Safety of cryogenic liquid hydrogen bunkering operations

- the gaps between existing knowhow and industry needs

Jennifer X Wen, Antoine Dutertre, Lee Phillips, Christophe Proust, Benjamin Truchot, Felicia Tan, Gabriele Landucci, Dan Allason, Yura Sevcenco

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Shell's operating plan, outlook and budgets are forecasted for a ten-year period and are updated every year. They reflect the current economic environment and what we can reasonably expect to see over the next ten years. Accordingly, they reflect our Scope 1, Scope 2 and Net Carbon Intensity (NCI) targets over the next ten years. However, Shell's operating plans cannot reflect our 2050 net-zero emissions target and 2035 NCI target, as these targets are currently outside our planning period. In the future, as society moves towards net-zero emissions, we expect Shell's operating plans to reflect this movement. However, if society is not net zero in 2050, as of today, there would be significant risk that Shell may not meet this target.

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This **presentation** may contain certain forward-looking non-GAAP measures such as [**cash capital expenditure**] and [**divestments**]. We are unable to provide a reconciliation of these forward-looking Non-GAAP measures to the most comparable GAAP financial measures because certain information needed to reconcile those Non-GAAP measures to the most comparable GAAP financial measures is dependent on future events some of which are outside the control of Shell, such as oil and gas prices, interest rates and exchange rates. Moreover, estimating such GAAP measures with the required precision necessary to provide a meaningful reconciliation is extremely difficult and could not be accomplished without unreasonable effort. Non-GAAP measures in respect of future periods which cannot be reconciled to the most comparable GAAP financial measure are calculated in a manner which is consistent with the accounting policies applied in Shell plc's consolidated financial statements.

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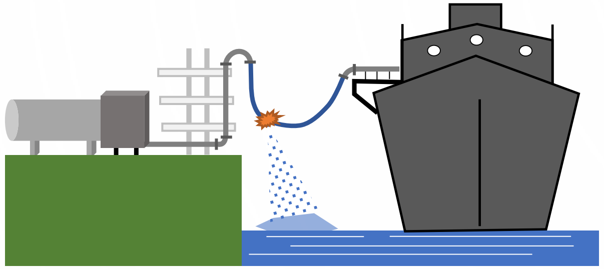
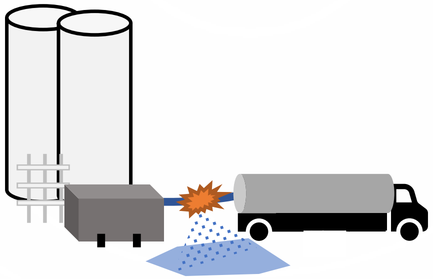
- Introduction
- State of the art *vs* Industry need
- JIP HySOON (2024-2027)

Liquid Hydrogen (LH_2) Bunkering Applications





Applications and LOC scenarios

Application / operation	LOC	LOC Scenario (e.g. see Fig.1.1)
1. Bunkering (ship to/from shore)	LOC (hose / hard arm) Question: safeguards, isolation, steady state	Spill on ship
		Spill between ship & harbour
2. Land-based transfers	a. Leak / Hose failure	spill on different substrates
3. Bunkering (land-based)	a. Aviation	as "2"
	a. Heavy duty (rail)	as "2"

Potential accidental scenarios (1/4)

Pressurised releases

Rupture/leaks of hoses, vents, vacuum jacketed liquid transfer lines, control valves, and flexible bunkering hose

No ignition

LH_2 jets, flash evaporation with potential for pooling

Freezing of surrounding gases, especially O_2

VCE

Multiple explosions

Ignition

LH_2 jet fires

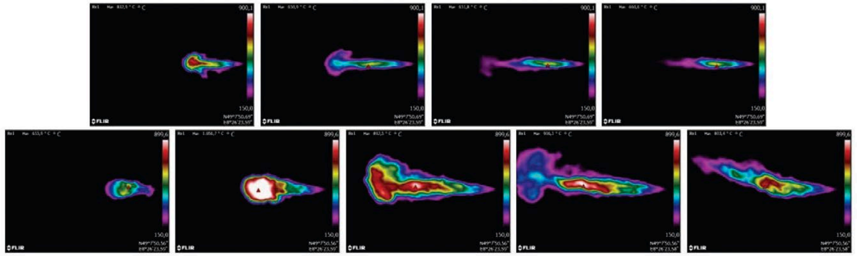


Figure 15: Temperature distribution within jet fire structure. Jet fire radiation for 2-mm nozzle and 10 MPa of initial pressure at T=285 K (upper) and T=80 K.

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.

Figure 2a: Solid deposits accumulated after 7 minutes

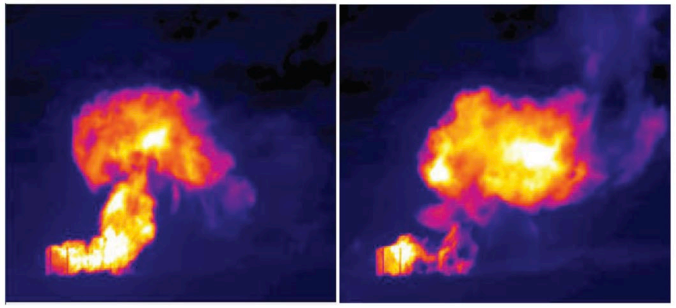


Figure 4: Comparison between fireball caused by the initial flash fire (left) and the secondary condensed phase explosion (right)

G Atkinson, 2021, Condensed phase explosions involving liquid hydrogen, Ebook - ICHS 2021.

Potential accidental scenarios (2/4)

Catastrophic failure of LH_2 storage tanks

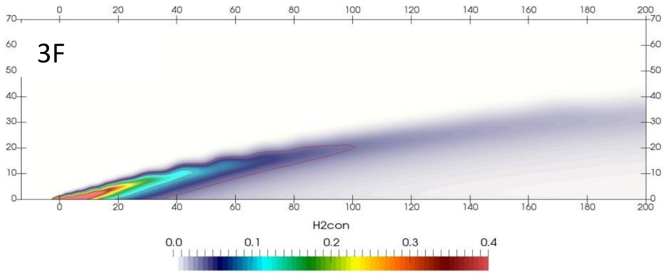
Low probability
High consequences

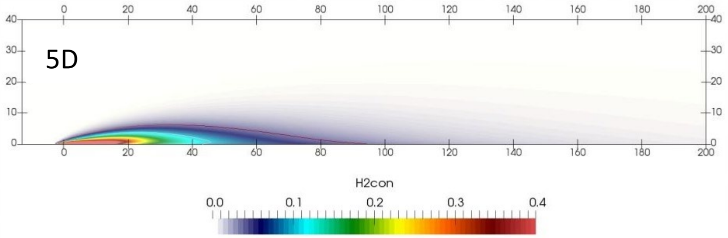
No ignition → Cloud formation and dispersion; Freezing of O_2

- No ignition → Rising up
- Ignition → Vapour cloud explosions (VCE)

Ignition → Instantaneous fireball

https://technokontrol.com/en/products/bunding.php





The predicted dispersion of the 1 ton cloud at ambient temperature 293 K at t =100 s. The red line denotes LFL.

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

Potential accidental scenarios (3/4)

Fire attack on LH_2 tanks

Safety valve opens → LH_2 jet fires

Safety valve does not open → Boiling liquid expanding vapour explosion (BLEVE)

Probability can be reduced by robust insulation

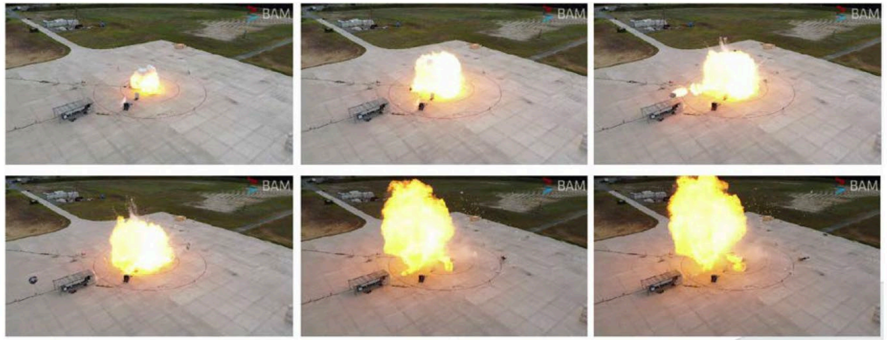


***Figure 11**: Fireball development after the failure of an MLI-insulated vessel positioned horizontally filled with LH2 a seen from an UAV flying over the H2TA*

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.

Potential accidental scenarios (4/4)

LH$_2$ spill over water

Ignition

- VCE in semi-confined environment
- Rapid phase transition

Theoretically possible in certain situations but not evidenced experimentally

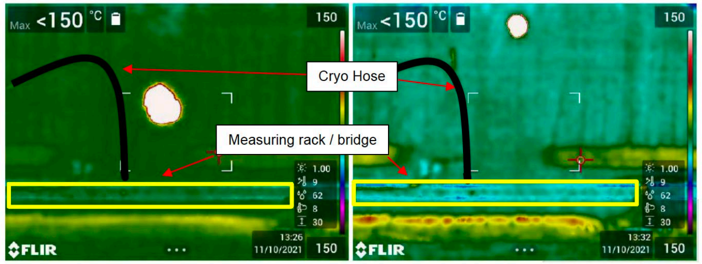


Figure 6: *Moment of initial flame propagation in hydrogen-air clouds generated by releases of LH2 onto and under water with all measuring equipment at the water basin switched off. The ignition location appears to be somewhere in the cloud at a distance from any physical object. The locations of the release point (cryo hose) and measuring rack/bridge have been indicated.*

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.

State of the Art & the gaps

- Physical properties
- Experiments
- CFD Modelling
- Engineering Tools
- Risk Analysis
- Regulations, Codes and Standards

Key physical properties of LH_2

- Temperature 20 K or -252.88 ^{0}C < the freezing temperature of oxygen (90.2 K or 182.97 ^{0}C).
- Cryogenic LH_2 evaporates with a volume expansion of 1:848.
- Minimum ignition energy only slightly higher than that of gaseous H_2.
- The flammability range decreases slightly.

Hydrogen concentration in air (% vol.)	MIE at T = 298 K (μJ)	MIE at T = 173 K (μJ)
10	–	315.8
12	165.2	–
20	19.8	53.4
30	31.4	45.8
40	47.7	72.3
50	164.0	–

Table 1 : LIE/LSE of H_2-air mixtures as function of the temperature at atmospheric pressure

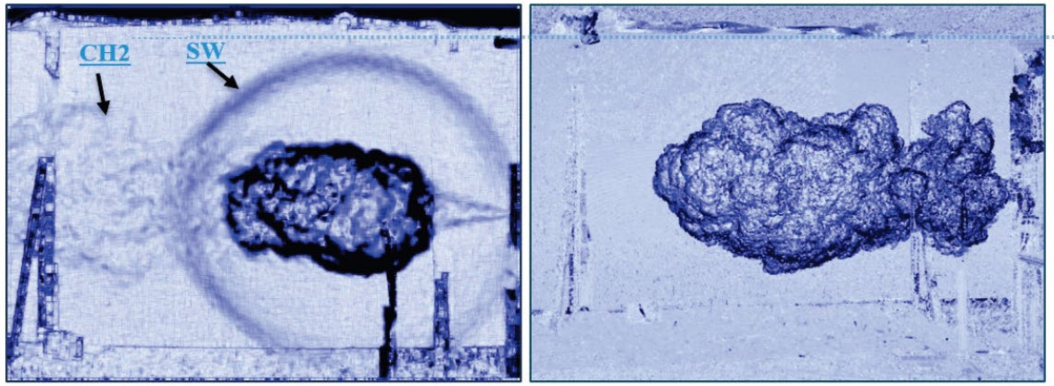
Temperature (°C)	LFL (% H_2 v/v)	UFL (% H_2 v/v)
20	5	70
-60	5.6	66
-120	6	60

C. Proust, D. Jamois, Some fundamental combustion properties of "cryogenic" premixed hydrogen air flames, in: International Conference on Hydrogen Safety, 2021.

Limitation: only one set of experimental results

Experiments (1/5) – ignited jet releases

Tests have been conducted for LH_2 and cryogenic H_2 gas (CryoH_2G) Jets with and without ignition



Shock wave formation (left) and a stationary jet fire (right) established following ignition of 4-mm nozzle and 20 MPa CryoH_2G release: SW –shock wave; CH2 –unignited H_2

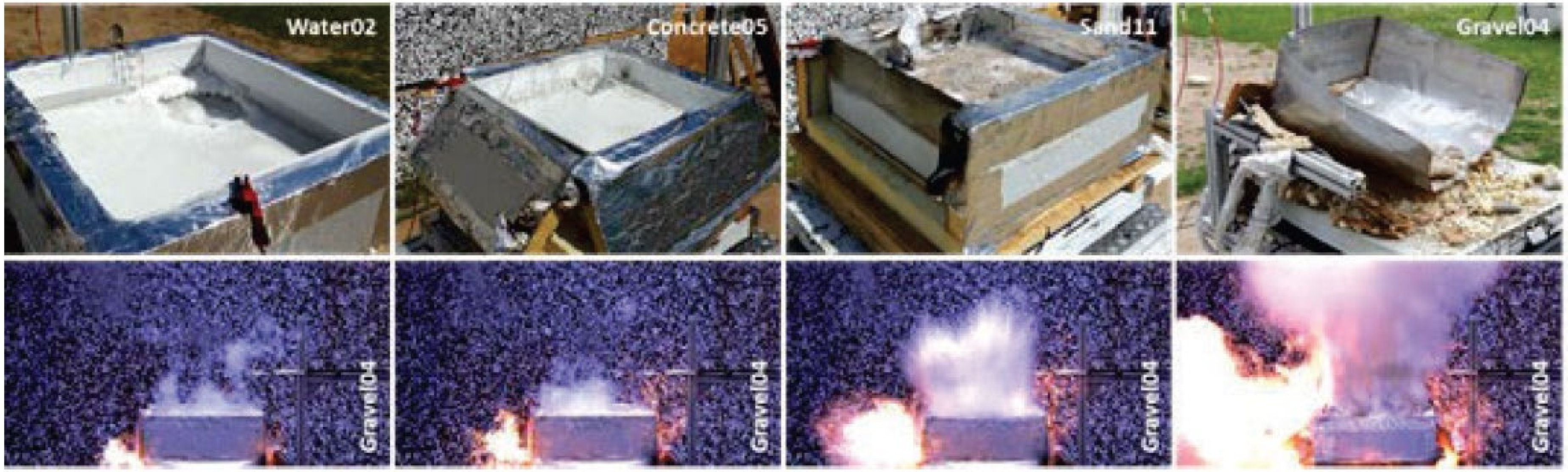
Jordan, T., Bernard, L., Cirrone, D., Coldrick, S., Friedrich, A., Jallais, S., Kuznetsov, M., Proust, C., Venetsanos, A. and Wen, J.X., Results of the pre-normative research project Preslhy for the safe use of liquid hydrogen, Ebook - ICHS 2021.

Still images of unignited (top) and ignited (bottom) tests in the vertically down release viewed from above

D Allason, A Halford, J Stene, Large volume liquid hydrogen releases, AIChE Spring Meeting &17th Global Congress on Process Safety, 2021.

Gaps: Impingement of LH_2 jets and jet fires on surfaces/equipment.

Experiments (2/5) – spill over different substrates

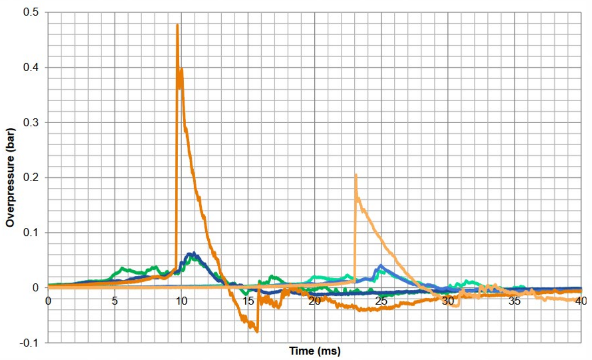


Different degrees of damage to the facility observed in the ignited pool experiments for the different substrates (upper row) and High-Speed video sequence of the final combustion event in experiment Gravel04 (2000 fps, lower row)

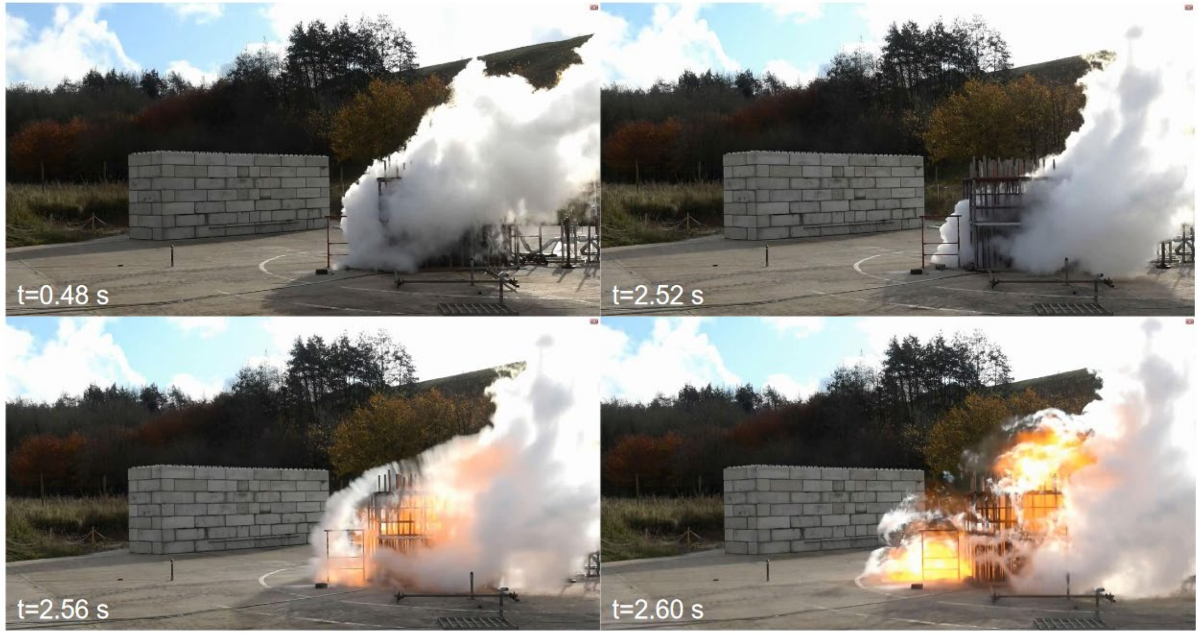
Jordan, T., Bernard, L., Cirrone, D., Coldrick, S., Friedrich, A., Jallais, S., Kuznetsov, M., Proust, C., Venetsanos, A. and Wen, J.X., Results of the pre-normative research project Preslhy for the safe use of liquid hydrogen, Ebook - ICHS 2021 – Sep.2021.

Limitation: not all substrates considered.

Experiments (3/5) – Vapour cloud explosions



Overpressure comparison for the repeated trials 21 to 23.



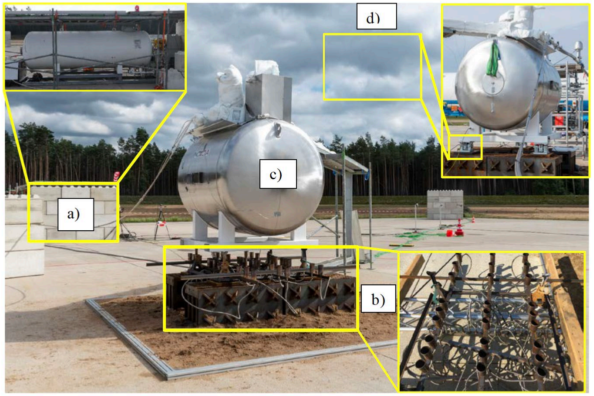
Stills images showing sudden gust immediately prior to ignition in Trial 23.

K Lyons, S Coldrick, G Atkinson, Ignited releases, PRESLHY dissemination conference, 5-6 May 2021, online event.

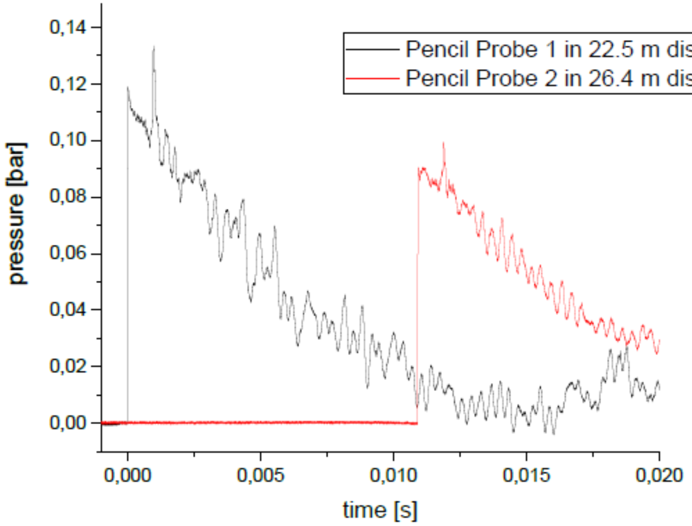
Gaps:

- Conditions for transition to detonation, effects of gusts and confinement.
- The formation of condensed H_2-O_2-N_2 mixture and effects on severity of explosions.
- DDT in open/semi-confined environment likely but not yet demonstrated.

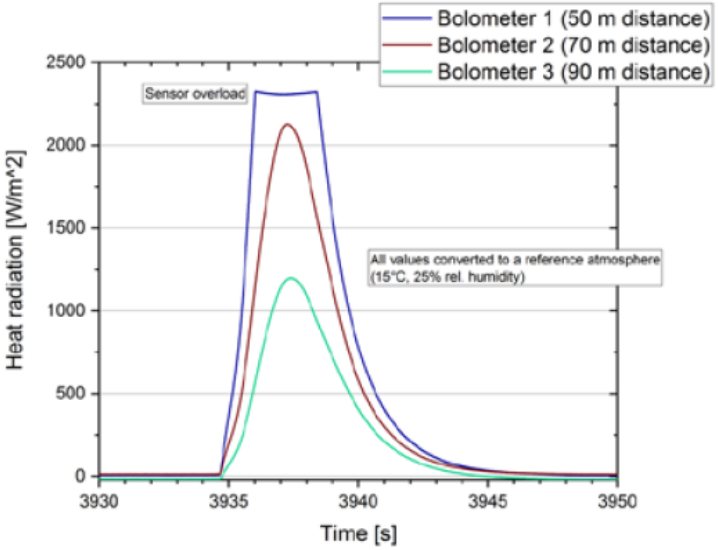
Experiments (4/5) - BLEVE



Experimental setup of a MLI-insulated vessel positioned horizontally filled with LH_2



Overpressures measured at 22.5 m and 26.4 m.



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.

Gaps: effect of insulation (e.g. perlite) pack density and material grade, limited instrumentation to inform analysis of tank response.

Experiments (5/5) – spill over water

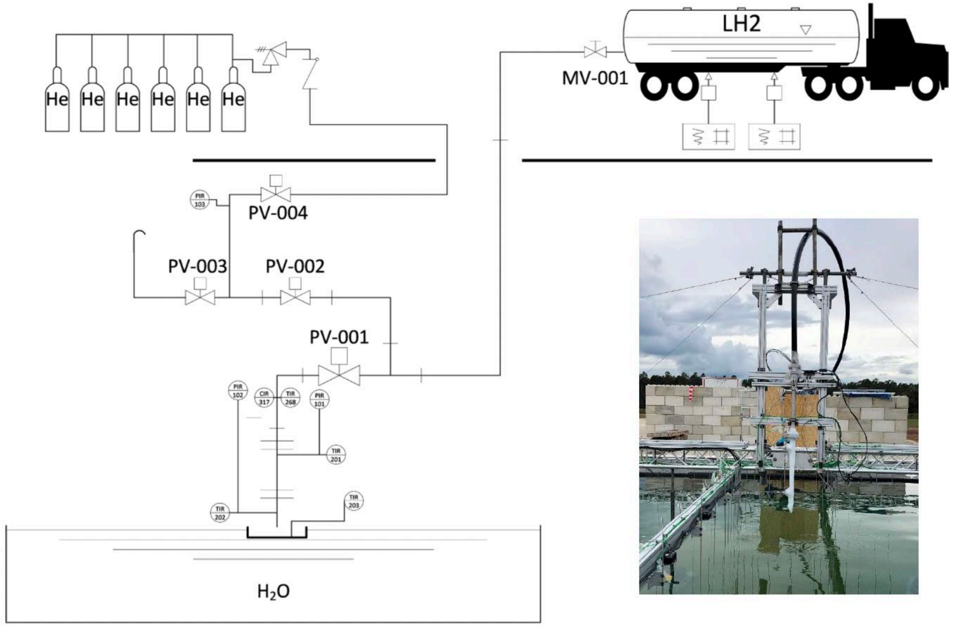
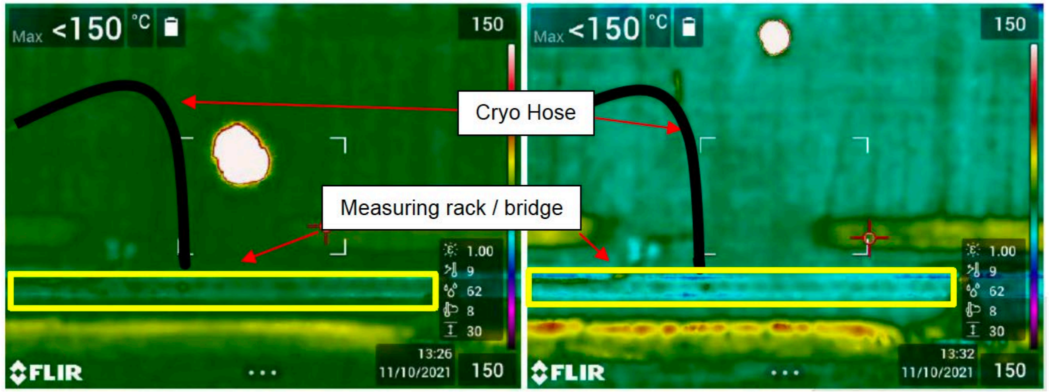


Figure 2: *Schematic showing the LH2 supply system. The system consists of double vacuum insulated hoses with valves designed for use with LH2. A special T-piece can be used as a safety system in case of freezing of the nozzle (due to contact with water) as well as for releasing flashed LH2 during the initial phases of a release. The system can be purged with helium before releasing LH2. The insert shows the release mechanism shortly after a release of LH2, 50 cm above the water level pointing downwards*



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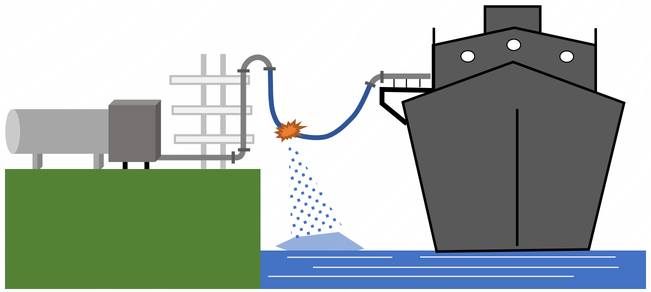
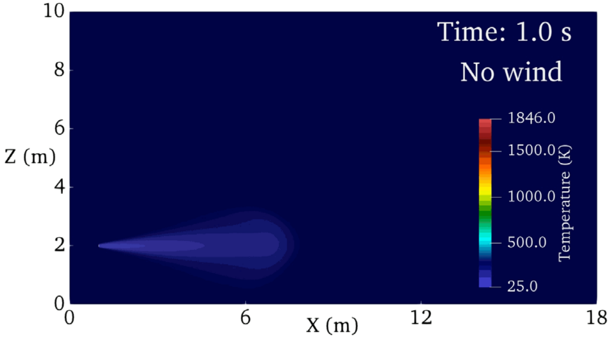


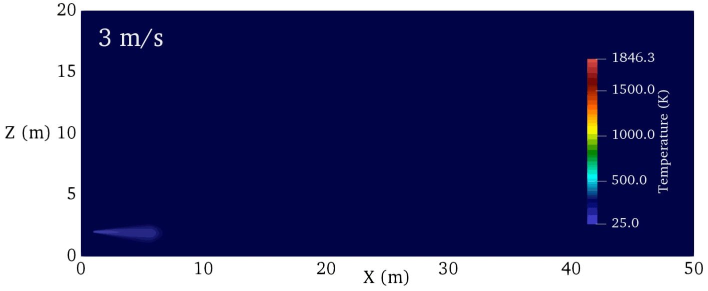
Gaps: effect of semi-confinement on the resulting vapour cloud explosions (VCE), spill height not representative bunkering conditions.

CFD models – exploratory study

$CryoH_2G$ jet fires

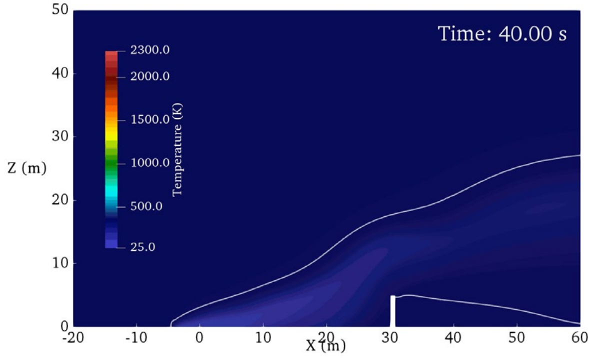


Time: 0.5 s



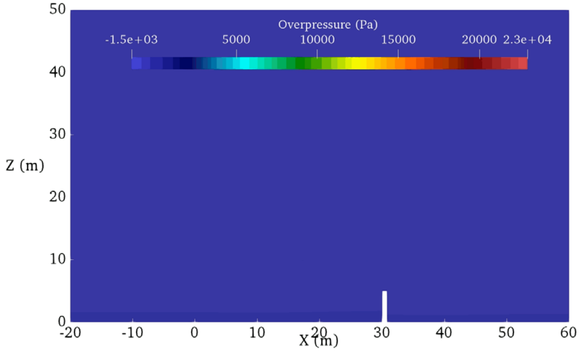
Vapor cloud explosions

Temperature



Overpressure

Time: 40.00 s



Baopeng Xu and Jennifer X. Wen, Exploratory numerical study of liquid hydrogen hazards, ICHS 2023.

Gaps: no validation, simplification in the model.

Engineering Tools

- HyPOND - extent of cryogenic pools, laminar burning velocity and expansion ratios [1].
- Evidence is lacking about the reliability to extrapolate some engineering tools for gaseous H_2 at ambient conditions to LH_2 jets [1].
- Empirical models for projectiles following BLEVE have not been tested for LH_2 BLEVE. Previous analysis neglected combustion [2].
- Previous thermodynamical analysis considered the physical processes following a film-boiling collapse. Early RPT involving LH_2 sinking and evaporating through water was not addressed.

1. *D Cirrone, et al., 2021, D6.5 Detailed description of novel engineering correlations and tools for LH2 safety, PRESLH2 deliverable.*
2. *Ustolin F, Paltrinieri N, Landucci G, An innovative and comprehensive approach for the consequence analysis of liquid hydrogen vessel explosions, J Loss Prev Proc Ind 2020; 68.*
3. *L H Odsæter, H.L. Skarsvåg, E. Aursand, F. Ustolin, G.A. Reigstad and N. Paltrinieri, Liquid hydrogen spills on water—risk and consequences of rapid phase transition, Energies, 2021, 14:4789, MDPI.*

Gaps: estimate of error bands for the predictions of simplified tools.

Risk Analysis

- QRA for LH_2 transfer applications received considerably less attention.
- The exploratory CFD analysis of Hansen [4] indicated the need for higher safety standards for LH_2 fuelled vessels than that of LNG.
- Engineering tools and reliability data for LH_2 systems are still to be implemented in HyRAM [6,7].
- H2Tools (https://h2tools.org/) contains Best Practice Recommendation for the handling of cryogenic LH_2.
- Neither H2Tools nor HIAID 2.0 [7] collects statistics that can facilitate derivation of failure rate or leak frequencies.

4. OR Hansen, Liquid hydrogen releases show dense gas behavior, Int. J. Hydrog. Energy, 2019, 45(2):1343-1358.
5. KM Groth, ES Hecht, HyRAM: A Methodology and Toolkit for QRA of Hydrogen Systems, Int. J. of Hydrogen Energy, 2017, 42(11).
6 B.D. Ehrhart, S.R. Harris, M.L. Blaylock, A.B. Muna, S. Quong, Risk assessment and ventilation modeling 8. JX Wen, M Marono, P Moretto, EA Reinecke, P Sathiah, E Studer, E Vyazmina, D Melideo, Statistics, lessons learned and recommendations from analysis of HIAD 2.0 database, Int. J. Hydrog. Energy, 2022, 37(38): 17082-17096.
7. JX Wen, M Marono, P Moretto, EA Reinecke, P Sathiah, E Studer, E Vyazmina, D Melideo, Statistics, lessons learned and recommendations from analysis of HIAD 2.0 database, Int. J. Hydrog. Energy, 2022, 37(38): 17082-17096.

Gaps: Failure data at equipment/component level seriously lacking.

Regulations, Codes and Standards (RCS)

- Lack of reliability data for bulk LH_2 storage systems located on site at fuelling stations limits the use of QRAs and hinders the ability to develop the necessary RCS for LH_2 transfer technologies [8].
- Kim et al. [9] considered the interactions between LH_2 tanks and recommended that the neighbouring facilities need to be considered and the design judgement should be made from the holistic view over the entire LH_2 supply chain with appropriate operation scenarios.

Gaps: RCS for LH_2 bunkering are yet to be established.

8. C Correa-Jullian, KM Groth, *Data requirements for improving the QRA of liquid hydrogen storage systems, Int. J. Hydrog. Energy, 2022, 47(6): 4222-4235.*
9. J Kim, H Park, W Jung, D Chang, Operation scenario-based design methodology for large-scale storage systems of liquid hydrogen import terminal, *Int. J. Hydrogen Energy, 2021, 46(80): 40262-40277.*

Joint Industry Project (JIP) (2024 – 2027)
Improving liquid Hydrogen Safety for mobile applications (HySOON)

CONSORTIUM	
Coordinator	Professor Jennifer Wen, University of Surrey
Industry Sponsors	Shell, Total Energy, BP …
Research Partners	University of Surrey, DNV Spadeadam, INERIS, University of Pisa …

Main knowledge gaps to be addressed:

- Propensity for detonatable H_2-O_2 mixture formation upon LH_2 release in realistic environment.
- Propensity and consequences of BLEVE for real-scale LH_2 storage tanks under fire attack.
- Blast effects upon LH_2 release on water during bunkering operations.

Practical guidance for:

- Predicting the probability and frequency of occurrence of the associated hazards.
- Predicting the consequences of the associated hazards using industry modelling packages (PHAST, FRED, FLACS) and recommendations for necessary adaptations.
- The safe design and operations of bunkering facilities.