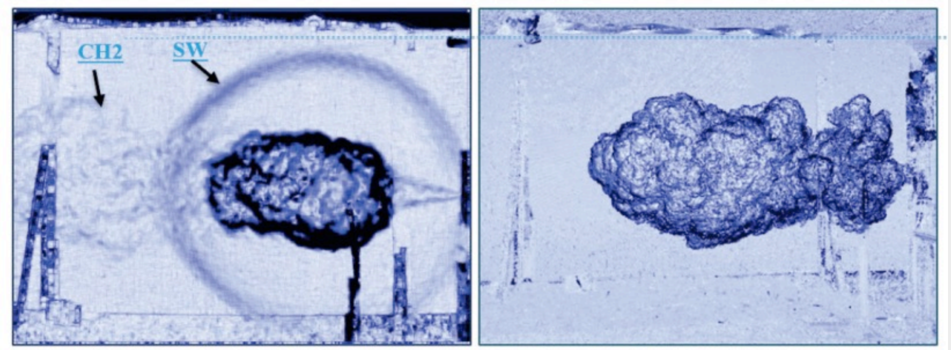
Liquid hydrogen jet fires

Knowledge gasps: Validation is needed.



Unpublished and unvalidated cryogenic hydrogen jet fires.



Shock wave formation (left) and a stationary jet fire (right) established under ignition of 4-mm nozzle and 20 MPa pressure hydrogen release: SW –shock wave; CH2 –unignited hydrogen

Jordan, T., Bernard, L., Cirrone, D., Coldrick, S., Friedrich, A., Jallais, S., Kuznetsov, M.Proust, C., Venetsanos, A. and Wen, J.X., Results of the pre-normative research project Preslhy for the safe use of liquid hydrogen, Ebook - ICHS 2021 – Sep.2021.

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Gaseous hydrogen deflagrations (1/2)

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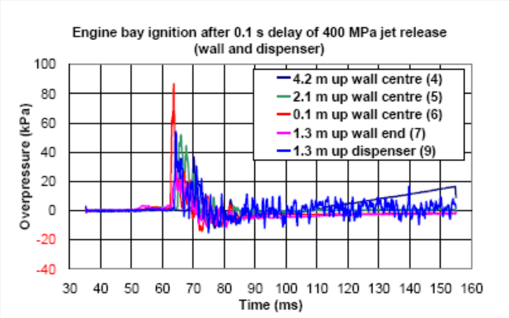
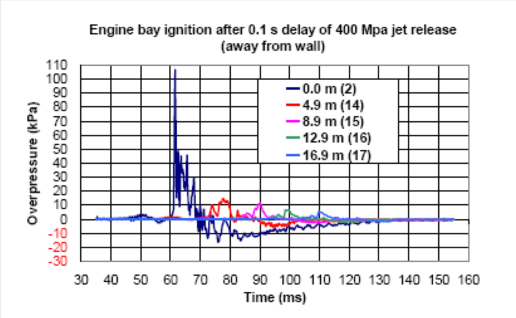
Knowledge gasps: challenging to include detailed geometry for large-scale congested rigs (academic research?)





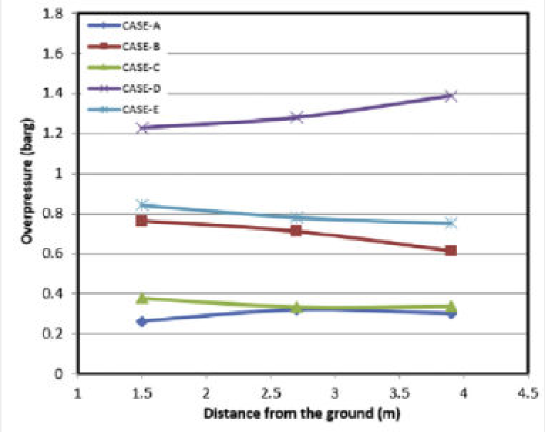


Fig. 22 – Maximum overpressure obtained using simulations on the High wall. CASE–A: One wall scenario (High wall ignition), CASE–B: Two wall scenario (Low wall ignition), CASE–C: Two wall scenario (High wall ignition), CASE–D: Three wall scenario (Low wall ignition) and CASE–E: Three wall scenario (High wall ignition).

Tests were conducted to demonstrate worst case scenarios
Reservoir pressure - 400 bar
Mass flow rate - 2.62 kg/s
Nozzle -1.2 m above ground, vertically downward between the engine bay and dispense

Shirvill, L.C., Royle, M. and Roberts, T.A.,, Proc. 2nd Int Conf on Hydrogen Safety, Sep. 2007, Spain.
M Rao, J.X. Wen, V.H.Y. Tam - Process safety and environmental protection, IChemE Symposium and exhibition on 10th–12th Nov. 2009,University of Manchester, UK.

Vendra C. Madhav Rao, Pratap Sathiah and Jennifer X. Wen, Effects of congestion and confining walls on turbulent deflagrations in a hydrogen storage Facility-Part 2: Numerical Study, Int J of Hydrogen Energy,43(32), 2018.

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Hydrogen vapor cloud explosions (VCE) from cryogenic LH_2 releases

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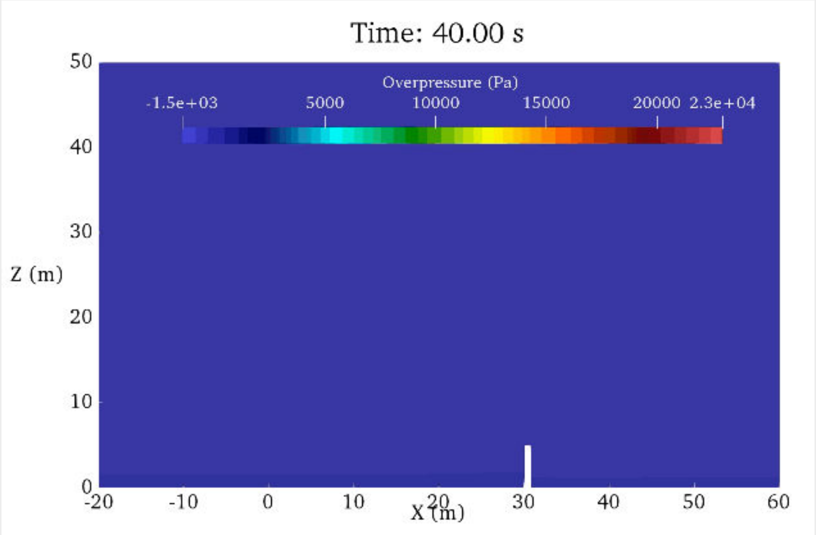
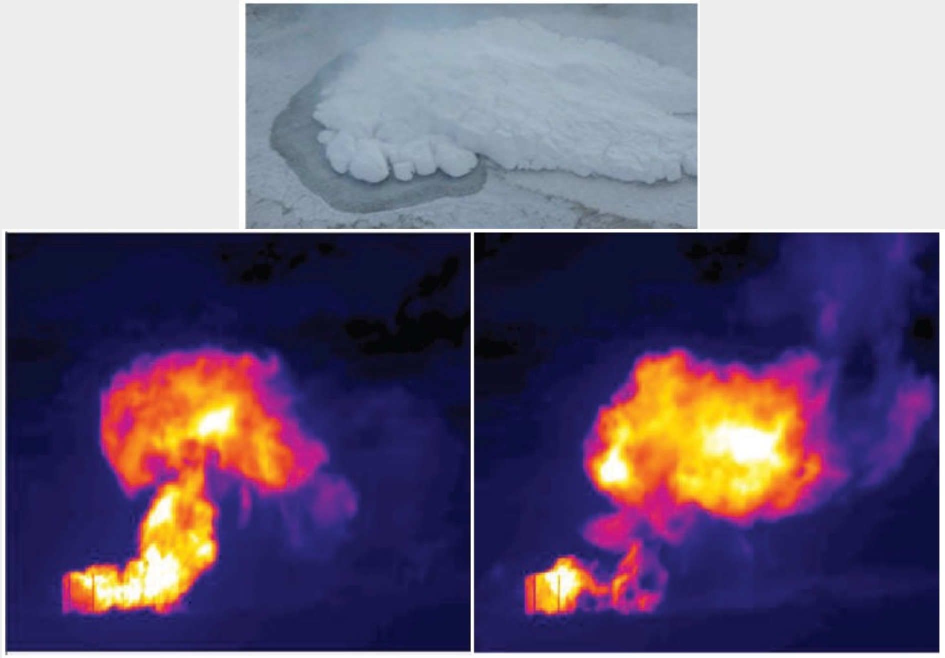
Knowledge gasps: Validation

Critical safety related knowledge gaps still exist about the formation of condensed H_2-O_2-N_2 mixture with potential for transition to detonation.



Predicted overpressure of a VCE (*Unpublished*)



G Atkinson, 2021, Condensed phase explosions involving liquid hydrogen, *Int Conf. on Hydrogen Safety.*

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Boiling liquid expanding vapour explosion (BLEVE)

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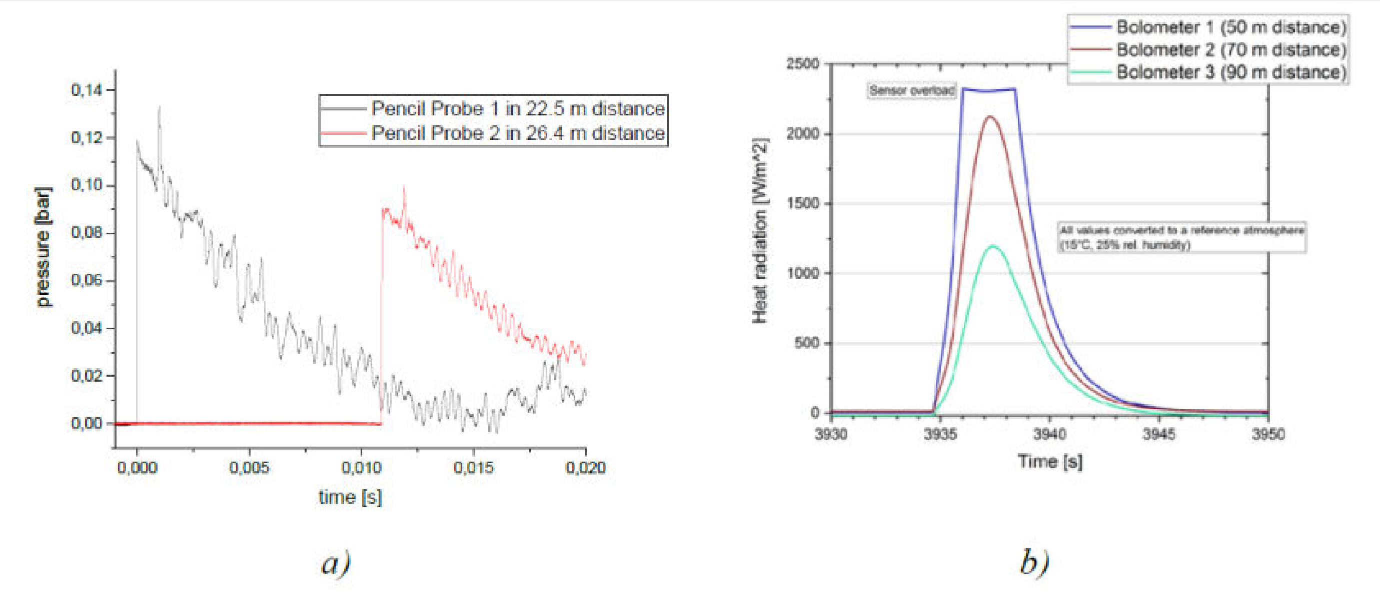
Knowledge gasps: effect of perlite density and grade



Overpressure and thermal radiation after the failure of an MLI-insulated vessel positioned horizontally filled with LH_2 (a) Blast waves measured at distances of 22.5 m and 26.4 m; (b) heat radiation from the burst of the MLI-insulated vessel

K. van Wingerden, M. Kluge, A.K. Habib, F. Ustolin, N. Paltrinieri, Medium-scale tests to investigate the possibility and effects of BLEVEs of storage vessels containing liquified hydrogen, CHEMICAL ENGINEERING TRANSACTIONS, VOL. 90, 2022.

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Concluding remarks

» Knowledge gaps have been identified for the relevant topics in the slides, focusing on the underpinning sciences

» These exclude large-scale experiments which are beyond the capability of the UK academic community in size and costs