Hydrogen and fuel cell stationary applications: key findings of modelling and experimental work in the HYPER project

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Outline

- Introduction to HYPER
- Who is involved?
- Phenomena considered for modelling and experimental work
- How is the work grouped? Scenarios considered?
- Snapshot of key activities and results in each scenario – detailed descriptions in other ICHS 3 papers
- Main conclusions

Introduction to HYPER

- Installation Permitting Guidance (IPG) for Small Stationary Hydrogen and Fuel Cell Systems
- EC FP6 specific targeted research project
- HYPER: Develop guidelines to enable fast track approval of safety and procedural issues
- Aimed at developers, design engineers, manufacturers, installers and authorities
- November 2006 –January 2009
- Extensive modelling and experimental programme to:
  - Generate new scientific knowledge and data
  - Where possible use this data as a basis for IPG

Who was involved?

- Collaboration between 15 partners from the European community, Russia and USA
- 9 Partners contributed to work presented here

Programme of work

- Gap analysis performed
- Relevant topics identified:
  - High pressure release / low pressure release
  - Moderate – foreseeable release / catastrophic release
  - Explosive atmosphere: inside equipment casing / outside equipment casing
  - Explosive atmosphere inside room/building
  - Quiescent / turbulent explosive atmosphere, Early ignition / late ignition
  - Explosion / jet fire; Mitigated / non mitigated scenarios
- Key scenarios for further modelling and experimental work

  1. High pressure releases: typical of those associated with storage

  2. Small foreseeable releases; around the FC etc

  3. Catastrophic releases: combustion inside the FC

  4. The effect of walls and barriers

  5. Sensors and detection

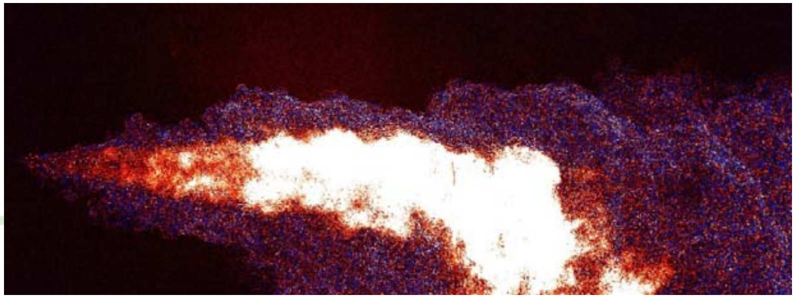
High Pressure Releases

Overview and objectives

- Relates to failure of high pressure hydrogen storage
- Pressures in experiments up to 900+ bar (INERIS) , pipe diameters up to 10 mm (HSL)
- Data from the literature used to support modelling (UU, CEA)
- Assess the hazard on failure of pipe-work/components and how the risk of this hazard causing injury or further damage can be minimised.
- Phenomena studied:
    - jet fires, unignited jets,
    - delayed ignition of a flammable cloud formed by a release
- Better understanding and evaluation of the risks
- Enables estimation of safety distances

HSL experiments

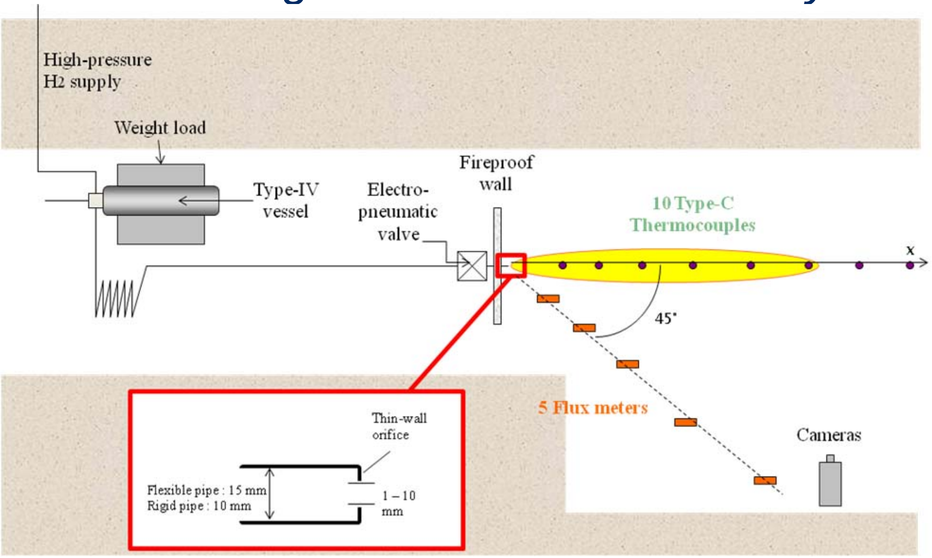
- Release scenarios included effect of jet attachment and of varying: orifice size, ignition delay and ignition position
- Flammability envelope, flame size and heat fluxes for various geometries and pressures investigated
- Restrictors 1.5, 3.2 and 6.4 mm, full bore 9.5mm
- Change ignition timing and location
- 205 bar to free air
- Flame lengths are longer in the case of attached jets
- Max overpressure versus ignition position given amoung other results
- See ICHS 3 Paper for further details



INERIS experiments

- 80m long gallery, 12m² cross section
- Jet fires
- Low pressure tests (100 bar)
- High pressure tests (900 bar)
- Orifices: 1, 2, 3, 4, 7 and 10 mm
- Horizontal jet, 1.5m above ground level
- Flame length results shown later on nomogram
- Max width: length ≈ 1/6

Figure: Schematic of facility



- See ICHS 3 Paper for further details

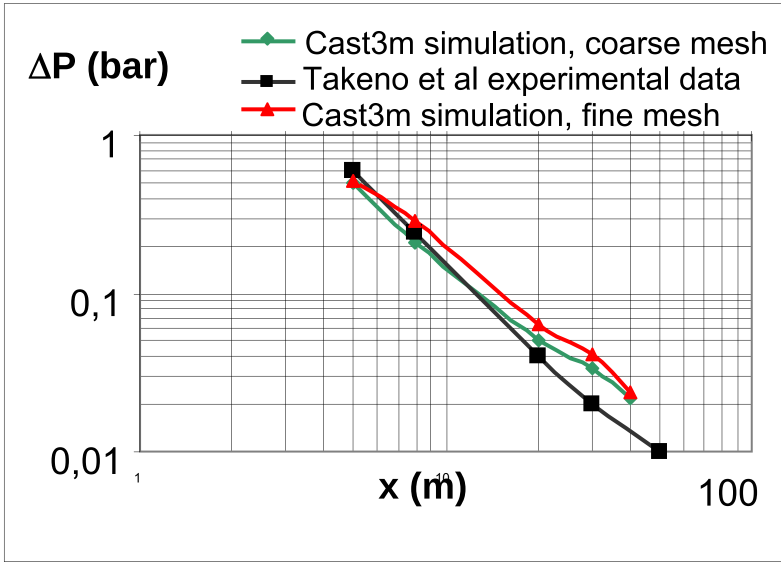
Selected simulations

CEA:

- Dispersion cloud in large domain
- Subsequent combustion
- Takeno experiments of delayed ignition

  [*Takeno K. et al. Phenomena of dispersion and explosion of high pressurized hydrogen, 2nd ICHS, 2007 San Sebastian, Spain*]
- 10mm piping, 400 bar, horizontal release
- Reactive, fully compressible (Cast3m)

Maximum overpressure



UU:

- Parametric study of free jet fires

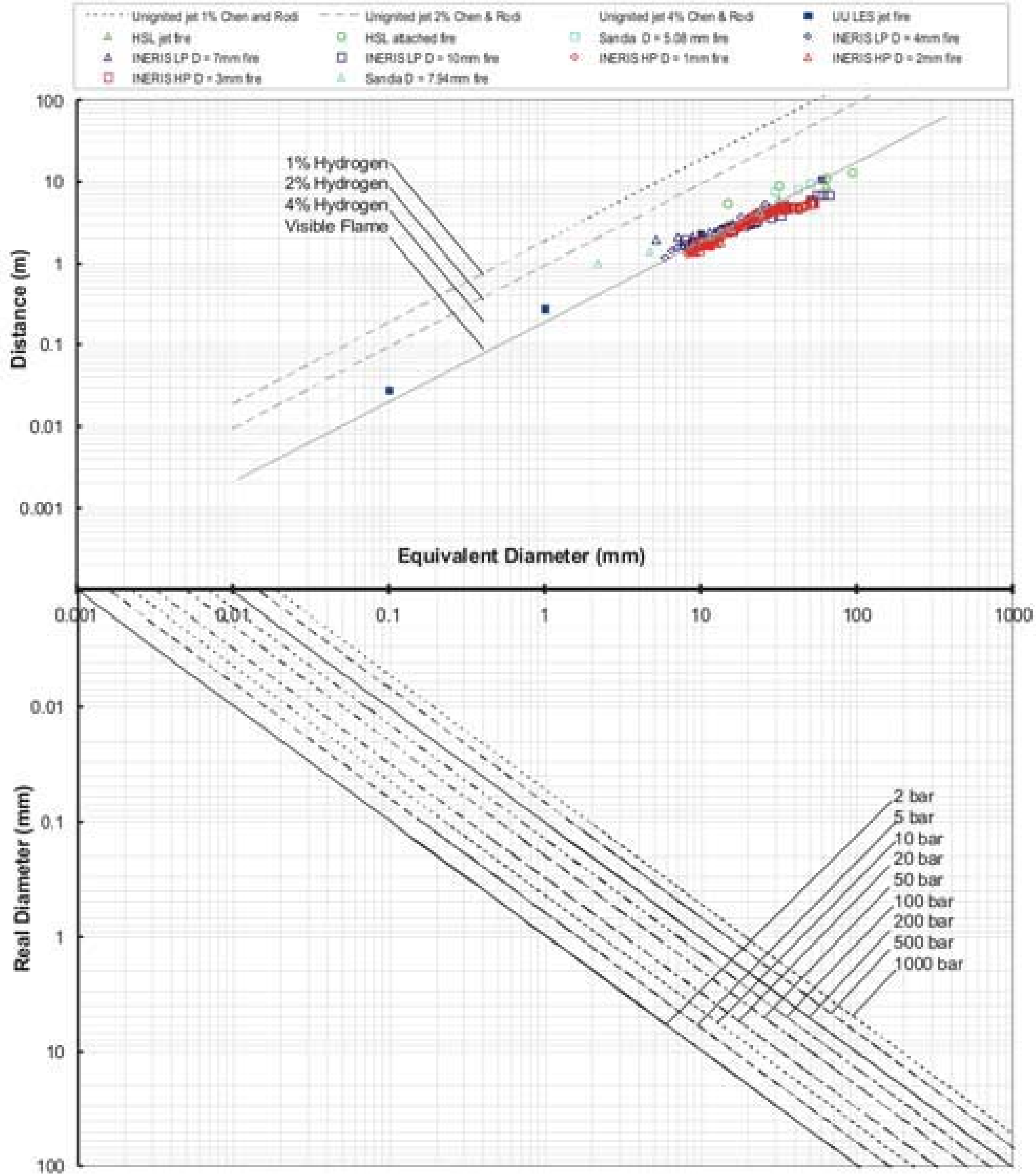
  UU equivalent diameter method, LES, validated approach

  Equivalent diameters 0.1mm to 100mm

Engineering Nomogram

incl. simulations, INERIS and HSL data

Further developments since HYPER



Small Foreseeable Releases

Overview and objectives

- Concerns “small” leaks that could potentially be controlled through ventilation
- Related to low-pressure hydrogen downstream of the pressure regulation controlling the flow of hydrogen to the fuel cell system.

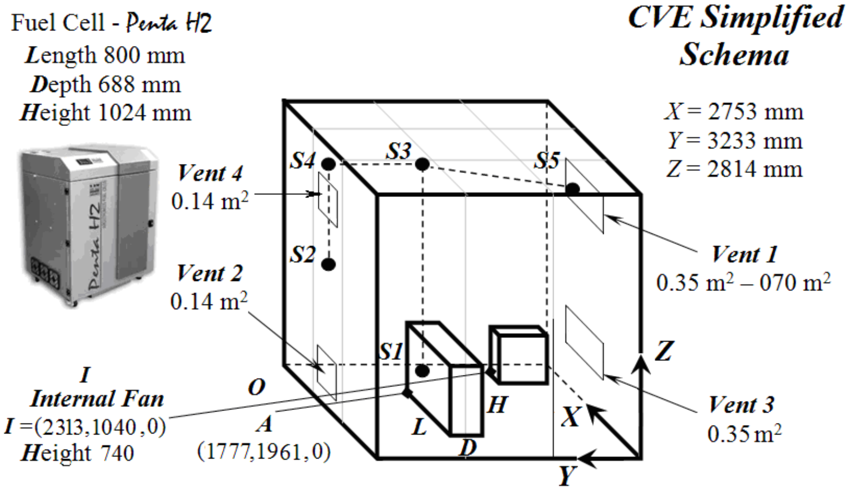
  (Leaks originating inside the fuel cell)
- Phenomena studied:
  - Dispersion of hydrogen
  - Concentration of H_2 for various natural and mechanical ventilation configurations
- Experimental work at UNIPI, Modelling work at NCSRD and UU

Work focused on the case of a fuel cell system located inside a typical enclosure. Ventilation configurations were varied to assess the resultant concentration of H_2 for different low leak rates

UNIPI experiments

- Determine ventilation requirements such that concentration of H_2 in air for Zone 2 ATEX (2% v/v) is not exceeded
- Volume of reference enclosure: 25 m^3
- Vary leak rate, vent location and vent area
  (min 0.35m^2, max 2.5m^2)
- Worst case of 5 bar taken
- Leak area: 0.25mm^2 (ATEX guidance)
- Gives max flow of 40 l/min
- Areas of 0.5mm^2 and 1 mm^2 also
- Natural Ventilation (NV):
  40 l/min, 90 l/min and 180 l/min
- Forced ventilation (FV):
  same rates + 2 fan flow rates
- FV tests were performed in cases where NV failed i.e. when H_2 %vol was not ≤ 2%

Figure: CVE Facility, showing sampling points and vent areas



Simulations

NCSRD

- Majority of UNIPI's NV experiments simulated by NCSRD
- ADREA-HF code
- Model included FULL interior of the FC
- See papers at ICHS 3 for full details!

UU

- UU investigated the effect of wind on the efficiency of NV
- Wind was directed oncoming to the upper vent
- Air velocities of 0, 0.11, 0.33 and 1.1 m/s

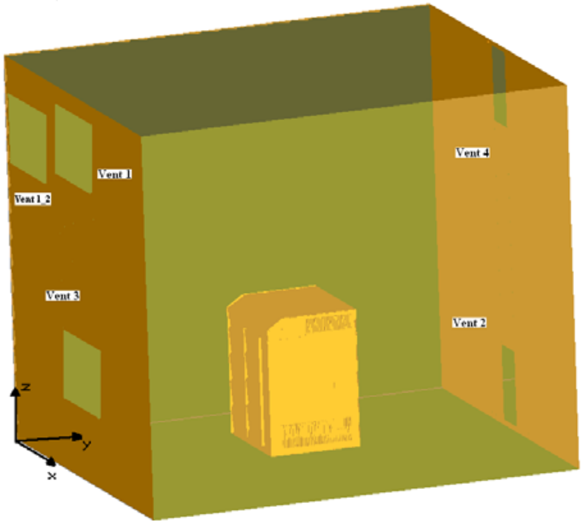
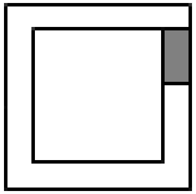


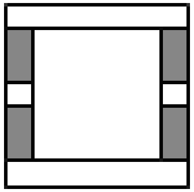
Figure : Facility and FC (DELTA-B Code)

Experimental results

- Full results and table can be found in the paper
- Natural ventilation is deemed to be "effective" only if ATEX zone 2 is respected
- Natural ventilation is effective when considering the worst leak (40 l/min) from the 5 bar pipe, except in the configuration with 1 upper vent



- For a higher leak rate of 90 l/min the natural ventilation is effective only for a configuration with 4 vents (2 upper and 2 lower on opposing sides of enclosure)



- For the maximum leak rate of 180 l/min natural ventilation is ineffective
- Both forced and natural ventilation results are given in the paper

Simulation results

NCSRD

- Good agreement between predicted and experimentally measured concentration time histories
- Comparison for test 3, release flow rate of 40l/min shown (nozzle diameter of 1mm and 1 vent open, horizontal release)
- See additional ICHS 3 paper

UU

- The ambient wind was found to worsen H_2 venting in a very narrow range of velocities
- In a realistic scenario effect may be diminished further as a result of turbulent fluctuations in wind both in velocity value and direction

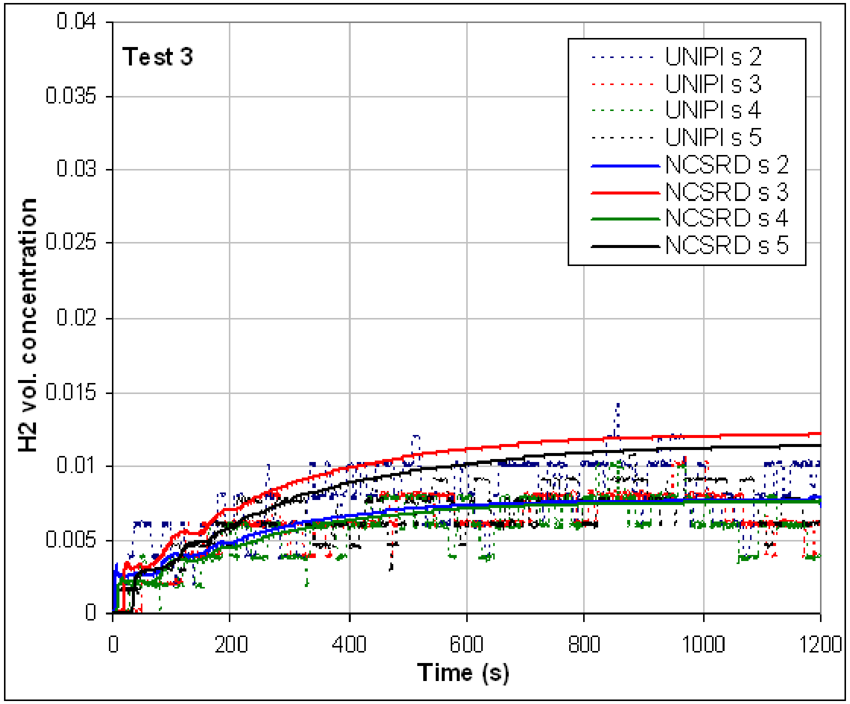


Figure : UNIPI-NCSRD comparison (sensors 2, 3, 4 and 5)

Catastrophic Releases

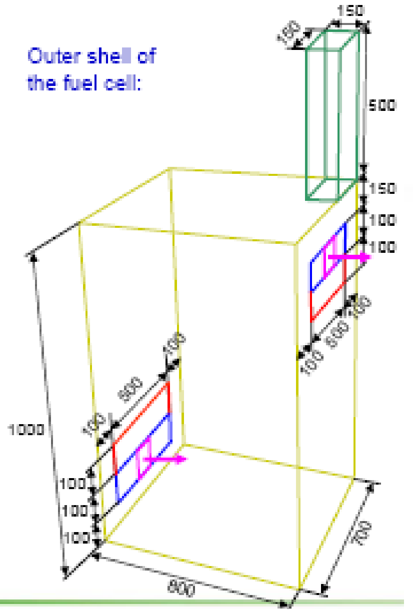
Overview and objectives

- Considers the rupture of the hydrogen feed line inside the fuel cell
- Hazard potential of a severe leakage investigated
- Experimental work performed by Pro-Science
- H_2 release rates of 1.5 g/s, up to 15g/s considered for a duration of 1s
- Phenomena studied:
  - Dispersion of hydrogen
  - Subsequent ignition of the hydrogen air mixture
- Objectives:

  Determine if DDT occurs and order of overpressures

  Assess effects of internal blockage ratio
- Modelling work by CEA included validation and assessment of overpressures

Methodology



Pro-Science Experiments

- Generic FC cabinet, with generic FC enclosure model
- Internal volume of 560 l, minimum blockage of 120 l
- H_2 release rates of 1.5 - 15g/s for a duration of 1s
- 3 cases, with 3 different venting characteristics
  - two opposing vent openings – passive (1a) and active venting (1b)
  - two enlarged opposing vents, doubled size – passive (2)
  - case with smaller vents + chimney at the top (3)
- Dispersion and combustion experiments
- 2 internal blockage ratios (50% & 67%), 2 ignition positions (inside & outside)
- 2 ignition times (immediate continuous and after 4s for 300ms)

CEA Simulations

- Distribution & combustion, case 1a, H_2 release rate of 6g/s, ignition 4s
- Fluent (dispersion), Cast3m with CREBCOM combustion model (combustion)

Pro-Science results

Dispersion experiments

- Low internal obstruction: - “Chimney effect” in all experiments
- High internal obstruction:

  outside enclosure: only small H_2 concentrations measured
  inside: inhomogeneous mixture with high concentrations near walls and top
  no combustion experiments with such geometry due to high concentrations

Combustion experiments

- Combustion in all cases of durable internal ignition even 1.5g H_2
- Ignition of 3g H_2 > pressure waves max. 40mbar (breakage of large windows)
- Ignition of 4g H_2 > pressure waves max 100mbar (human injury)

See Pro-Science ICHS 3 paper for full details

CEA results

- Qualitatively experimental results were recovered
- At 4s, when ignition occurs, simulation predicts flammable mass of 5.5g
- Combustion simulations showed flame acceleration occurred in the cube obstacle and close to the rear wall leading to high overpressures
- For a remaining mass of H_2 mass in FC, predicted overpressure 0.2bar

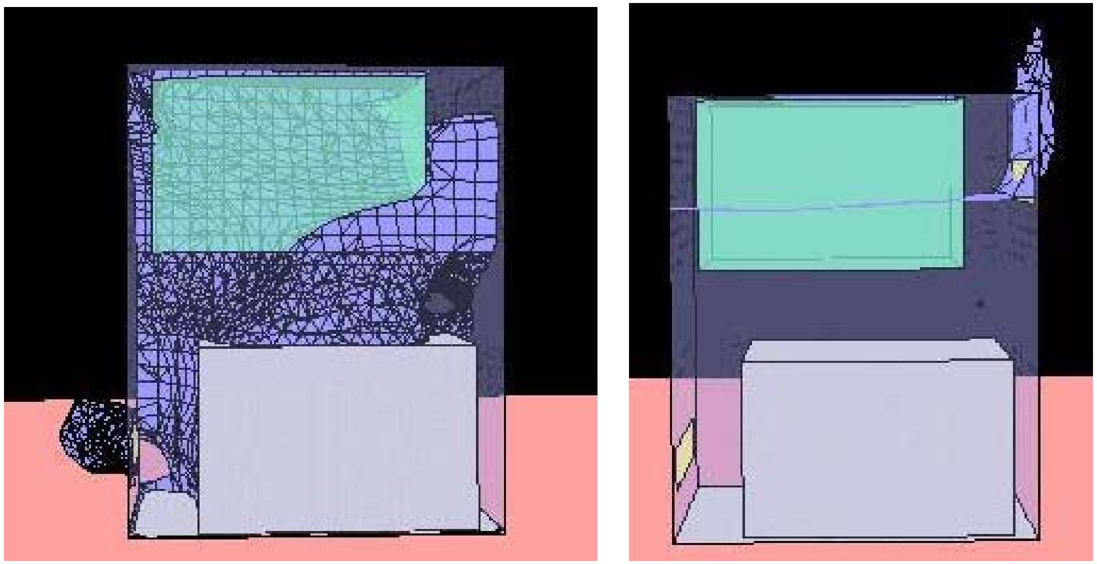


Figure : Isosurface 4% H2 after 0.31 s (L), and 21.5 s (R)

The Effect of Walls and Barriers

Overview and objectives

- Concerned with the use of barriers to control the impact of releases from high pressure hydrogen storage.

Objectives:

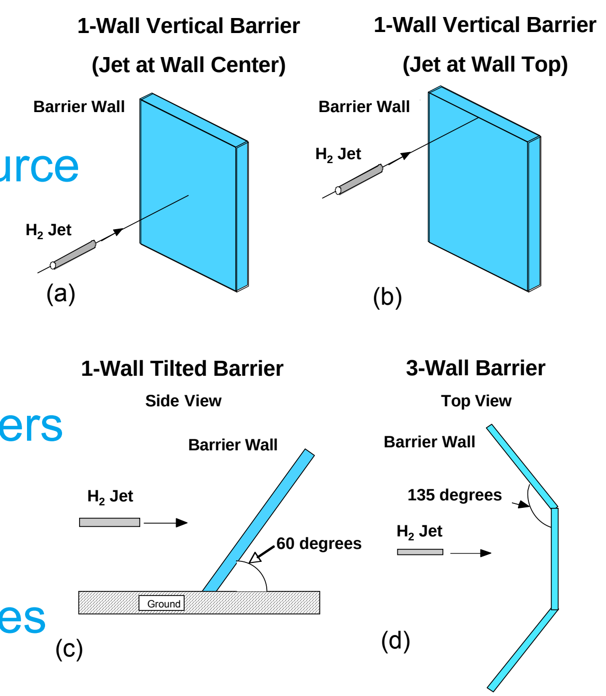
- Determine barrier wall effectiveness as a mitigation strategy
- Determine the resulting overpressures and radiation
- Various angles of impingement are considered

- Experimental and modelling work by Sandia (HSL not described here)
- Additional papers at ICHS 3 by Sandia
- Modelling work FZK

Methodology

Sandia modelling and experimental programme

- Experimental measurements included:
  - Study of initial flame propagation from ignition source
  - Ignition overpressures, wall deflection,
  - radiative heat flux, wall and gas temperature
- Modelling included: (FUEGO and FLACS codes)
  - 3D calculations of jet flame deflection by the barriers
  - thermal radiation field around barriers
  - predicted overpressures from ignition
  - concentration field - deflected unignited H_2 releases
- 4 barrier wall tests and 1 free jet as a baseline

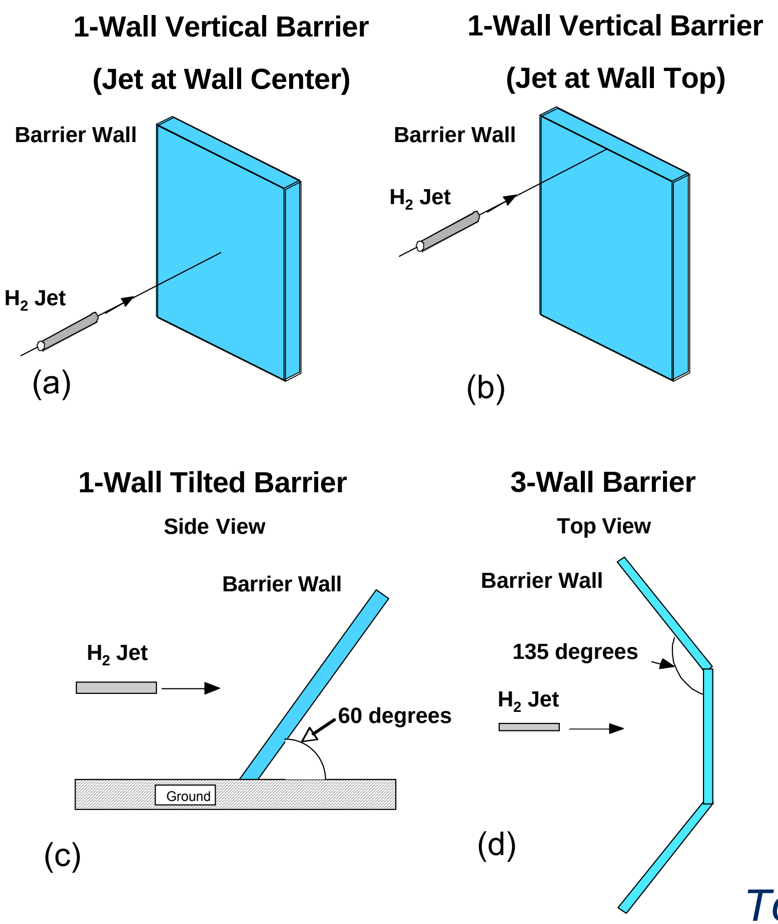


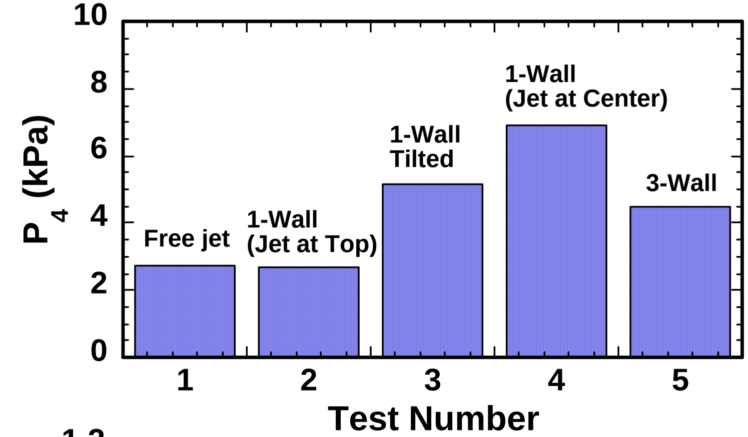
FZK modelling

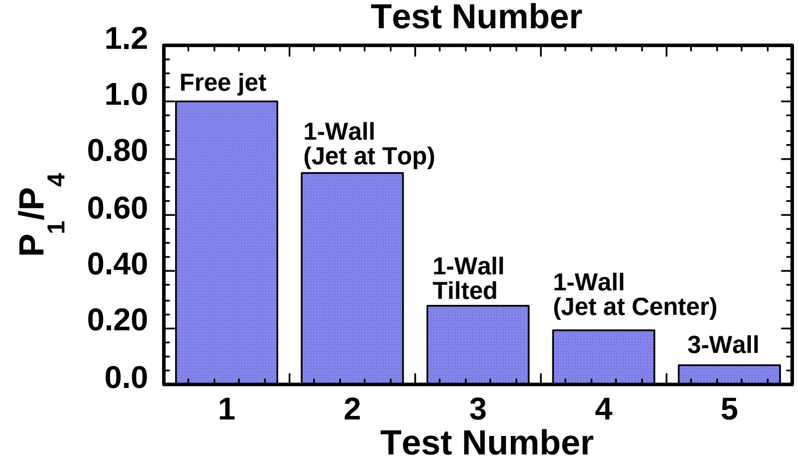
- Two geometries simulated: free jet and impingement in wall centre
- COM3D code, ignition at 140, 260 & 640ms
- Results deemed of acceptable accuracy for practical purposes

Sandia results

See ICHS 2 and 3 papers for further details







Top graph: Max. overpressure measured prior to wall;

Lower graph: Ratio of max. overpressure measured after the wall to that prior to the wall.

Conclusions (1/2)

High Pressure Releases:

- Engineering nomogram can be used to estimate flame length, or extent of the flammable envelop, for a given storage pressure and diameter
- Inclusion of flow restrictors in supply lines reduces flame length
- When a jet is orientated close to a surface, jet length may be enhanced
- Ignition in weak region of the cloud: slow burn and smaller overpressure

Small Foreseeable Releases:

- Where possible, it is recommended to use one or more suitable solutions:
- Increase vent areas beyond the min. value calculated using ATEX;
- Incline the roof making the NV easy and efficient
- Install a small fan able to remove the internal mixture from the enclosure.

Conclusions (2/2)

Catastrophic Releases:

- Reduce the H_2 amount that can be released from a ruptured pipe inside the FC enclosure to below 1.5 g.
- The feed line pressure and/or diameter should by design limit the flow rate to what is necessary for FC consumption (inventory 1g for case studied)
- The release duration should be reduced as much as possible
- Obstacles should be avoided by a careful design of the cell itself
- Vent design should allow for a rapid dispersion of H2 during a leak and efficient pressure relief during an explosion

The effect of walls and barriers:

- For the conditions investigated the barrier configurations studied:
- Reduced horizontal jet flame impingement hazard by deflecting the flame
- Reduced radiation hazard distances for horizontal jet flames
- Reduced horizontal unignited jet flammability hazard distances

Overall the modelling and experimental work in HYPER provided insight into the key scenarios related to the safety of stationary FC systems

For further information the HYPER Installation Permitting Guidelines are available online

http://epshypp.web.its.manchester.ac.uk/