Hydrogen safety research supporting fuel cell and hydrogen market introduction

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Outline

Overview of progress in hydrogen safety research (examples):

- The similarity law for hydrogen unignited jet decay (the original under-expanded jet theory)
- Microflames
- The universal dimensionless jet flame length correlation
- The pressure peaking phenomenon (unique for hydrogen compared to all other fuels)
- Understanding of blast wave and fireball after tank rupture in a fire
- Quantitative risk assessment (criteria for risk acceptance on London roads)

Examples of Ulster’s Safety Research impact through Regulations, Codes and Standards

What needs to be done (examples):

- Explosion-free in a fire composite cylinders for hydrogen storage
- Fuelling protocol for light- and heavy-duty vehicles
- UN Global Technical Regulation #13 on Hydrogen and Fuel Cell Vehicles (fire test reproducibility)
- Hydrogen vehicles in tunnel and confined spaces
- Hydrogen safety education, including online e-Laboratory of Hydrogen Safety
Overview of progress in hydrogen safety research (examples)
The similarity law for unignited jet decay
Based on the original under-expanded jet theory

\[ C_{ax} = 5.4 \sqrt{\frac{\rho_N}{\rho_S}} \frac{D}{x} \]

**Conclusion:** decrease a pipe diameter as distance to LFL (hazard distance), i.e. the flammable envelop size is proportional to the leak diameter.
Microflames
Experiments and CFD model

- **Hazard**: the small leak burns undetected for a long period, damaging the containment system and providing an ignition source.

- **Left flame**: hydrogen downward into air (3.9 μg/s, 0.46 W). ID=0.15 mm. Exposure 30 s.

- **SAE J2600 permits** hydrogen leak rates below 200 mL/hr (0.46 μg/s) – no flame!
Hydrogen jet flames
Universal correlation

\[
\frac{\rho_N}{\rho_S} \left( \frac{U_N}{C_N} \right)^3 = \frac{g \cdot \mu_N}{\rho_S \cdot C_N^3} \cdot \text{Re} \cdot \text{Fr}
\]

Validation:
- \( P = 0.1 - 90 \) MPa
- \( D = 0.4 - 51.7 \) mm
- \( L/T; SS/S/SS \)

There are three hazard distances from flames – we know how to calculate them.
The pressure peaking phenomenon

Physics

Example of garage: 4.5x2.6x2.6 m with a “brick” vent (25x5 cm)

Car: mass flow rate 390 g/s (H2 storage: 350 bar, TPRD 5.08 mm orifice)

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

Overpressure limit for structures (10-15 kPa)

Solution: decrease TPRD diameter (and increase fire resistance of tank at the same time!)
The pressure peaking phenomenon
Validation (Ulster model versus KIT tests)

Enclosure of about 1 m³ volume (0.96x0.98x1.00 m) with 1x1 cm vent.
- Air release – no PPP (as predicted).
- A smaller release of hydrogen gives higher pressure peak than a larger release of helium.

Helium 0.99 g/s

Hydrogen 0.56 g/s

Air 2.8 g/s (no PPP!)
Pressure peaking phenomenon
Case 1: TPRD $D=2.0 \text{ mm}$, $P=70 \text{ MPa}$

Unignited release in the garage

Ignited release in the garage
Pressure peaking phenomenon
Case 2: TPRD \( D=0.3 \text{ mm}, \ P=70 \text{ MPa} \)

- **Ignited** release (garage 2.6x2.6x4.5 m), vent 1 brick (\textit{left}) or 0.5 brick (\textit{right}).
- Reminder: garage can withstand overpressure 10 kPa.
Tank rupture in a fire: reduced model vs experiment

Stand-alone tank (USA test)

New dimensionless radius:

\[ \bar{R} = \frac{R \times p_0^{1/3}}{3^{1/3} \cdot \frac{R_{shk}}{R_{com}}} \]

- \( \times E_m \) only (\( \alpha = 1.8 \))
- \( \times E_m \) and \( \times E_{ch} \) (\( \alpha = 1.8 \), \( \beta = 0.052 \))
Tank rupture in a fire: reduced model vs experiment

Under-vehicle tank (USA test)

![Graph showing overpressure vs distance from a car]

- Car test, side
- Car test, rear
- Car test, west
- $E_m$ only ($\alpha=1.8$)
- $E_m$ only ($\alpha=0.14$)
- $E_m$ and $E_{ch}$ ($\alpha=0.12$, $\beta=0.09$)
Tank rupture in a fire: CFD model vs experiment
Pressure dynamics

USA test (350 bar)

Japanese test (700 bar)
Tank rupture in a fire
Fireball dynamics (in atmosphere, Japanese test 2)
Quantitative risk assessment of hydrogen cars
Example of London roads

The QRA methodology:

- Considers previously “missed” hazards of blast wave and fireball, which accompany tank rupture in a fire (not limited to a jet fire or deflagration as in existing QRA tools).
- Uses validated engineering tools to calculate hazard distances.
- Merges contemporary deterministic and probabilistic methods.
- Risk is assessed as:
  - Fatality rate (fatality per vehicle per year), and
  - Cost per an accident with a hydrogen-powered vehicle fire
Risk assessment methodology for onboard hydrogen storage

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QRA methodology
Risk assessment frameworks: fatality and cost

Consequence analysis
- Identification of key hazards:
  - Blast wave
  - Fireball
- Consequence modelling:
  - Pressure hazard
  - Thermal hazard
- Effects modelling:
  - Fatality
  - Serious injury
  - Slight injury
- Number of affected individuals (Fatality/accident)

Frequency analysis
- Initiating fire frequency (Fire accident/vehicle/year)
- Fire escalation probability
- TPRD failure probability
- Tank rupture probability
- Tank rupture frequency (Accident/vehicle/year)

Probability analysis
- Identification of key hazards:
  - Blast wave
  - Fireball
- Consequence modelling:
  - Pressure hazard
  - Thermal hazard
- Effects modelling:
  - Fatality
  - Serious injury
  - Slight injury
- Number of affected individuals (Fatality/accident)
- Cost of life (£/accident)

Risk
- (Fatality/vehicle/year)
- (Fatality/accident)
- (£/accident)
Effect of fire resistance rating (FRR) on risk

Fatality rate (acceptable risk is $10^{-5}$ fatality/vehicle/year)

For mean population density 0.008 $\text{person/m}^2$ acceptable FRR level is 47 min!
Effect of fire resistance rating (FRR) on risk

Accident cost (£/accident)

- For FRR=8 min cost of fire accident is £4.00M!
- Drastic reduction of cost of fire accident by increasing tank’s FRR
Examples of Ulster safety research impact through Regulations, Codes and Standards
Regulations, codes and standards

Ulster contribution

- **ISO/TR 15916**. Basic considerations for the safety of hydrogen systems. ISO Technical Committee 197 Hydrogen Technologies.
- **ISO 19880-1** “Gaseous hydrogen - Fuelling stations - Part 1: General requirements” (“hazard distance”, can be calculated by Ulster models and tools).
- **ISO 19882** “Gaseous hydrogen – Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers” (requires to exclude PPP).
- **European Guidelines on Inherently Safer Use of Hydrogen Indoors** (HyIndoor project)
- **European Guide for First Responders** (HyResponse project)
- **European Model Evaluation Protocol** (SUSANA project)
- Guidelines on safe use of LH2 (PRESLHY)
- Guidelines on safe use of hydrogen in tunnels and other confined spaces (HyTunnel-CS)
What needs to be done (examples)
Explosion-free in a fire composite cylinders
Breakthrough leak-no-burst (LNB) safety technology

- A vessel comprises a load bearing fibre-reinforced polymer (FRP) layer, inner liner against gas permeation to the regulated level and outer thermal protection layer (TPL) that can be load bearing too.
- Liner, e.g. HDPE, melts to leak the gas through walls before rupture.

[Diagram showing a vessel with layers labeled: Thermal protection layer (TPL), Fibre-reinforced polymer (FRP) layer]
Explosion-free in a fire composite cylinders
Breakthrough leak-no-burst (LNB) safety technology

- The TPL thickness is a function of its thermal properties, the ratio of nominal working pressure (NWP) to initial burst pressure (IBP) in the vessel, and thermal properties of FRP and TPL.

- The TPL thermal conductivity is below that of FRP to provide a failure of the liner, e.g. its melting, before a load-bearing fraction of the FRP wall is degraded to value:

\[ \alpha \cdot \frac{NWP}{IBP}, \]

where \( \alpha \) - coefficient of pressure increase above NWP.
LNB safety technology

Schematic description

Original tank: rupture
LNB tank: no rupture!

Numerical “testing”: LNB performance preserved for pressures up to 125% NWP and any fire regimes (different heat release rate per unit burner area, HRR/A)
First prototypes manufactured and tested in USA

Tanks parameters

<table>
<thead>
<tr>
<th>ID</th>
<th>OD of liner, in</th>
<th>OD of finished part, in</th>
<th>FRP#1 thickness, in</th>
<th>FRP#2 thickness, in</th>
<th>Weight, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>#4</td>
<td>6.334</td>
<td>8.178</td>
<td>0.450</td>
<td>0.472</td>
<td>27.5</td>
</tr>
<tr>
<td>#5</td>
<td>6.336</td>
<td>8.465</td>
<td>0.366</td>
<td>0.699</td>
<td>32.3</td>
</tr>
</tbody>
</table>

Test results

<table>
<thead>
<tr>
<th>ID</th>
<th>Charge pressure</th>
<th>Vent pressure</th>
<th>Leak starts</th>
<th>Leak duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>#4</td>
<td>700 bar</td>
<td>812.4 bar</td>
<td>9m 27s</td>
<td>16m 29s</td>
</tr>
<tr>
<td>#5</td>
<td>700 bar</td>
<td>854.5 bar</td>
<td>12m 23s</td>
<td>14m 37s</td>
</tr>
</tbody>
</table>

The hazards and associated risks of hydrogen vehicles could be eliminated or reduced drastically:

- No blast wave!
- No fireball!
- No long flames!
- No pressure peaking phenomenon in confined spaces!
First prototypes testing
Blowdown with equivalent diameter 0.20-0.25 mm

LNB resolves the issue of the destructive pressure peaking phenomenon in confined spaces like garages (insignificant leak!)
Steps after first prototype testing

Comments on Proof of Concept project results

- No experimentally data available for thermal parameters of different fibre-resin composites (need to measure for prototype optimisation to original size).
- “Conservative” values of parameters from literature were selected to provide LNB performance of the prototype (achieved).
- “Negative” consequence: first LNB tank prototype wall is somewhat thicker compared to the original 700 bar tank (concern of OEMs!).

Steps in new prototyping:

- Measure thermal parameters of fibre-resin composites
- Manufacturing LNB tank prototype of a larger volume with the same wall thickness as original tank (but cheaper!)
Forthcoming prototype

Industrial requirement: size of original tank

Original tank with partial change of carbon fibre to another fibre of smaller thermal conductivity and different resins: *the same size but cheaper* and *LNB performance*.

Here TPL of 3 mm only! No change of 2.25 factor (within production “scatter”).
Physical model of onboard hydrogen storage tank thermal behaviour during fuelling

Vladimir Molkov, Mohammad Dadashzadeh, Dmitriy Makarov

https://doi.org/10.1016/j.ijhydene.2018.12.115
Fuelling (validation)  
Type IV tank, 29 L

Test (Miguel et al., 2016):
- Initial pressure 2 MPa; target pressure 77 MPa  
- 3 mm orifice

Tank (Acosta et al., 2014):
- Volume 29 L (LxD=827x279 mm; ID=230 mm).  
- CFRP: thermal conductivity 0.74 W/m/K; $C_p=1120$ J/kg/K; $\rho=1494$ kg/m.  
- HDPE liner: thermal conductivity 0.385 W/m/K; $C_p=1580$ J/kg/K; $\rho=945$ kg/m.
Fuelling (validation)  
**Type III tank, 74 L**

Test (Zheng et al., 2013):
- Initial pressure 5.5 MPa; target pressure 70 MPa; 5 mm orifice.

Tank (Zheng et al., 2013):
- Volume 74 L (DxL=1030x427 mm; ID=354 mm).
- CFRP: thermal conductivity 0.612 W/m/K; $C_p=840$ J/kg/K; $\rho=1570$ kg m$^{-3}$.
- Aluminium liner: thermal conductivity 238 W/m/K; $C_p=902$ J/kg/K; $\rho=2700$ kg/m. 

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![Graphs](image.png)
Fuelling model application: Type IV tank, 50 L
Effect of pressure ramp: $T_{\text{amb}} = 50^\circ \text{C}; T_{\text{del}} = -10^\circ \text{C}$
UN GTR#13 on Hydrogen and Fuel Cell Vehicles

Fire test protocol reproducibility (FRR is a function of HRR/A)

New requirement:
HRR/A > 1000 kW/m²
UN GTR#13 on Hydrogen and Fuel Cell Vehicles

Localised in-situ fire

Localised fire dynamics:
HRR/A=1 MW/m²
Hydrogen vehicles in tunnel and confined spaces

Calculation domain and grid

Hexahedral block-structured grid inside the tunnel

Hydrogen storage tank (floor level): 140 L, H₂=5.5 kg, p=700 bar

Total CVs: 396,272
External: 79,712
Tunnel: 30,760
Tank: 14,800
Hydrogen vehicles in tunnel and confined spaces

Blast wave and fireball dynamics

Pressure

OH

Temperature

Velocity
Hydrogen safety education

e-Laboratory of Hydrogen Safety

Course information
- Principles of Hydrogen Safety
  This course focuses on the fundamentals of hydrogen safety to existing and foreseeable hydrogen and fuel cell systems and infrastructure.
- Hydrogen Safety Technologies
  This course focuses on advances in hydrogen safety technologies, including but not limited to prevention and mitigation strategies.

Duration & mode of delivery
These part-time courses run for 12 weeks each and are delivered fully online (face-to-face block-release may be possible for a group of more than 12, subject to demand). Principles of Hydrogen Safety runs in semester one and Hydrogen Safety Technology runs in semester two.

Assessment
100% coursework – two pieces of coursework per course focusing on problem-based solutions and qualitative questions (50% each).

Entry requirements
Any undergraduate degree

Credit points
30 points per course, 60 credits for both leading to the award of a Postgraduate Certificate of Professional Development.

Frequently asked questions

How much will each course cost?
- Northern Ireland and EU: £983.40*
- England, Scotland and Wales: £983.40*
- International: £2,363.30*

What next?
Applications are made online. Please go to: ulster.ac.uk/apply/how-to-apply/postgraduate, click on the Short courses, and follow the instructions provided. Applications are accepted until the start of the academic year (mid of September).

Find out more
W: ulster.ac.uk/cebe
W: ulster.ac.uk/courses/201920/principles-of-hydrogen-safety-20407
W: ulster.ac.uk/courses/201920/hydrogen-safety-technologies-20408

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Acknowledgement to HySAFER staff and our funders (EPSRC, FCH JU, Invest NI, INTERREG)