Snapshots of liquid hydrogen safety research and possible knowledge gaps

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The Context

://www.airproducts.co.uk/industries/Energy/Hydrogen-Energy/Material-Handling/projects.aspx

http://www.jobs.net/jobs/usairliquide/en-us/

RR987 - Ignited releases of liquid hydrogen – HSE (2014)

The Context

http://www.greening.usda.gov/hydrogen-vehicle.htm

Liquid hydrogen property

- **LH2 POOL**: http://h2bestpractices.org/h2introduction/basics/liquid_behaviors.asp

Fluid	Boiling temperature Celsius	Boiling temperature Fahrenheit
Oxygen	-183°	-297°
Nitrogen	-196°	-320°
Neon	-246°	-411°
Hydrogen	-253°	-423°
Helium	-270°	-452°

The volume ratio of liquid to gas is 1:848)

Comparing with LNG: 1:600

Temperature: -162 ^{0}C

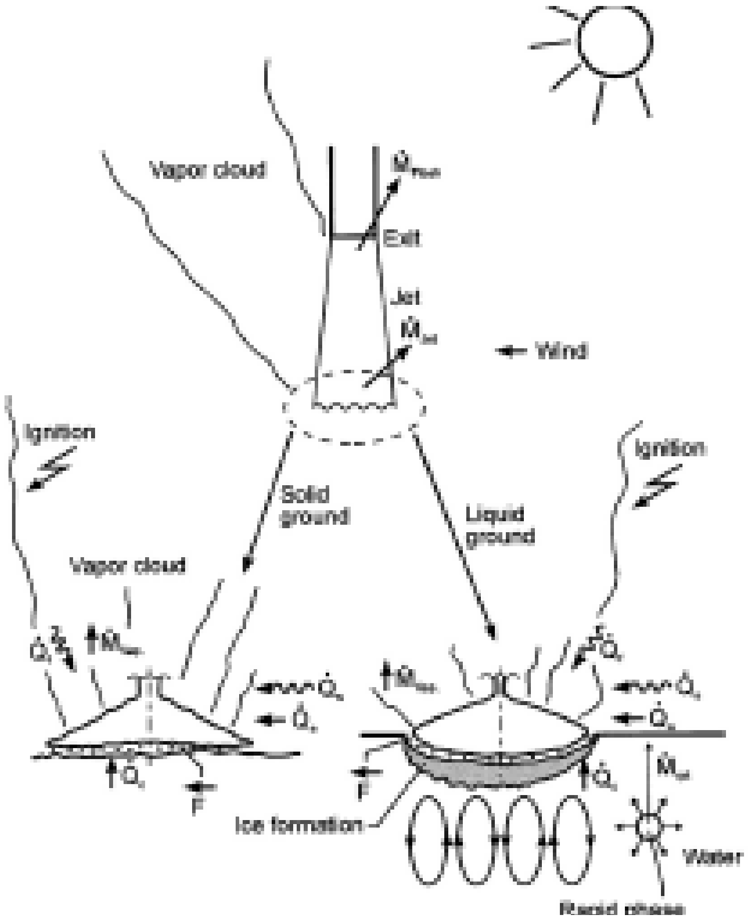
The associated hazards

- Air Products Safetygram 9: Liquid hydrogen
- EIGA (European Industrial Gas Association): SAFETY IN STORAGE, HANDLING AND DISTRIBUTION OF LIQUID HYDROGEN
- *Air Liquide* Gas Encyclopedia

- Hazards of liquid hydrogen: Position paper RR769 – HSE

…

The associated hazards



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Jet & potential ignition

Liquid hydrogen pool fire

Jet fire

Secondary explosion

More to be identified in the last two slides

Pool spreading and vaporization of liquid hydrogen Original Research Article

International Journal of Hydrogen Energy, Volume 32, Issue 2, February 2007, Pages 256-267

K. Verfondern, B. Dienhart

Outline

- **Pool spreading**
  - Dataset available for model validation – pool spreading
  - Earlier work of Verfondern and co-workers (1994 to 2007…)
  - Some recent work of others

- **Jet fires, pool fires and secondary explosion**
  - Some more recent experimental and modelling investigations

- **Possible knowledge gaps**

Dataset available for model validation – pool spreading

- BAM (Marinescu-Pasoi and Sturm, 1994)
- NASA (Chirivella and Witcofski, 1986) trials
- HSL data (RR986 - Releases of unignited liquid hydrogen – HSE, 2014)

HSL data (RR986 - Releases of unignited liquid hydrogen – HSE, 2014)

Figure 21 Liquid hydrogen during the release

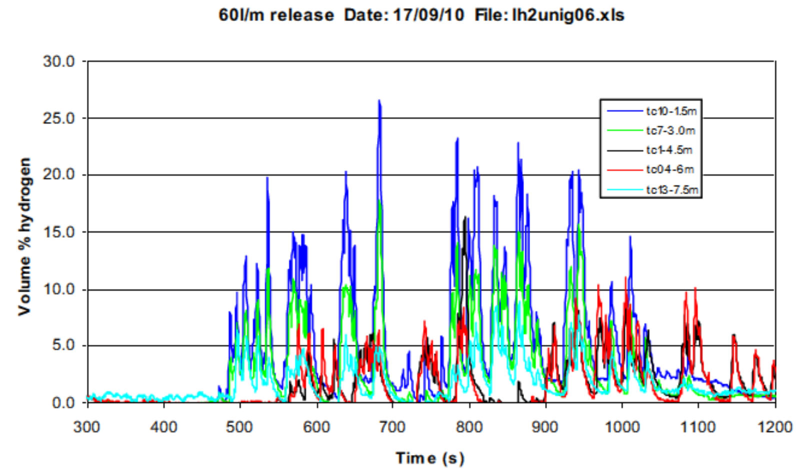

Figure 23 Hydrogen concentrations at varying distances from the release at a fixed height of 0.25 m

TEST 6 – VERTICALLY DOWNWARD RELEASE 100 mm ABOVE THE GROUND

M. Ichard, O.R. Hansen, P. Middha, D. Willoughby,
CFD computations of liquid hydrogen releases

International Journal of Hydrogen Energy, *Volume 37, Issue 22*, *November 2012*.

- **FLACS with HEM, rain out and pool model, condensation of oxygen and nitrogen**
- **Knowledge gaps identified:**
  - Source term evaluation
  - better representation of the turbulence
  - accurate model to evaluate source terms for flashing releases is needed.

Pool spreading modelling

- **Integral models**

  GASP (Webber, 1990)

- **Shallow layer models**

  Verfondern and co-workers (1994 to 2007…)

- **CFD models**

  ADREA-HF (Statharas et al., 2000), FLACS (FLACS, 2010), FLUENT and CFX (Schmidt et al., 1999,

  Molkov et al., 2005, Sklavounos and Rigas, 2005).

Verfondern and co-workers (1994 to 2007…)

- ☐ Simulation of accidental spills of cryogenic hydrogen in a residential area Original Research Article
  Cryogenics, Volume 34, Supplement 1, 1994, Pages 401-404
  U. Schmidtchen, L. Marinescu-Pasoi, K. Verfondern, V. Nickel, B. Sturm, B. Dienhart
- ☐ Experimental and theoretical investigation of liquid hydrogen pool spreading and vaporization Original Research Article
  International Journal of Hydrogen Energy, Volume 22, Issue 7, July 1997, Pages 649-660
  K. Verfondern, B. Dienhart

Pool spreading and vaporization of liquid hydrogen Original Research Article
International Journal of Hydrogen Energy, Volume 32, Issue 13, September 2007, Pages 2106-2117
K. Verfondern, B. Dienhart

3D Modeling of the Different Boiling Regimes During Spill and Spreading of Liquid Hydrogen Origi
Research Article
Energy Procedia, Volume 29, 2012, Pages 244-253
C. Jaekel, K. Verfondern, S. Kelm, W. Jahn, H.-J. Allelein

Validation strategy for CFD models describing safety-relevant scenarios including LH_2/GH_2 release and the use of passive auto-catalytic recombiners Original Research Article
International Journal of Hydrogen Energy, ***In Press, Corrected Proof***, *Available online 15 May 2014*
Christian Jäkel, Stephan Kelm, Ernst-Arndt Reinecke, Karl Verfondern, Hans-Josef Allelein

LAUV code: Verfondern and co-workers (1994 to 2007…)

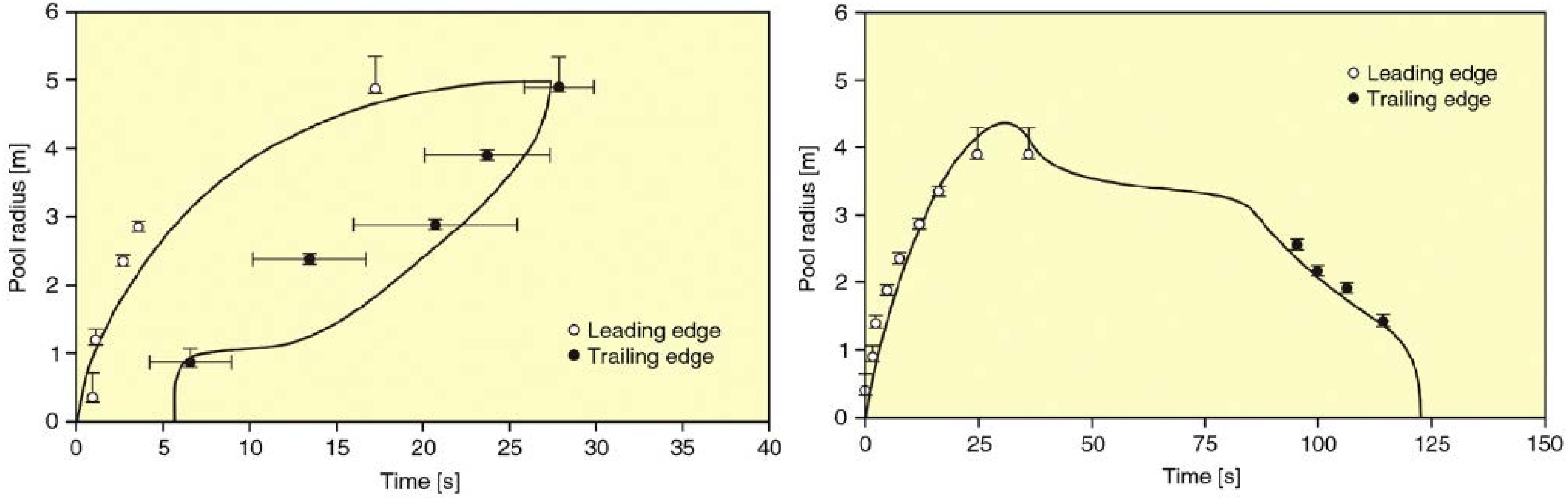

Fig. 5. Comparison of LN2 pool measurements with respective LAUV calculations instantaneous release of 40 l (top) and continuous release at a varying rate over 121 s (bottom).

HSL data (RR986 - Releases of unignited liquid hydrogen – HSE, 2014)

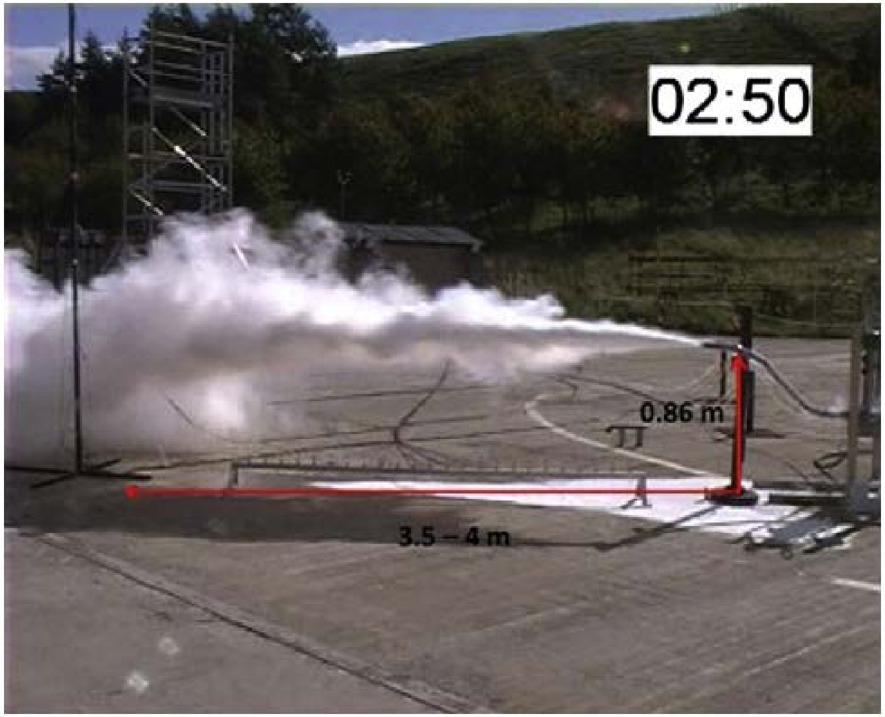

Fig. 2 — Picture of the hydrogen jet for Test-07 (170 s after start of release).

Figure 11. Solid deposit 3 minutes after release

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CFD computations of liquid hydrogen releases

M. Ichard, O.R. Hansen, P. Middha, D. Willoughby

International Journal of Hydrogen Energy, *Volume 37, Issue 22*, *November 2012*.

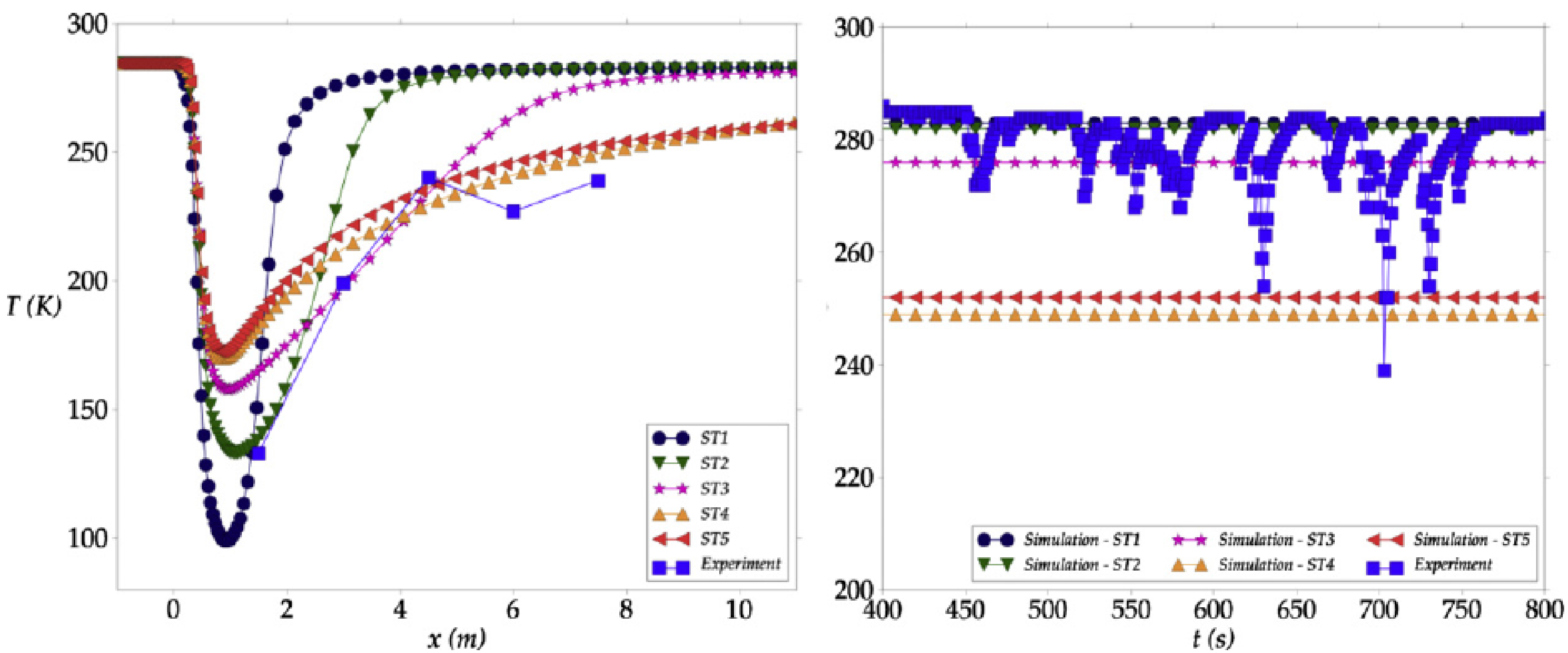
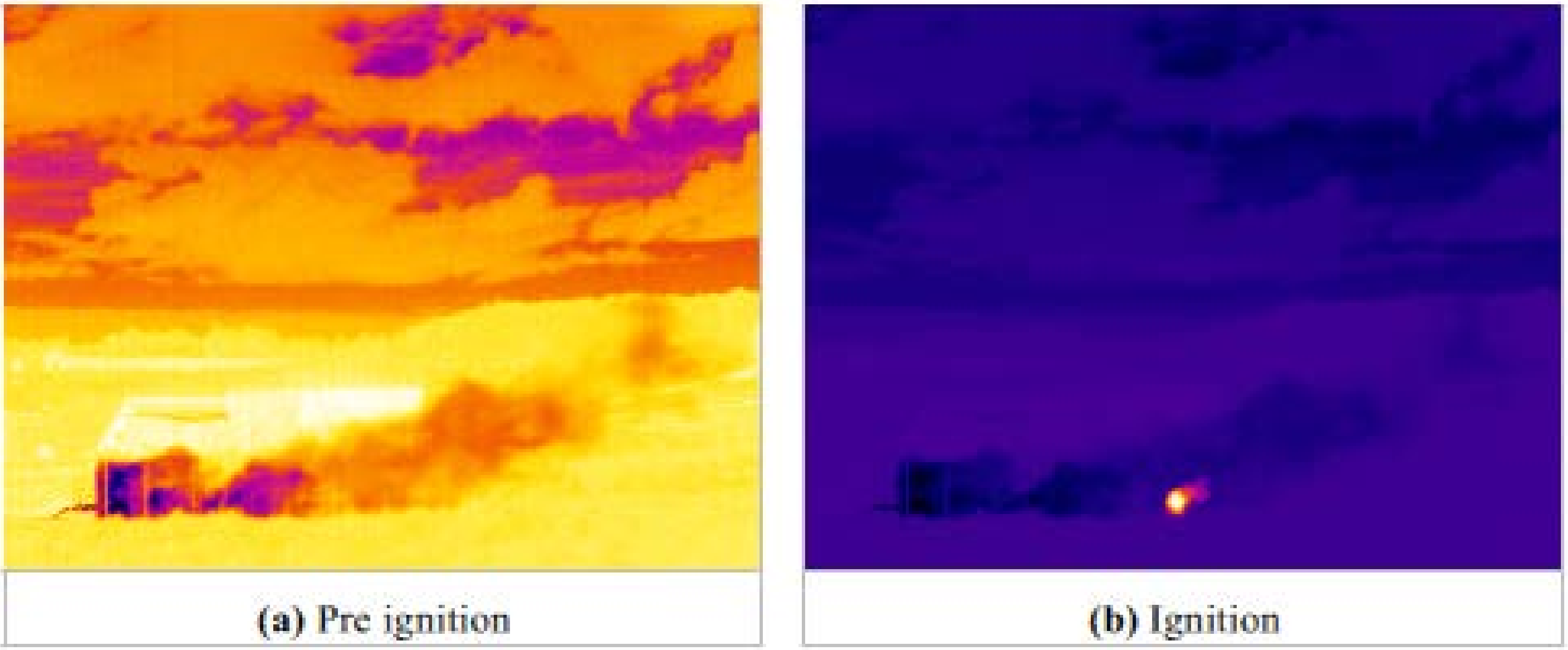


Fig. 4 – [Left] Minimum temperature as a function of distance at steady state conditions for the horizontal release Test 07 0.75 m above the ground. [Right] Temperature time-series for Test-07 at sensor M26: X = 7.5 m; Z = 0.75 m.

RR987 - Ignited releases of liquid hydrogen – HSE (2014)



(a) Pre ignition

(b) Ignition

Ignition downstream from the release point

RR987 - Ignited releases of liquid hydrogen – HSE (2014)

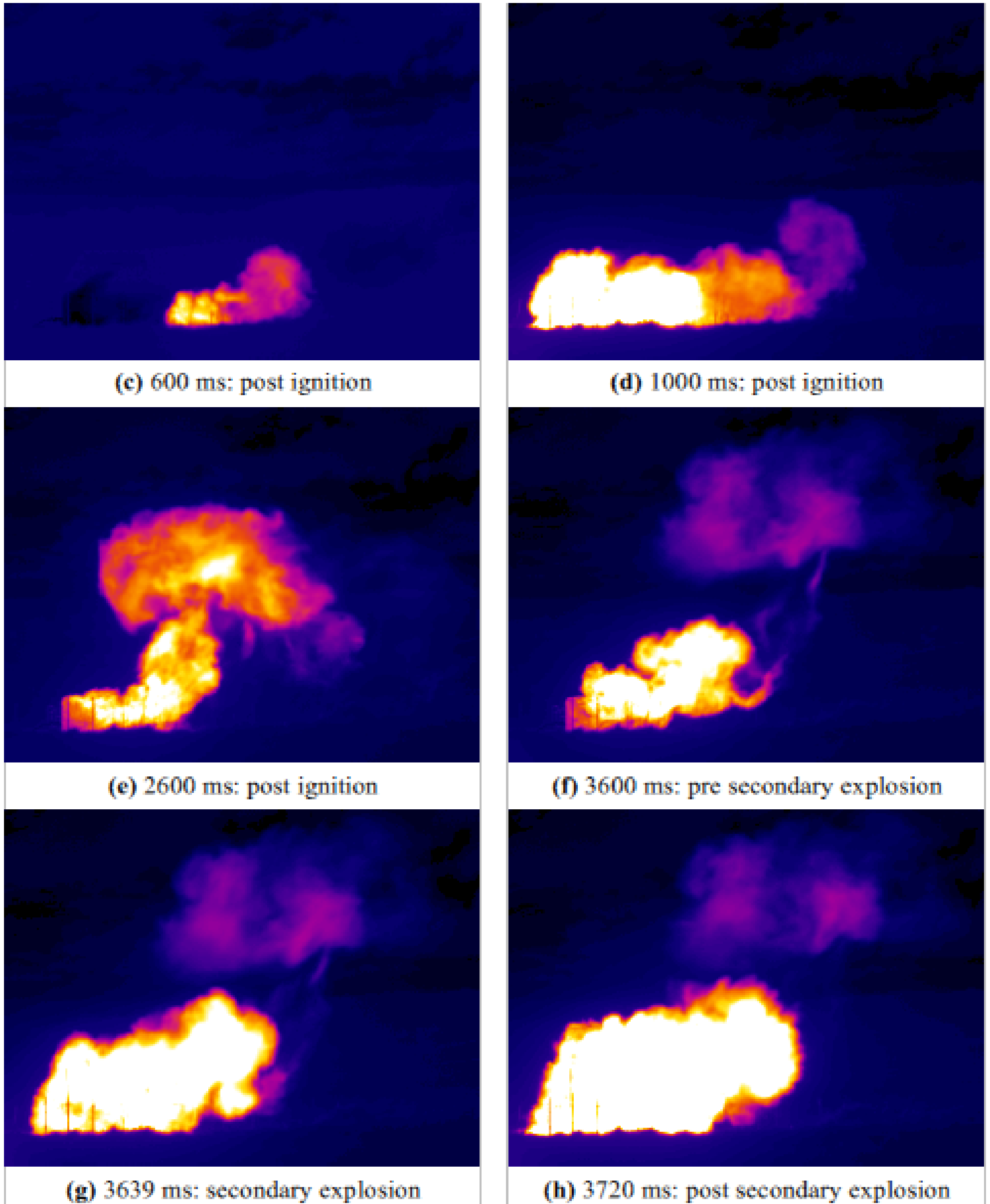


Figure 4.3 (a-h): IR video stills of Test 6 including the secondary explosion

Test 6

- Initial deflagration burn back
- Flame front reached 50 m/s
- Uplift of the flame front
- secondary explosion occurred emanating from the liquid/solid pool location
- Jet flame

(wind speed 1.9 m/s)

RR987 - Ignited releases of liquid hydrogen – HSE (2014)

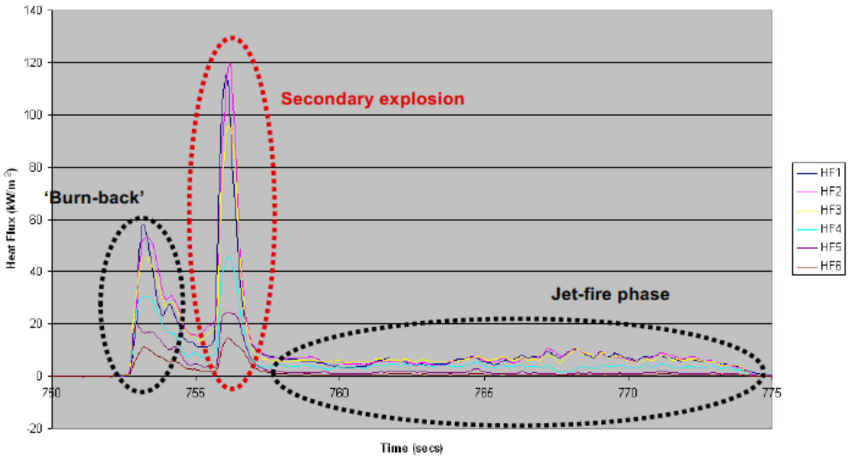


Figure 4.4: Radiometer readings from ignited release (Test 6) exhibiting a secondary explosion

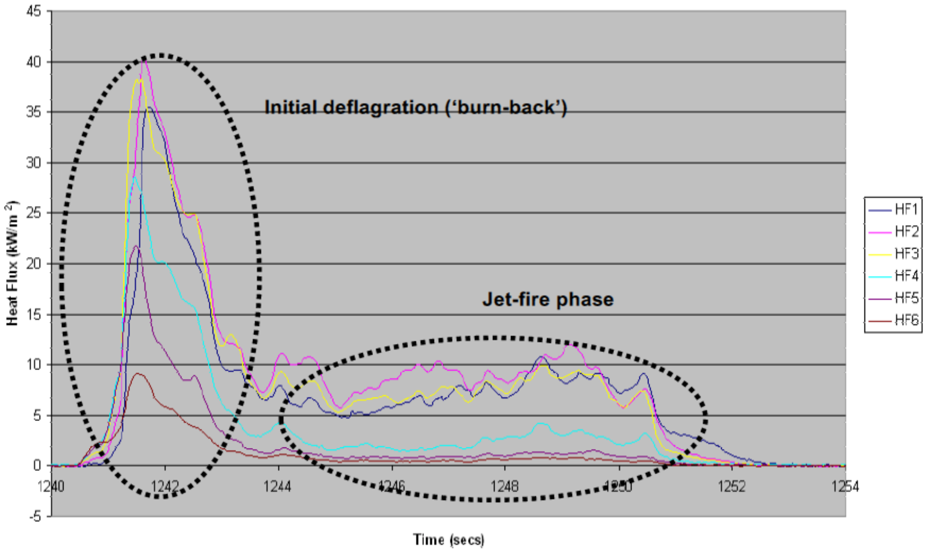


Figure 4.2: Radiometer readings from ignited release (Test 4)

RR987 - Ignited releases of liquid hydrogen – HSE (2014)

Figure 4.5: Ignition of the vapour cloud during Test 10 during low wind conditions

Possible knowledge gaps (1)

Tests in in controlled laboratory conditions

- Source term quantification
- Solid deposition, especially oxygen
- Secondary explosion

Theoretical and modelling

- Coupled shallow layer and CFD, i.e. spill, cloud formation and dispersion
- Insight and predictive tools for the ignited release

Scenarios

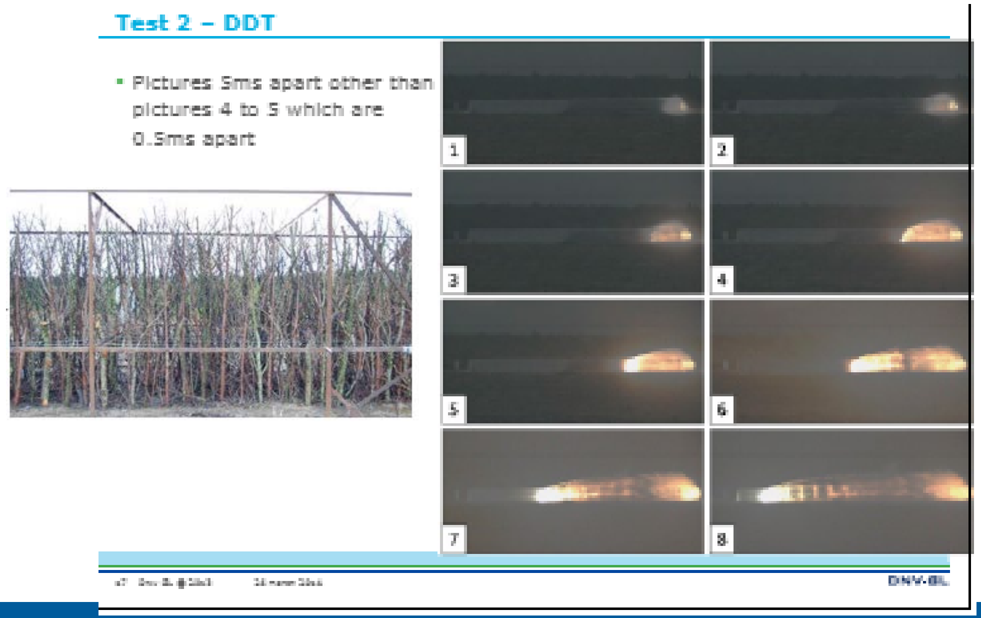
- The future hydrogen station will be co-hosted by gasoline stations. The associated risks need to be built into future safety research.

Possible knowledge gaps (2)

Possible DDT

- Large quantities in open but congested area
- Potential for DDT
- Needs theoretical understanding or very large scale experiments

(g) 3639 ms: secondary explosion



B.J. Lowesmith, G. Hankinson, S. Chynoweth, Safety issues of the liquefaction, storage and transportation of liquid hydrogen: An analysis of incidents and HAZIDS, *Int. J of Hydrogen Energy*, *In Press, Corrected Proof*, *Available online, 2014*

- The lack of available models that can be applied to LH2 releases.

- Lack of experimental data on LH2 pool fires and none at large scale.
- Some small scale experiments were conducted in a Dewar so the observed mass burning rate was probably much lower than would be expected during the early stages of a fire on a normal substrate.

- No experimental data on BLEVEs **(**Boiling Liquid Expanding Vapour Explosion or fireball) was identified; although such an incident has occurred demonstrating it is a possible hazard.

- The lack of quantitative data on failure frequency and ignition probability (?)