IGNITED RELEASES OF LIQUID HYDROGEN: SAFETY CONSIDERATIONS OF THERMAL AND OVERPRESSURE EFFECTS

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Background

- HSE funded research program
- If hydrogen economy takes off there will be an increase in LH2 road tanker traffic in UK
- Increase in refuelling operations
- Therefore a need to assess the risk from a delivery hose failure in standard operation
Background

• Commissioned as four programs of work:
  – Positions paper: Hazards of LH2 (RR769)
  – Un-ignited releases
  – Computational modelling of the releases (un-ignited)
  – Ignited releases
Project aims

- Flammable extent of a vapour cloud
- Flame speeds through a vapour cloud
- Radiative heat levels generated during ignition
Experimental set-up
Experimental set-up

- P&ID of release system
Experimental set-up

- LH2 tanker containing 2.5 tonnes
- 1” n.b. horizontal release line
- Release pressure of 1barg
- Flow rate measured to be \( \approx 60 \text{ litres per minute} \)
- Ignition system:
  - 1kJ chemical igniters in four locations due to variability in cloud direction
  - Ignition positions close and far from release
Experimental set-up

• Igniter positions
Experimental set-up

- **Instrumentation:**
  - Flammable extent and flame speed
    - Standard and IR video at 50fps
    - Some high speed video at 500fps
  - Radiative heat
    - Ellipsoidal radiometers, range: $110\text{ kW/m}^2$, $160^\circ\text{ field of view}$
  - Meteorological measurement
    - Temperature, humidity, wind speed and direction
Experimental set-up

- Radiometer positions
Experimental releases

- 14 tests performed, of which 10 ignited
- Variables:
  - Release duration
  - Weather conditions (wind direction/speed)
  - Ignition position
Experimental releases

• Video of test 2
Experimental releases

- Video of test 3
Experimental releases

• High speed video of test 7
Experimental releases

- IR stills of test 11

300ms post ignition

2000ms post ignition
Experimental releases

- Test 6
Experimental releases

- ‘Snow’ formation prior to ignition on long releases

- Secondary explosion appears to emanate from this location
Experimental releases

- Radiometer trace of test 6
Overpressure estimation

• During test 6 a one off secondary explosion occurred
• \( \approx 260 \) second release
• Secondary explosion occurred \( \approx 3 \) seconds after ignition
• Produced an 8m hemispherical fireball emanating 2.5m in line with release
• No pressure measurements at time of explosion, only standard video and radiometers
Overpressure estimation

Two methods used:

1. Pressure Effects

- Perspex windows in small cabin 20m away failed to break, therefore a maximum can be deduced.
- This is modelled in Hazl®, however, nearest material available is Polycarbonate (stronger than Perspex).
- TNT equivalent calculated to be < 4kg.
- If the H₂ were act like a condensed phase explosive (i.e. all H₂ used to generate blast wave) then this equates to < 150g H₂ yielding 18MJ.
Overpressure estimation

Two methods used:

2. Radiative Fraction

- Use radiometer data and relate to the radiative fraction
- Jet-fire phase used for estimate of radiative fraction

\[ Q_r = \chi M \Delta H_c \]

where \( Q_r \) - heat radiated, kW; \( \chi \) - radiative fraction (between 0 and 1); \( M \) - mass rate of fuel combustion, kg/s; \( \Delta H_c \) - heat of combustion of the fuel, kW/kg

- Normally radiative fraction based on significant distance from flame
- In this case the flame was elongated along the line of radiometers and close to the ground
Overpressure estimation

• Therefore a semi-cylindrical radiating heat source assumed:

\[ Q_r = (1 + \alpha) \frac{\pi d L q}{2} \]

where \( Q_r \) - heat radiated, kW; \( d \) - distance to radiometer, m; \( L \) - length of flame, m; \( q \) - heat flux at radiometer, kW/m\(^2\); \( \alpha \) - reflection coefficient of concrete surface below the flame

• Reflection co-efficient taken as 0.55
• Giving radiative fraction of 0.054 for jet-fire phase

• Estimate is based on the furthest radiometer, a hemispherical heat flux and a similar radiative fraction as during jet-fire phase

• Gives 675g H\(_2\) yielding 82MJ, \( \approx \) 18kg TNT equivalent!!

• Reported that H\(_2\) explosions of a particular energy would cause less damage at a given distance than a TNT explosion of same energy
Safety distances: thermal effects

- Levels of harm equated to thermal dose units (TDUs)
  \[ TDU = I^{\frac{4}{3}} \times t \]
  where TDU - thermal dose units; I - thermal radiation intensity, kW/m\(^2\); t - duration for which the radiation is experienced, secs

- Using the radiometer data from the ignited tests and historical IR burn severity data an assessment of the thermal dose from LH2 spills can be made

- Four test regimes considered:
  - Steady state jet-fire during high wind speeds > 0.6m/s
  - Steady state jet-fire during low wind speeds < 0.6m/s
  - Initial deflagration or ‘burn back’ of the release cloud to source
  - Secondary explosion seen after the initial deflagration

Continuous events

Instantaneous events
Safety distances: thermal effects

• **Continuous jet-fires**
  – No harm 1.6kW/m² (grey area)

Test 7
Wind speed: 0.59m/s

Test 4
Wind speed: 2.15m/s

Time to ‘pain’ at 7.6m = 44 seconds

Time to ‘pain’ at 7.6m = 28 seconds
Safety distances: thermal effects

- Instantaneous deflagration and explosion
  - Test 6
Safety distances: thermal effects

- Approximate safety distances

<table>
<thead>
<tr>
<th>Minimum separation distance from source to avoid ‘pain’ (m)</th>
<th>Initial cloud deflagration</th>
<th>Secondary explosion</th>
<th>Jet-fire (High wind)</th>
<th>Jet-fire (Low wind)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 11.1</td>
<td>&gt; 11.3</td>
<td>12.6 &gt; 13.7</td>
<td>12.6 &gt; 13.7</td>
<td></td>
</tr>
<tr>
<td>Exposure time (secs)</td>
<td>0</td>
<td>0</td>
<td>∞</td>
<td>∞</td>
</tr>
</tbody>
</table>

Note: These values consider radiative heat only, not pressure effects.
Conclusions

From experimentation, four separate regimes have been found to occur when a full bore failure of a 1” liquid (60 l/min) hydrogen tanker transfer hose is ignited:

- An initial deflagration of the cloud back to source, travelling at speeds up to 50 m/s
- A possible secondary explosion emanating from the solid deposit generated after the initial deflagration of the release cloud due to oxygen enrichment.
- A buoyancy driven jet-fire when wind conditions are minimal (wind speeds < 0.6 m/s), with flame speeds > 25 m/s
- A momentum dominated jet-fire when wind conditions are high (wind speeds > 0.6 m/s), with flame speeds > 50 m/s