European Integrated Hydrogen Project [www.eihp.org]

EIHP

Proceedings

of the Mid-Term Assessment Workshop of the

European Integrated Hydrogen Project - Phase II [EIHP2]

Proceedings
Volume 5
Breakout Session
Safety

held at the European Commission's

CCAB - Centre Albert Borchette

Brussels, 02 October 2002

WP5 Safety - Breakout Group - Topics & Contributors

Moderator: Daniele Baraldi

- **14:10: “Structure of Hydrogen Safety Problems ” (S. Dorofeev, FZK)**
- **14:30: “Properties of Hydrogen in Comparison with Other Fuels ” (L. Shirvill, Shell)**
- **14:50: “Release Scenarios and Modeling of Hydrogen Mixing and Combustion” (A. Venetsanos, NCSRDemokritos)**
- **15:10: “Evaluation of Hazards Associated with Hydrogen Combustion - Achievements and Issues” (S. Dorofeev, FZK)**
- **15:30: “Risk Analysis - Problems and Issues” (H. Rikheim, DNV & S. Nilsen, Norsk Hydro)**
- **15:50: General discussion and formulation of conclusions/findings**

WP5 Satfety - Breakout Group - Summary 1

Session notes and remarks by Dr. Daniele Baraldi, EC-JRC

Several comments highlighted that the current knowledge about hydrogen safety is less thourogh than the knowledge of safety of conventional fuels. In particular, Dr. Schmidtchen (Bam) expressed the need for more experimental data on the hydrogen release and combustion in confined enviroments such as tunnels and garages. Dr. Les Shirvill (Shell) put the emphasis on the general lack of data on frequency and size of hydrogen releases. Dr. Perrette (Ineris) stated that currently most of the safety studies are focused on worse case scenarios and expressed the need for investigations also on mild case scenarios.

WP5 Satfety - Breakout Group - Summary 2

Prof Carvalho (Instituto Superior Tecnico Lisbon) suggested that some knowledge could be transferred from other fields to hydrogen safety and that the sharing of information and data on hydrogen safety among universities, research institutes and companies should be larger than it is in the current situation.

The ***final conclusion*** was that since the EIPH2 project cannot cover all the gaps identified in the current state of hydrogen safety due to limited time and resources, further projects and investigations are required in the near future in order to reach a thorough knowledge of hydrogen safety.

Structure of hydrogen safety problems. Proposals for FP6 IP HySafe

Mid-Term Assessment Workshop

Brussels

02 October 2002

Presentation by
S. Dorofeev
FZK,
Germany

Structure of hydrogen safety problems

Motivation

- Introduction of hydrogen as an energy carrier requires significant efforts in the field of safety

- The central goal is that H_2-technologies should provide at least the same level of safety, reliability, and comfort as today's fossil energy carriers

- Public acceptance of H_2-technologies should be reached through
  - General safety studies
  - Comparative risk studies,
  - Dissemination, education, training activities, and demonstrative hardware

- Although hydrogen safety has been a subject of numerous research efforts, no solutions are available in terms of widely accepted standards, methodologies, mitigation techniques, and regulatory issues

Structure of hydrogen safety problems

Background

- Chemical and physical properties of H_2 allow concentrating efforts on studies of **fire and explosion safety** of hydrogen mixed with air

- The properties of hydrogen are different from today's fuels
  - H_2 is expected to be less dangerous in terms of thermal and fire hazards,
  - H_2 may be responsible for stronger pressure effects

- A comparison of specific and overall risks can be useful to highlight advantages of H_2 fuel and to identify areas, where additional accident management measures or regulations can be recommended

- Hydrogen mitigation techniques and safety devices for detecting, dilution and removal of hydrogen still possess significant innovation potential

Structure of hydrogen safety problems

Applications

- Accident scenarios, initial conditions, hazard potential, and risk depend on the particular application of hydrogen as an energy carrier
- The following main blocks of applications can be identified:
  - Infrastructure (transport and distribution, refueling stations)
  - Storage (LH2, CGH2)
  - Vehicles powered with H_2 (passenger cars, trucks, repair shops)
  - Public parking and private garage
  - Tunnels
  - Portable or stationary H_2 based applications

Structure of hydrogen safety problems

Issues

- To evaluate hydrogen safety the following set of issues should be addressed for each of the applications
  - Hydrogen release, mixing, and distribution
  - Thermal, pressure, and missile effects from H_2 fires and H_2-air cloud explosions
  - Mitigation techniques for detection, dilution, and removal of hydrogen
  - Risk evaluation, both specific and in comparison with today's fossil energy carriers

Structure of hydrogen safety problems

Structure of IP 'Safety of hydrogen as an energy carrier'

	V1. Hydrogen release, mixing, and distribution	**V2.** Thermal and pressure effects from H_2 fires/explosions, missiles	**V3.** Development of hydrogen accident mitigation techniques	**V4.** Safety and risk studies
H1. Infrastructure				
H2. Storage (LH2, CGH2)				
H3. Vehicles powered with H2				
H4. Parking and garage				
H5. Tunnels				
H6. H_2 based applications				
H7. Education, dissemination, and training				

RESULTS:

- Experimental databases for hydrogen safety analyses for different applications
- Validated analytical and numerical tools for assessment of safety for different applications
- Experimentally validated mitigation techniques and safety devices
- Innovative hydrogen mitigation technologies
- Methodologies for risk evaluation, both specific and in comparison with today's fuels
- Improved technical culture to handle hydrogen as an energy carrier
- Inputs to European/global regulatory and standardization activities

Structure of hydrogen safety problems

Objectives of vertical sub-projects

- Provide experimental data and develop database for hydrogen safety assessment of different applications, including full-scale test data

- Develop and validate analytical and numerical models using experimental data and provide validated tools for hydrogen safety assessment of different applications

Structure of hydrogen safety problems

Objectives of horizontal sub-projects

- Identification of representative accident scenarios
- Application of validated tools for safety assessment and comparative risk studies for each given application
- Support of regulatory issues and standardization
- Development of innovative mitigation technologies
- Dissemination of tools and education

Structure of hydrogen safety problems

Expertise needed

- Hydrogen applications (infrastructure, storage, vehicles, …) including state-of-the-art and innovative technologies
- Causes and frequencies of potential accidents with flammable gases, accident scenarios. Methodology, practice, and facilities for reliability analysis
- Methodology and practice in risk analyses
- Fire an explosion properties of hydrogen and other combustibles
- Experiments and modeling on fire and explosion hazards, effect of scale, experience in large-scale experimentation
- Validated tools for safety assessment, description of gaseous mixing, fires and explosions
- Hydrogen mitigation techniques and safety devices based on hydrogen detection, removal and dilution

Structure of hydrogen safety problems

Proposed consortium

- Forschungszentrum Karlsruhe (FZK), Germany (Coordinator)
- AB Volvo Technological Development, Sweden
- AEA Technology GmbH /CFX, Germany
- Air Liquide, France
- Bayerische Motoren Werke AG (BMW AG), Germany
- Commissariat à l'Energie Atomique, France
- CNRS-Orleans, France
- Det Norske Veritas AS, Norway
- ENSI-Bourges-LEES, France
- Federal Institute for Materials Research and Testing (BAM), Germany
- Forschungszentrum Juelich (FZJ), Germany
- Fraunhofer Institute Chemische Technologie (ICT), Germany
- Germanischer Lloyd AG, Germany
- GKSS Research Centre, Germany
- Institute Nationale de Environnment Industriel e des Risques (INERIS), France
- Joint Research Centre of the European Commission
- National Centre for Scientific Research Demokritos, Greece
- Norsk Hydro, Norway
- Renault, France
- RTD Centre INASMET, Spain
- TNO, Netherlands
- University of Pisa, Italy
- University of Ulster, UK

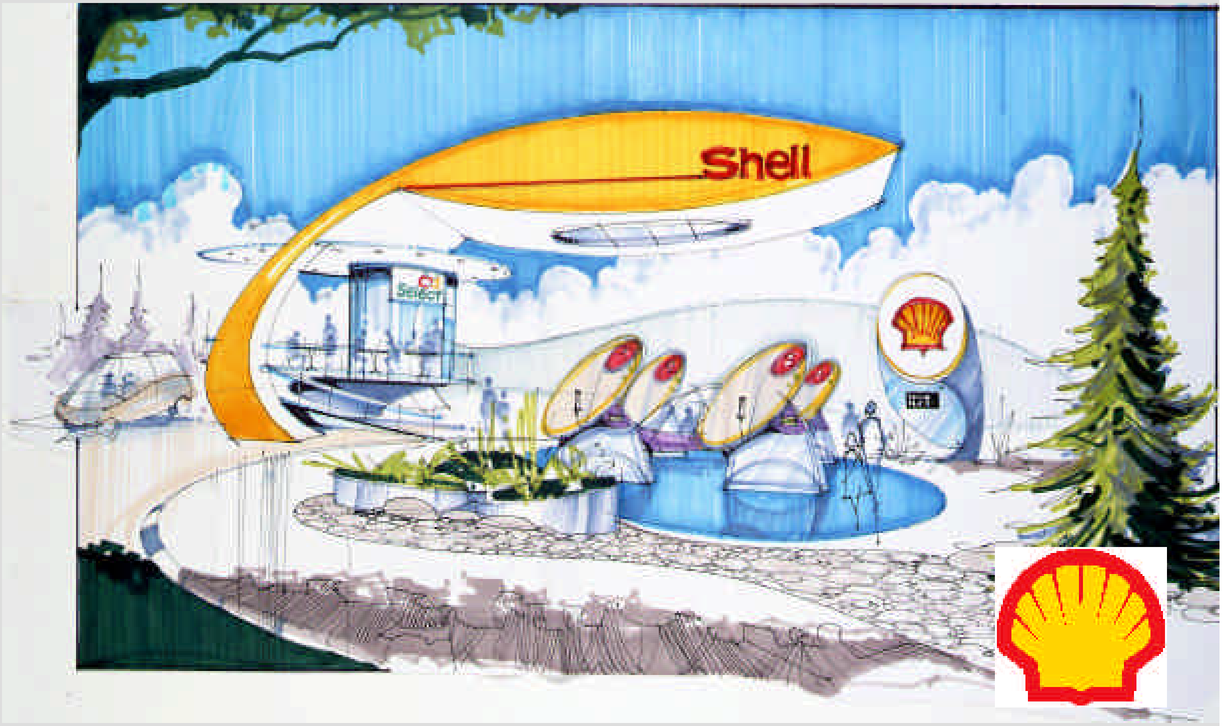
Structure of hydrogen safety problems

Safety tasks within EIHP 2

	V1. Hydrogen release, mixing, and distribution	**V2.** Thermal and pressure effects from H_2 fires/explosions, missiles	**V3.** Development of hydrogen mitigation techniques	**V4.** Safety and risk studies
H1. Infrastructure				
H2. Storage (LH2, CGH2)				
H3. Vehicles powered with H2				
H4. Parking and garage				
H5. Tunnels				
H6. H_2 based applications				
H7. Education, dissemination, and training				

Mid – Term Assessment Workshop

Work Package 5: SAFETY Breakout session



Brussels
02 October 2002

Presentation by
Shell Global Solutions for
Shell Hydrogen

Central Vs Onsite Hydrogen Generation

Central Generation:

Generate at central point.

- Large Steam Reformer
- Gasification of biomass, coal, other residues

Transport hydrogen to point of use

H_2 Distribution

- *Gas Pipeline*
- *Gaseous trucking*
- *Liquid on tanker*

On-Site Generation:

Transport raw material to point of use.

Generate hydrogen at (close to) point of use.

- Small Steam Reformer/ POx/CPO
- Electrolysis

(Ultimate distributed generation is on-board)

Not required

Will need to store some hydrogen at retail site to meet peak demand

Risk analysis for hydrogen as a fuel

Risk = Probability of Accident Occurring X Magnitude of Hazardous Consequences

- Distribution tanker accidents
- Distribution pipeline accidents
- Releases during fuel delivery to forecourt

} For central manufacture of H_2

- Releases during on-site manufacture

} For distributed manufacture of H_2 (reforming or electrolysis)

- Releases from on-site storage
- Releases from dispensing operations
- Vehicle safety - releases from vehicles

NB H_2 may also be produced onboard the vehicle by reforming methanol or liquid hydrocarbons.

Risk analysis for hydrogen as a fuel

Perceived risk may be exaggerated due to

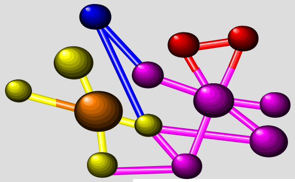
- unfamiliarity with H_2 as a fuel
- negative associations

To be used in public, untrained people must be able to handle hydrogen with the same degree of confidence and with no more risk than conventional liquid and gaseous fuels.

Must also be
- **Beneficial to the global environment**
- **Economic**

Hydrogen storage techniques (forecourt and vehicle)

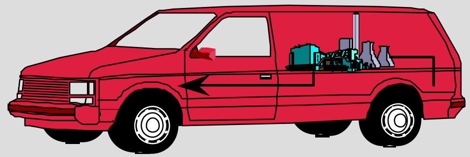
Metal Hydrides



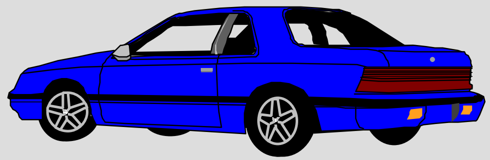
- High temperature (e.g Mg)
- Medium Temperature (alanates)
- Low temperature (e.g. Fe Ti)
- Hydrolysis

HERA
Hydrogen Storage Systems

H_2

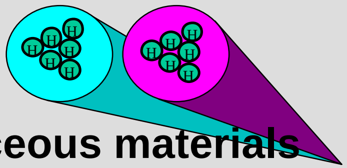


On Board Methanol Reformation



On Board Gasoline (ethanol) Reformation

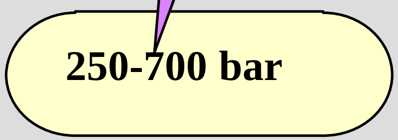
HYDROGENSOURCE



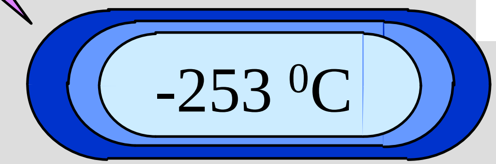
Carbonaceous materials

•Nanotubes
5-10% reported
Not complete system.

•Nanofibres
Up to 60 wt% reported
Not complete system
Results not confirmed



Compressed Gas
Bulky
Forecourt compressors



Liquefied
High energy for cooling

Fires and explosions

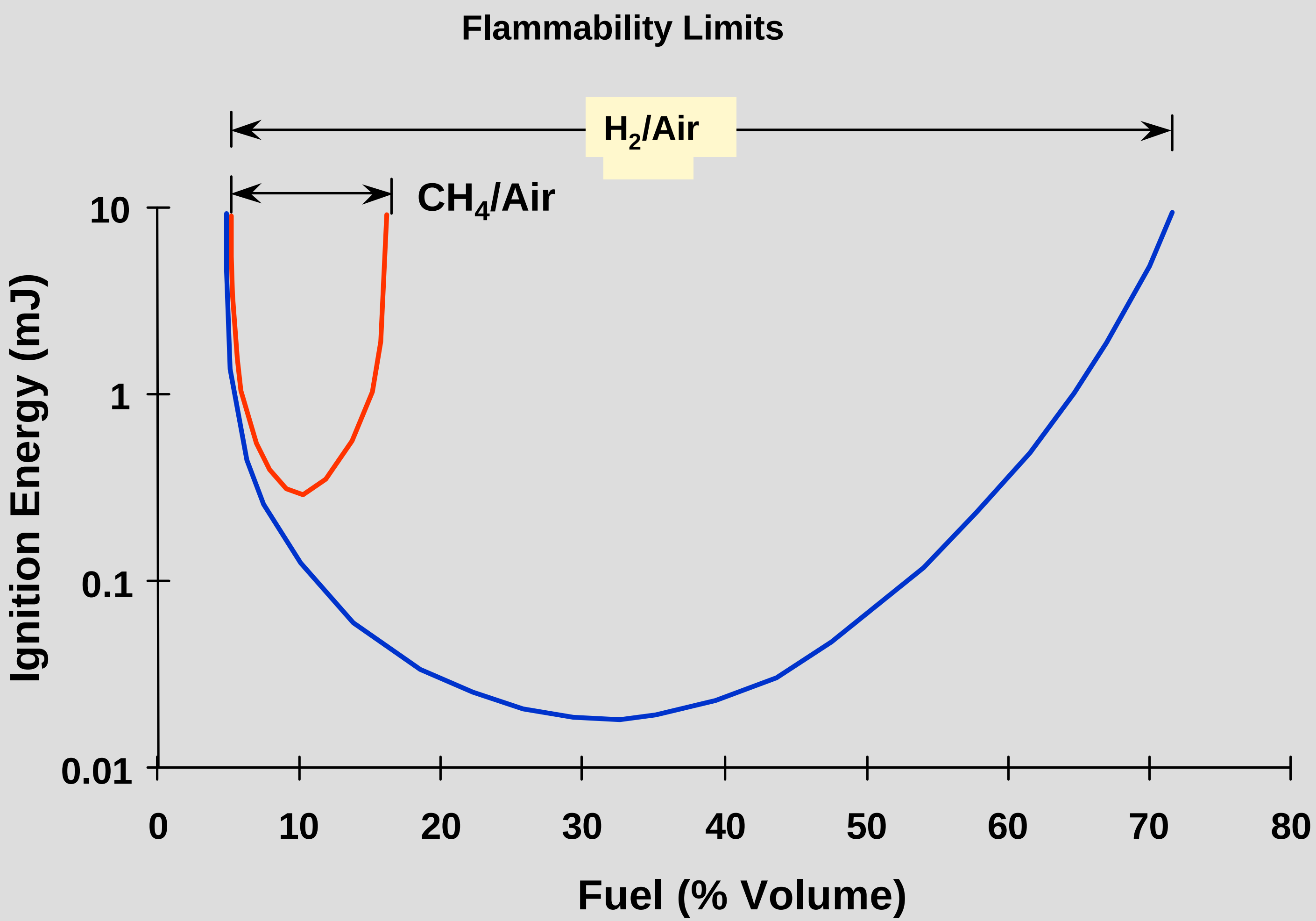
Behaviour is different to hydrocarbons

- wide limits of flammability and detonability
- ignition and detonation energies low
- non luminous flame.
- very buoyant - flammable cloud disperses rapidly.

For the safety case need to be able to estimate the consequences of a release

- how likely to ignite?
- how likely to detonate Vs deflagrate?
- what overpressures would be generated?
- what level of injury / structural damage / escalation is possible?

Flammable range and ignition energy



Hydrogen explosions

	Hydrogen	Methane	Propane
Detonability limits (vol. % in air) Lower limit (LDL) Upper limit (UDL)	 11-18 59	 6.3 13.5	 3.1 7
Maximum Laminar Burning velocity (m/s)	3.46	0.43	0.47

•Hydrogen more prone to detonate than hydrocarbons.

⇒Are there any credible retail scenarios in which hydrogen detonations could occur?

•Higher laminar burning velocity suggests deflagrative explosions could be much more severe for hydrogen than for hydrocarbons. O

HOWEVER

•Buoyancy and rapid dispersion of hydrogen limits size of flammable gas clouds Π

Shell Hydrogen safety experiments

Objectives

- To address gaps that currently prevent an adequate assessment of the risks associated with retailing hydrogen.
- To carry out experiments and measure key parameters to improve the quantitative assessment of the hazards and risks.
- To identify any potential showstoppers.

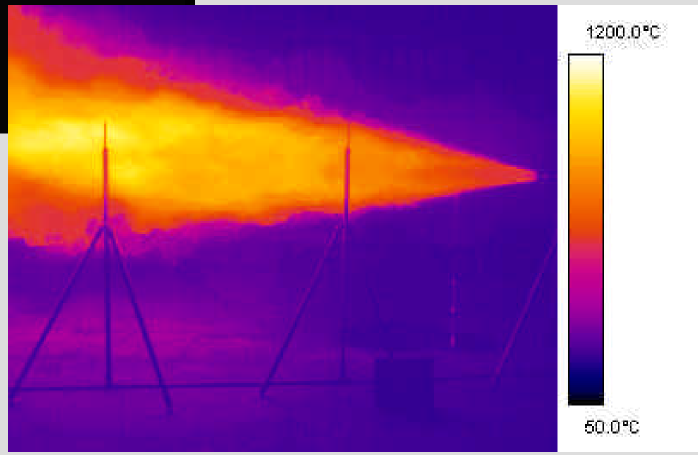
Small Scale Unconfined Explosions

Jet Releases

Jet Release experiments at 25 bar

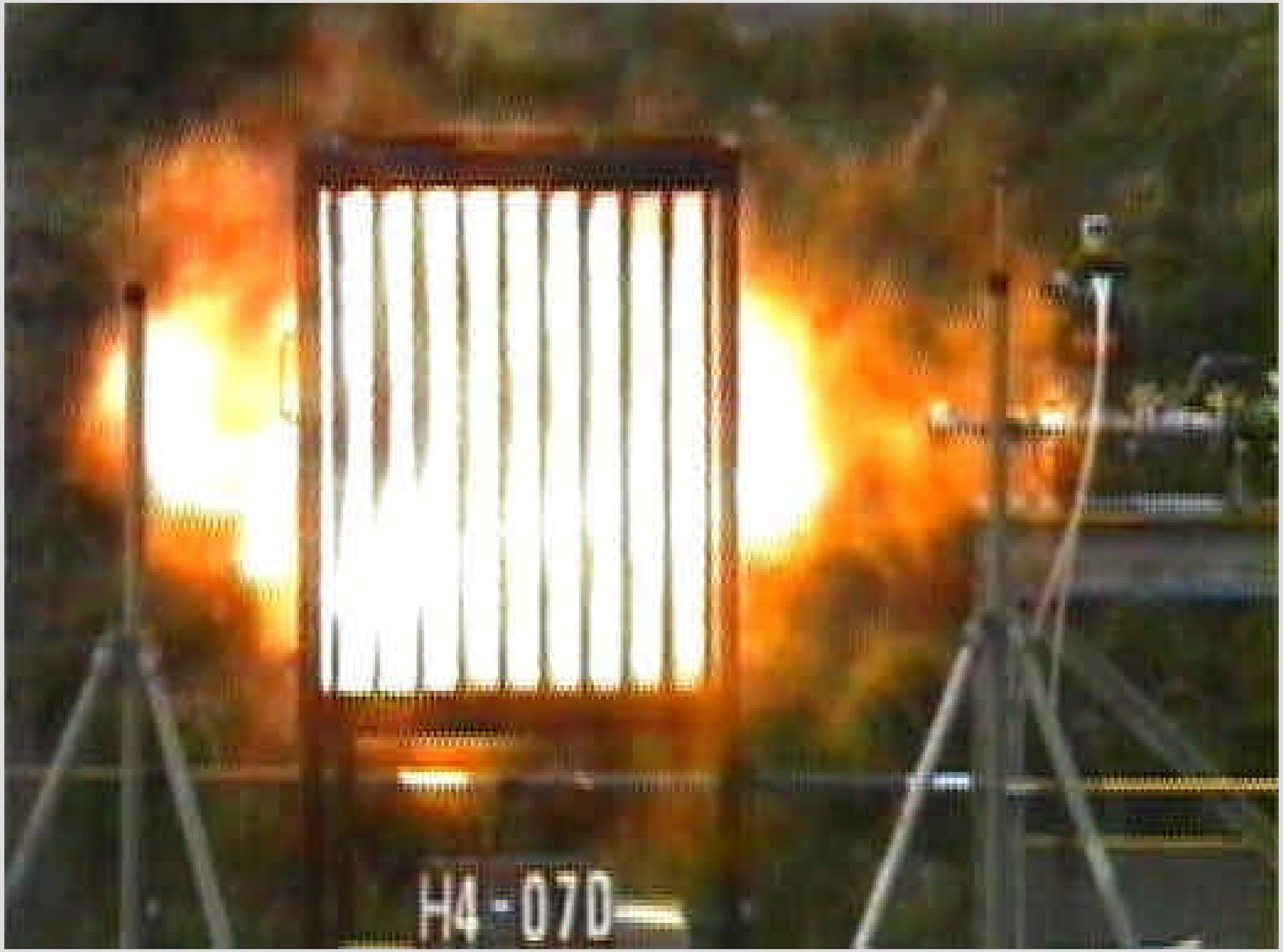
hydrogen jet fire
invisible in daylight!

but visible at
night

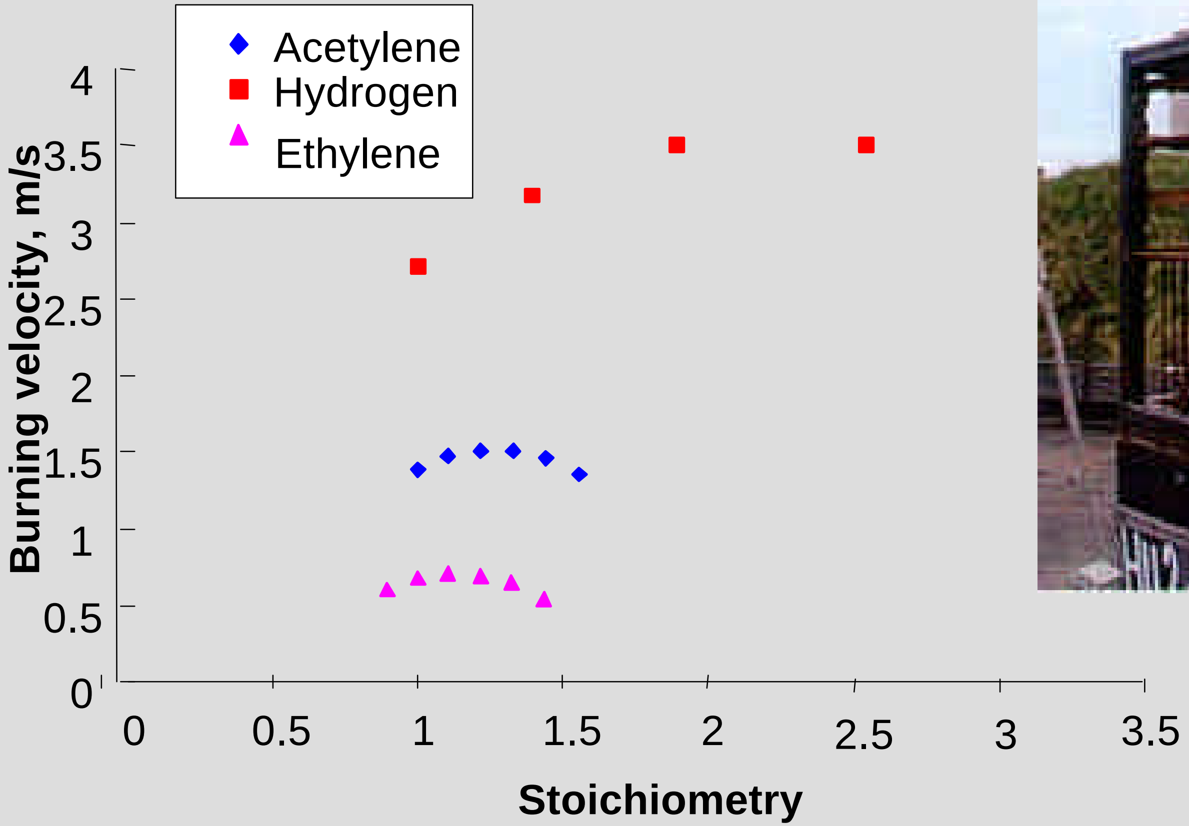


IR thermal
image

Jet release into congestion

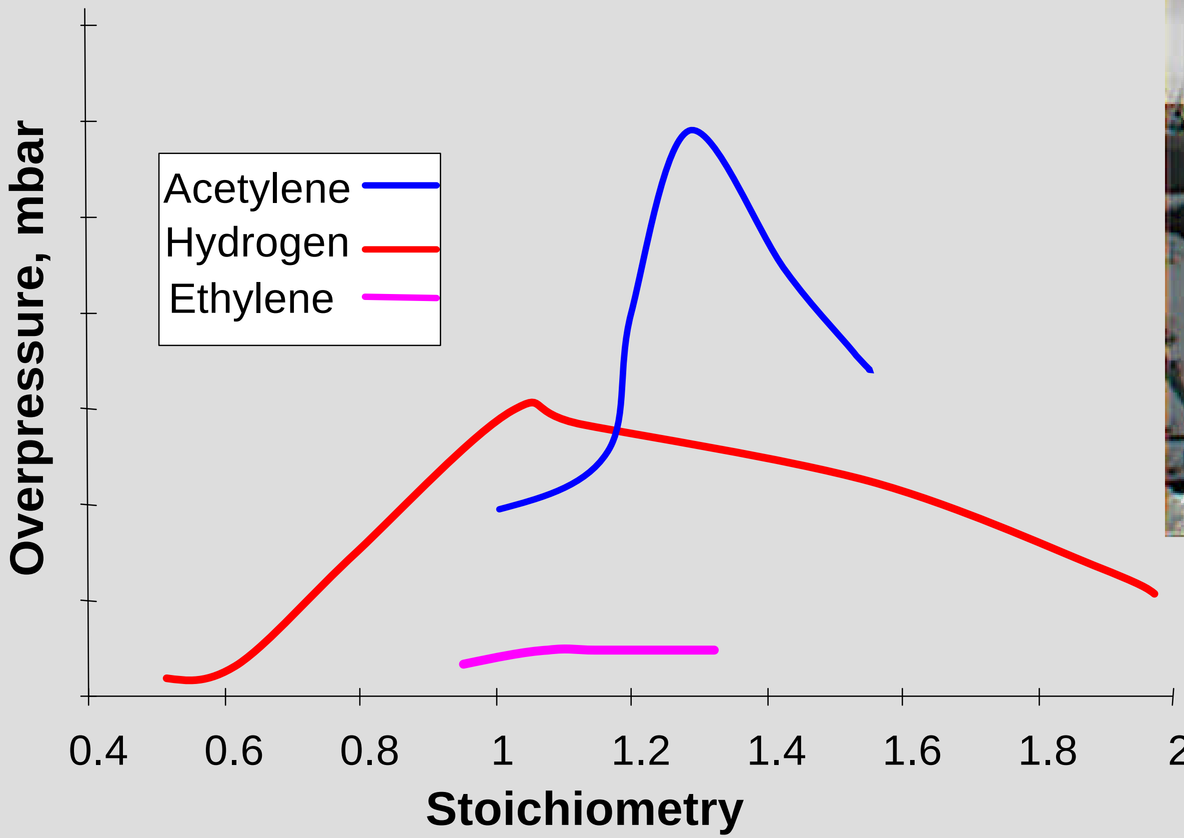


Small scale unconfined explosions



Comparison of literature burning velocities suggests hydrogen explosions could be <u>more severe</u> than acetylene

Small scale unconfined explosions



Hydrogen explosion actually <u>milder</u> than acetylene at length scales investigated.

Codes and Standards

- Jet release experiments are being used to validate hazard models and rationalise industry 'Safety Distances'.

- Standardisation of refuelling interfaces needed to reduce risk (e.g. nozzle geometry to prevent misfuelling)

- Vital importance of inter-industry projects in defining standards.
    - European Integrated Hydrogen Project Phase II
    - SAE Fuel Cell Committee
    - ICC Ad hoc hydrogen committee
    - NHA
    - ISO/IEC/CEN etc.

Conclusions

- Risk depends on both the probability of a release and the hazardous consequences. Shell is working to understand both.

- Severity of hydrogen explosions not as great as indicated by the magnitude of the laminar burning velocity of hydrogen relative to hydrocarbons (for length scales investigated).

- Mitigating factors:
  - propensity to dissipate quickly
  - relatively high LFL
  - low energy density.

.

- Codes and standards are critical but safety distances must be related to hazards.

- Jet release experiments at 150 bar in progress. Looking for partners for 350 and 700 bar

Mid-Term Assessment Workshop

Brussels
02 October 2002

Presentation by
Alexander Venetsanos

- **Objectives**
  - **Task 5.3**
    - Study the consequences of CGH2 releases from commercial vehicles (buses) in various environments, e.g. inner city streets and in comparison to existing fuels, using CFD modeling
    - CFD validation against existing data
  - **Task 5.2**
    - Study the consequences of H2 releases from refueling infrastructure, using CFD

- **Performed within WP5**
  - **Task 5.3**
    - CFD validation against the Stockholm 1983 hydrogen accident
      - **Joint paper submitted to Journal of Hazardous Materials**
    - City Bus Safety Analysis (**Stockholm**)
      - **Comparison between different CGH2 storage pressures (40kg of H2 at 200 and 350bar)**
      - **Comparison between CGH2 and CNG (40kg H2 and 168kg CH4, at 200bar)**
      - **Comparison between two release scenarios (8 bottles with 16 or 1PRD open)**
  - **Task 5.2**
    - Refueling Station Safety Analysis
      - **Preliminary results for typical STATOIL site in Norway (4050l at 440bar)**

- **Partners interactions**
  - **Task 5.3**
    - CFD validation
      - EC-JRC, VOLVO and NCSR Demokritos,
    - City Bus Safety Analysis
      - EC-JRC, VOLVO, RAUFOSS and NCSR Demokritos,
  - **Task 5.2**
    - Refueling Station Safety Analysis
      - NH, DNV, EC-JRC and NCSR Demokritos

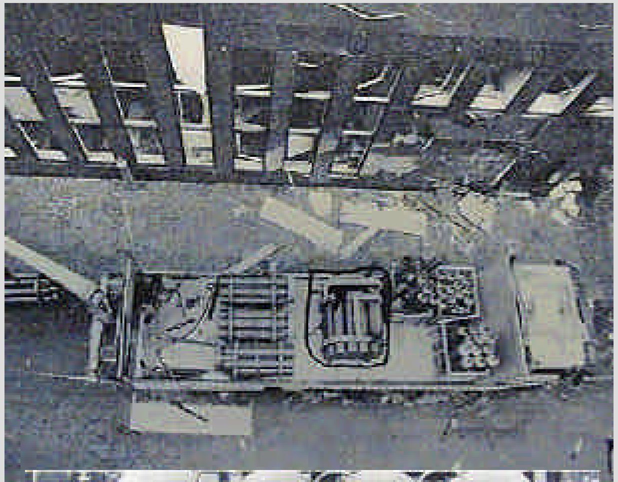
- **The ADREA-HF code main features**
  - Commercially available, in house CFD software
  - Solves the 3d, time dependent RANS Cartesian equations
  - Control Volume discretisation
  - Complex geometry (irregular terrain/man made structures) placed on Cartesian grid using Porosity formulation
  - Physical Properties: Arbitrary functions of pressure and temperature
  - Phase change (condensation/evaporation) using equilibrium model
  - One or two phase jets
  - Liquid phase slip velocity
  - Ground interaction
  - Stable/Neutral/Unstable stability conditions
  - Moving geometry (vehicles)
  - Concentration Fluctuations

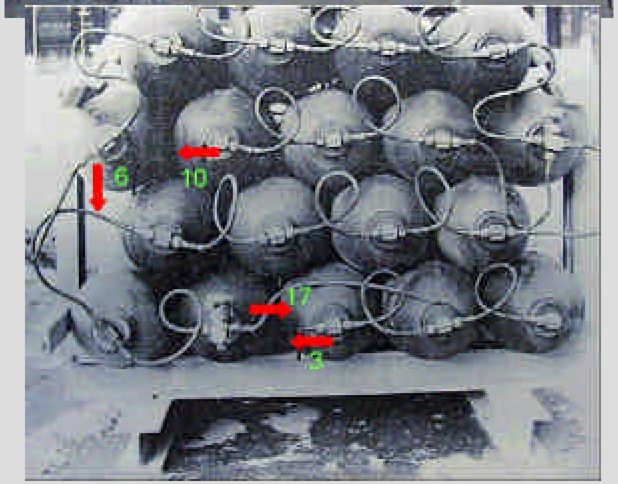
The REACFLOW code main features

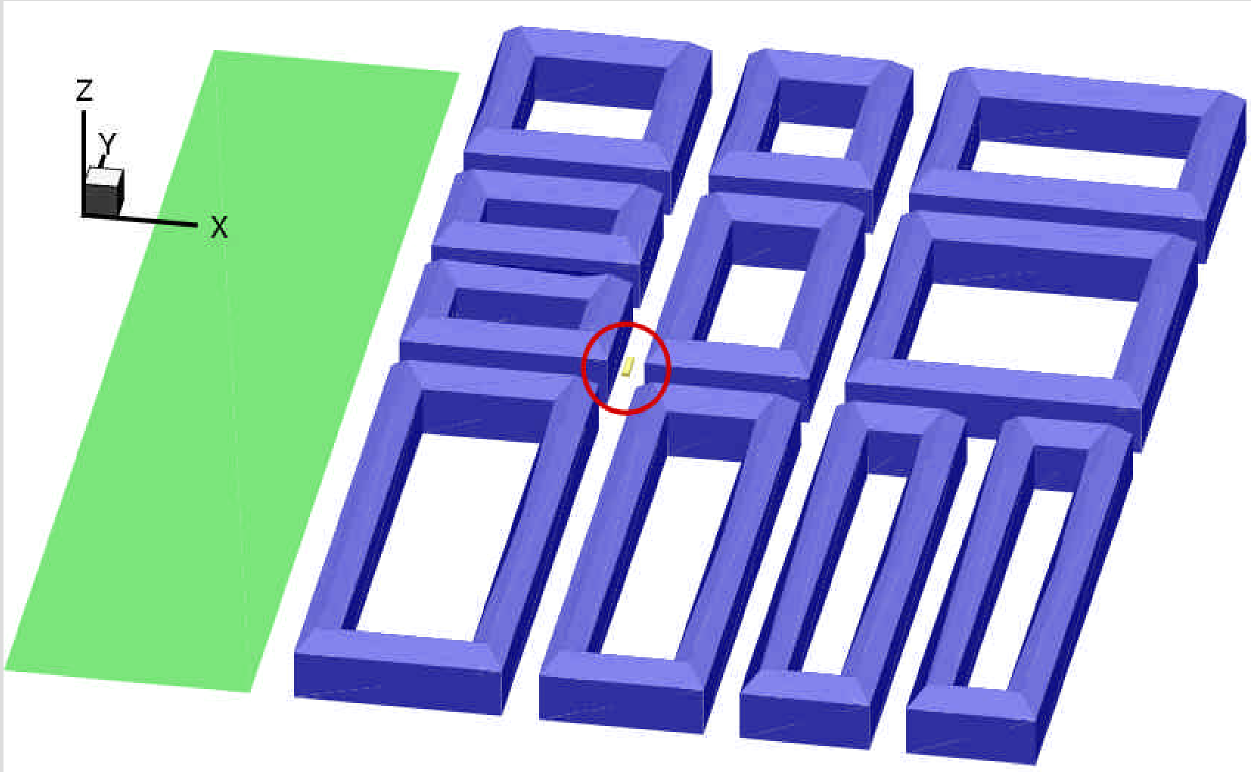
- In house CFD software.
- Solves the 2D and 3D, time dependent, reactive RANS equations.
- Finite Volume discretisation scheme.
- Unstructured mesh suitable for complex geometry.
- Adaptive meshing that is capable of capturing physical phenomena with very different length scales involved.
- Code both in serial and parallel version.
- K-epsilon turbulence model.
- Eddy break up combustion model for turbulent combustion.
- Finite rate combustion model, based on Arrhenius chemistry, for laminar combustion and detonations.

EIHP2, NCSR Demokritos, CFD validation

Prediction of the 1983 Stockholm accident dispersion using ADREA-HF

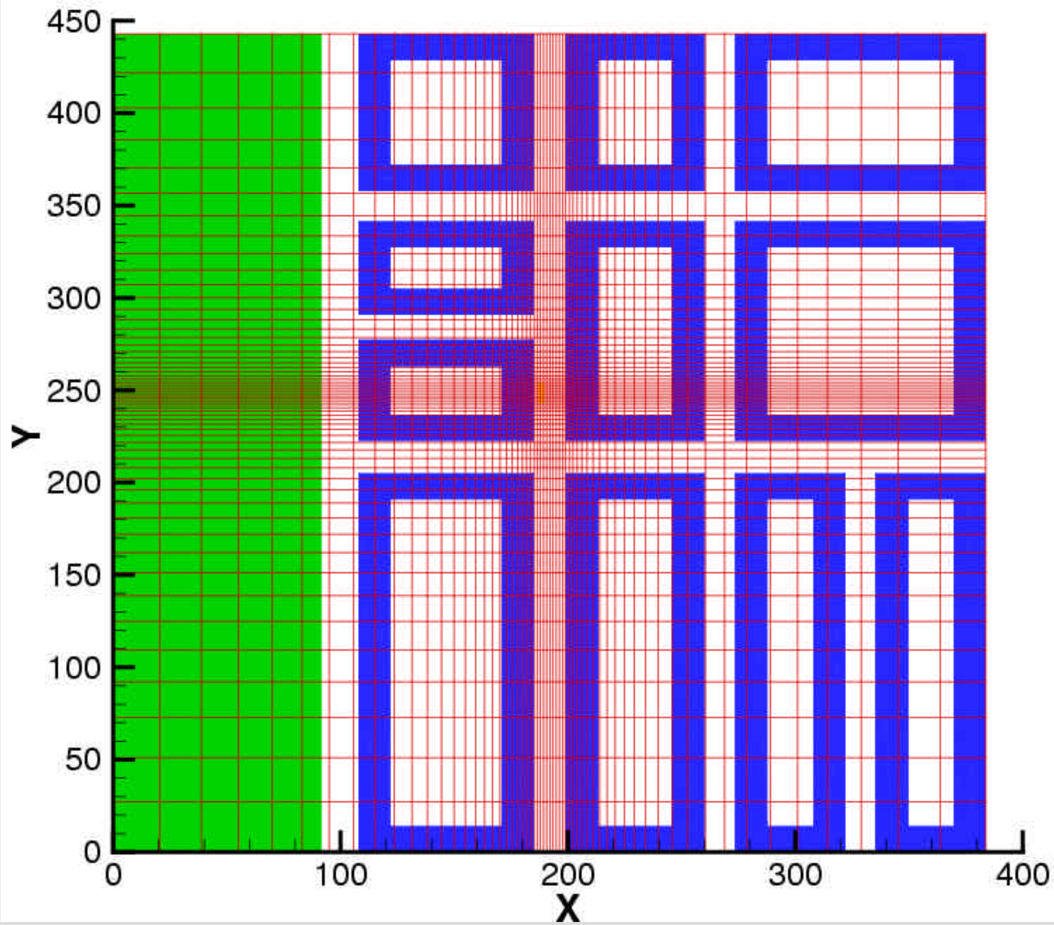






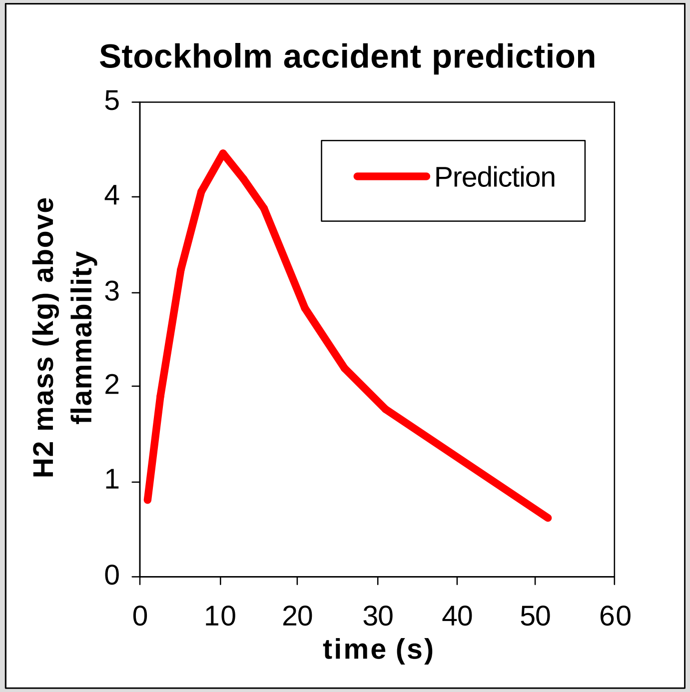
Modeled Stockholm accident site (park in green, lorry in yellow)

Prediction of the 1983 Stockholm accident dispersion using ADREA-HF

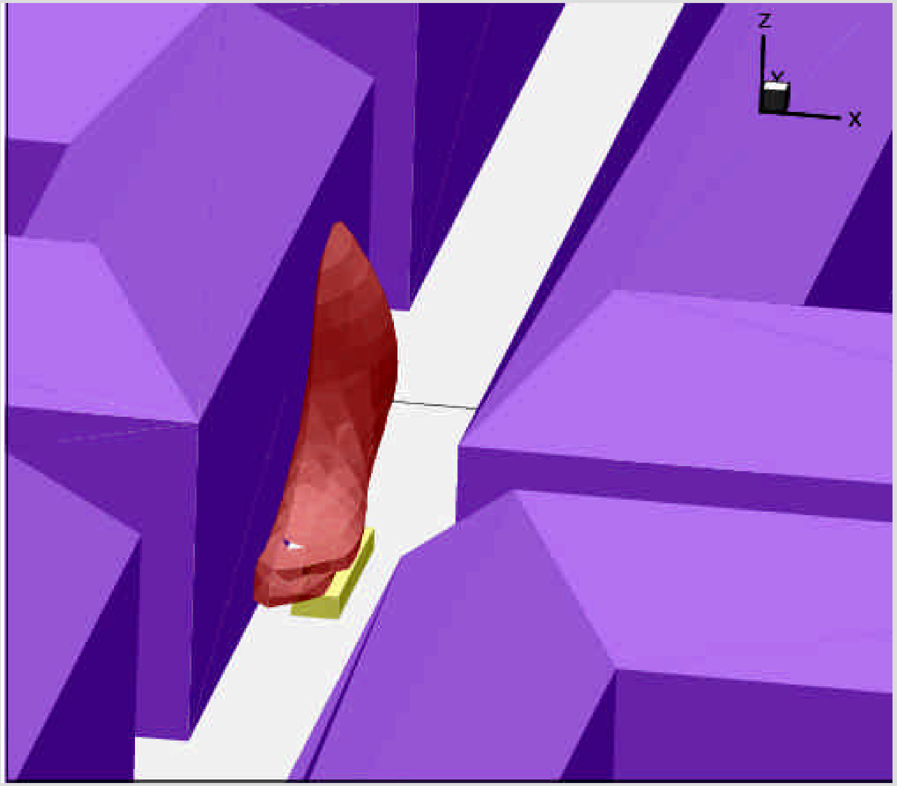


Horizontal grid used in the dispersion calculations. Shown are the modelled buildings and truck footprints

Prediction of the 1983 Stockholm accident dispersion using ADREA-HF



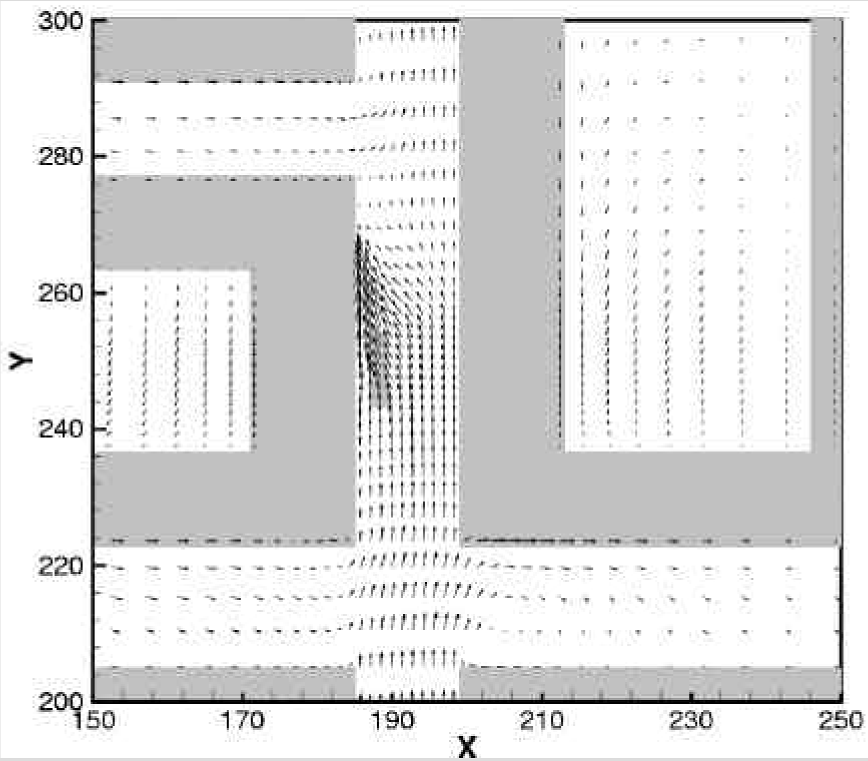
Predicted time history of the mass of hydrogen, above the lower flammability level (4% concentration)



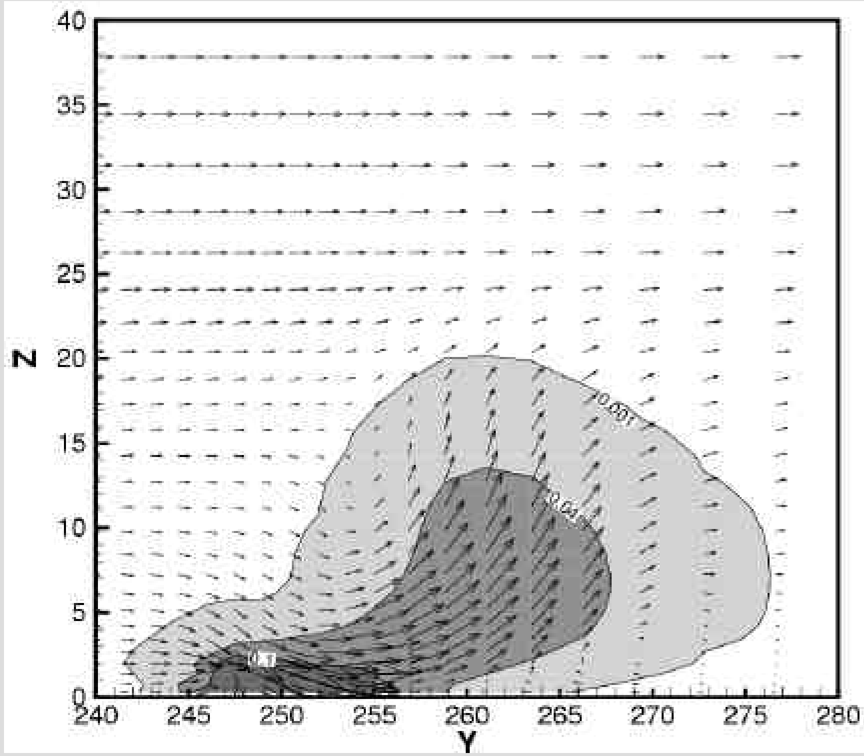
Predicted flammable cloud (hydrogen-air mixture with hydrogen concentration above 4%) at time 10 seconds after start of accident.

EIHP2, NCSR Demokritos, CFD validation

Prediction of the 1983 Stockholm accident dispersion using ADREA-HF

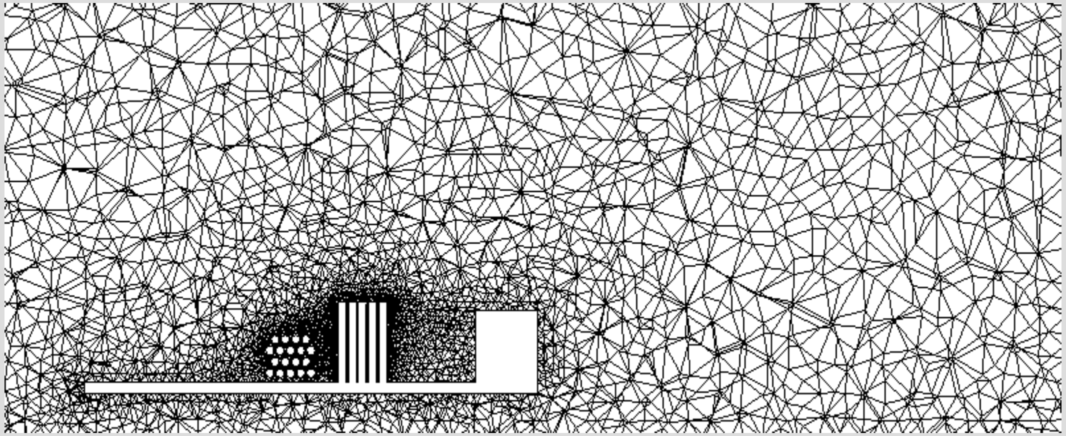


Predicted horizontal velocity field at 3m from ground and time 10 seconds after start of accident

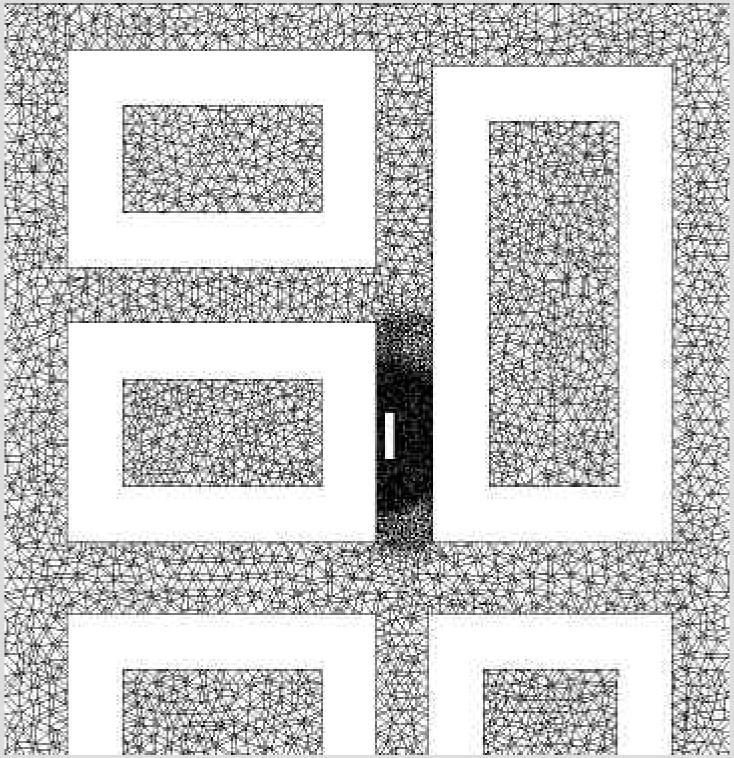


Predicted velocity and volume concentration field on a vertical plane along the street canyon, 1m between source and nearby building at time 10 seconds after start of accident

Prediction of the 1983 Stockholm accident dispersion using REACFLOW

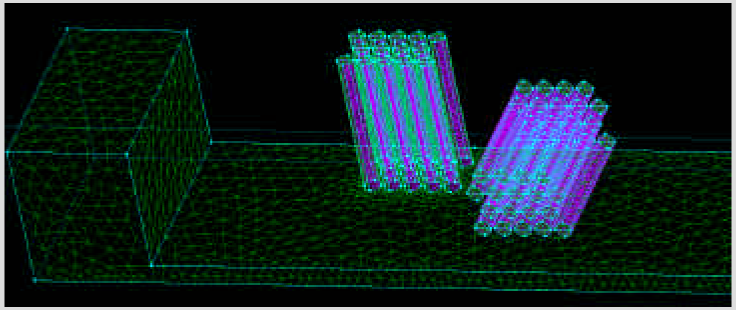


Vertical cut (at x=2.15m) through the grid for the first part of the combustion simulation. Note the varying grid density and the presence of the pressure tanks

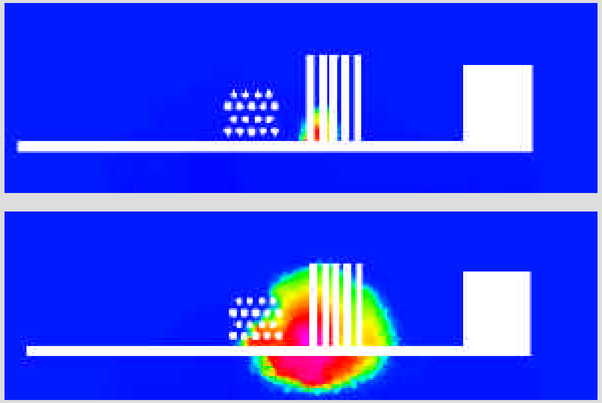


Horizontal cut (at z=1.2m) through the grid used for the second stage of the combustion calculation. The rectangular cut-outs represent the houses in the area

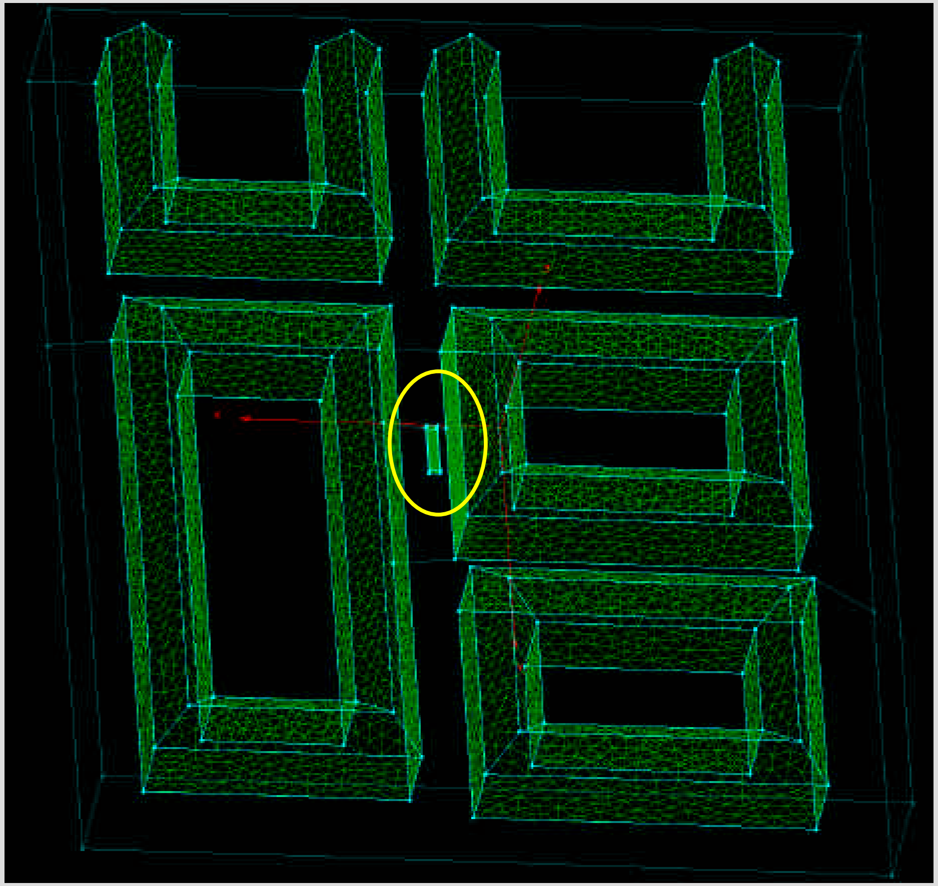
Stockholm Accident Simulation - ReacFlow



Computational mesh of the lorry with the bottles.



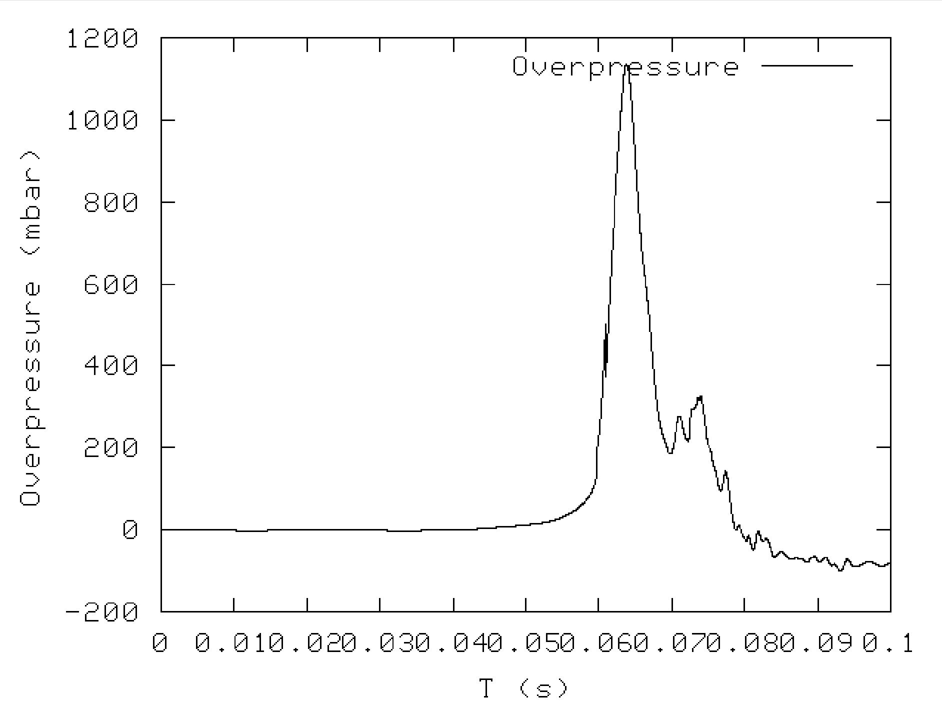
Temperature distribution at the initial stages of the explosion.



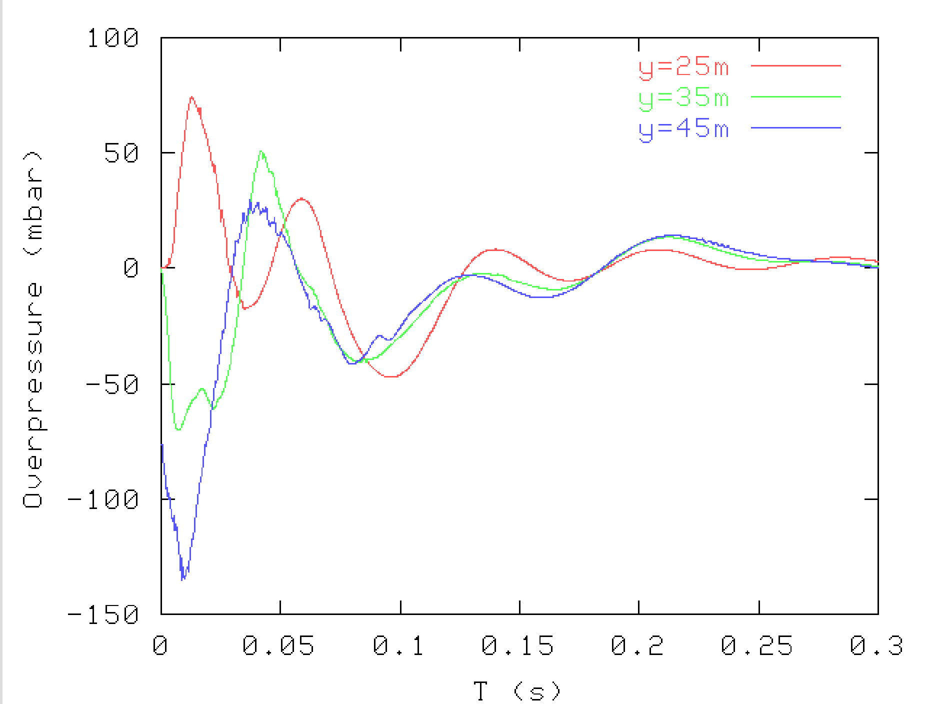
Computation mesh of the Stockholm district.

EIHP2, EC-JRC, CFD validation

Prediction of the 1983 Stockholm accident dispersion using REACFLOW

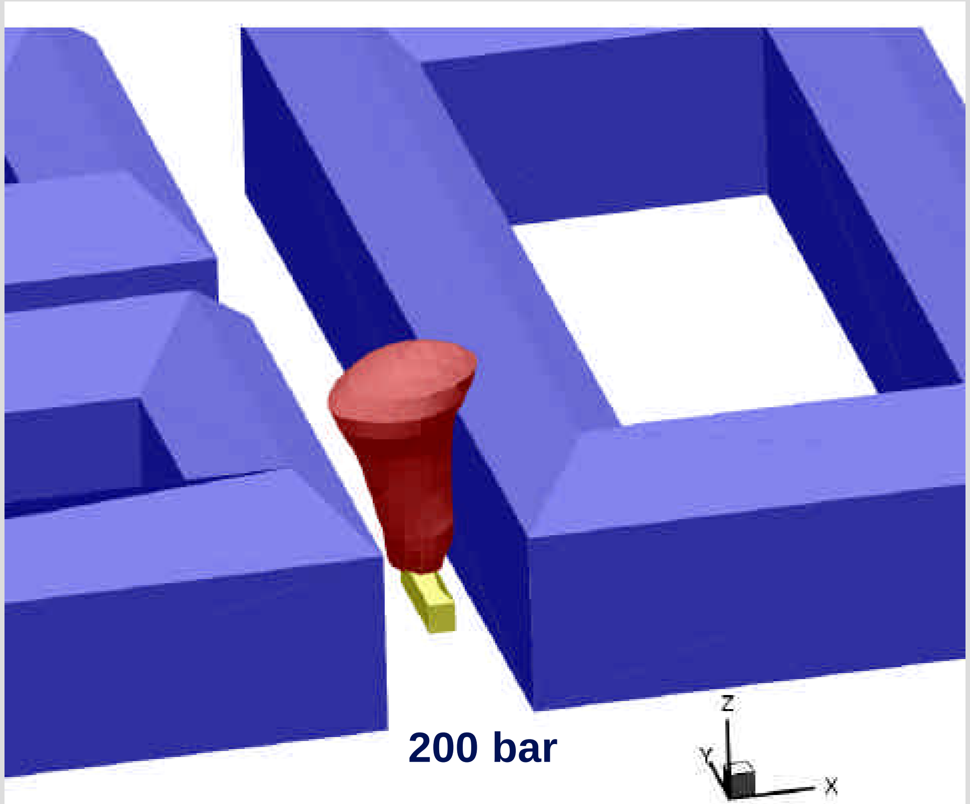


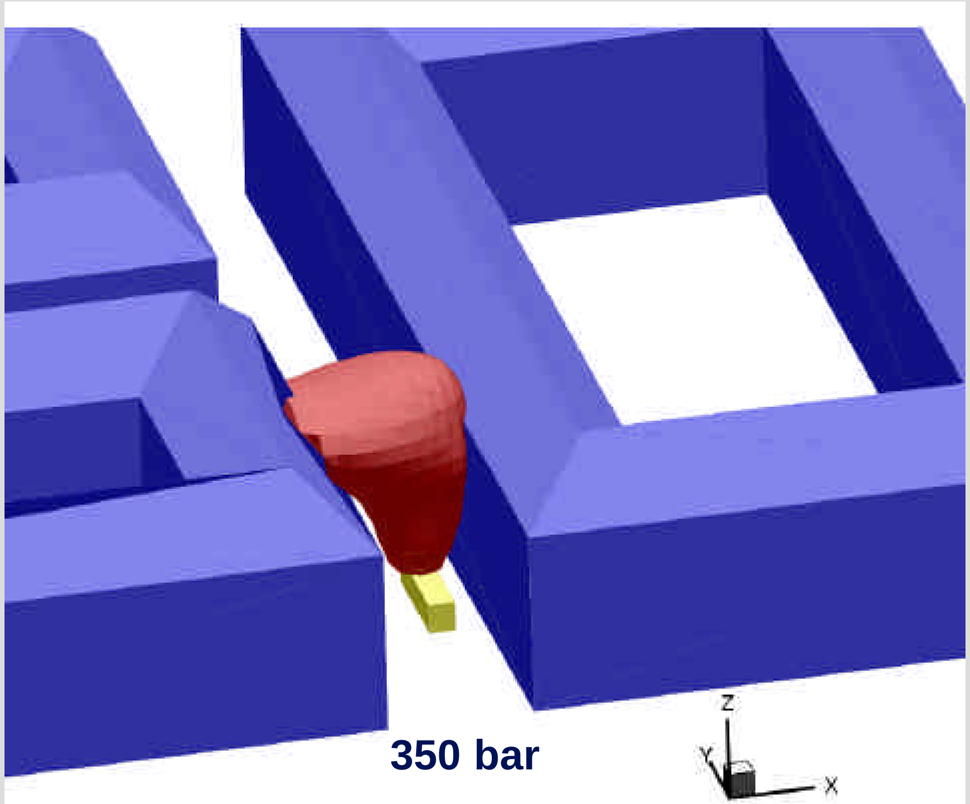
Plot of overpressure with time for a single point near the building wall closest to the truck at a height of 1.35m and a position along the street close to the rear end of the truck



Plot of overpressure with time for three different points along the street, at y=25m, y=35m, and y=45m from the street corner, at positions close to the building wall closest to the truck and at a height of z=1.35m.

Comparison between different CGH2 storage pressures using ADREA-HF

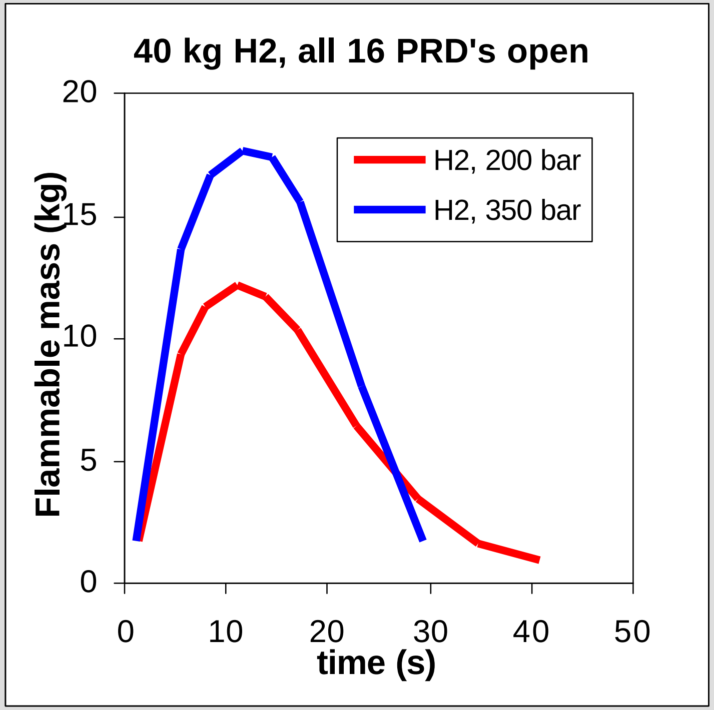


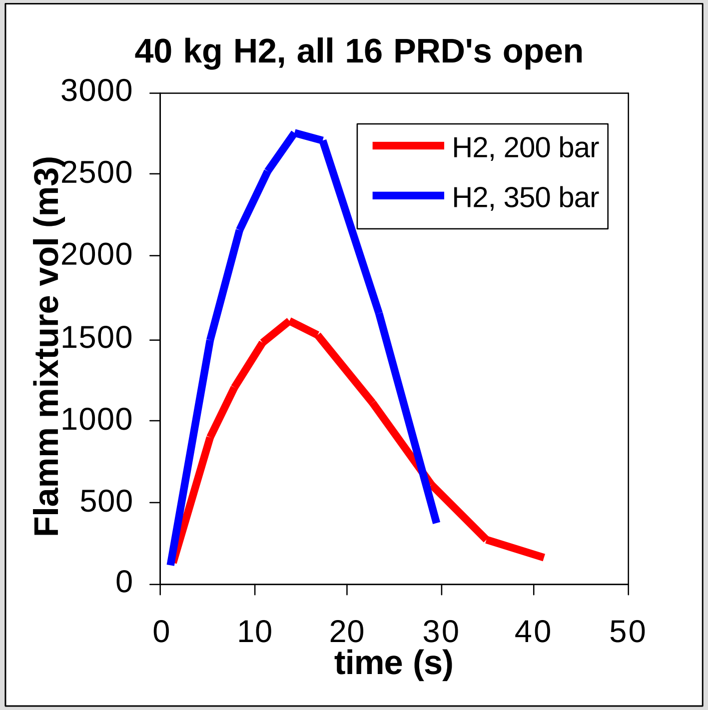


Predicted flammable cloud (hydrogen-air mixture with hydrogen concentration above 4%) at time 14 seconds after start of accident (8 tanks, 16PRD's open)

EIHP2, NCSR Demokritos, City bus Safety Analysis

Comparison between different CGH2 storage pressures using ADREA-HF

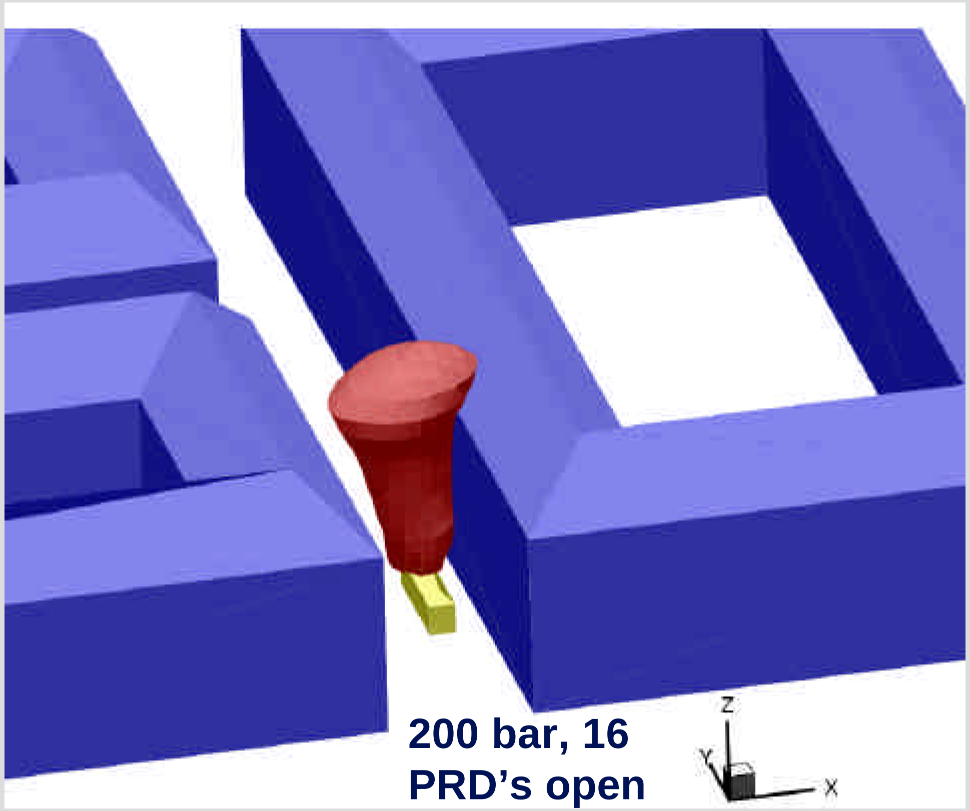




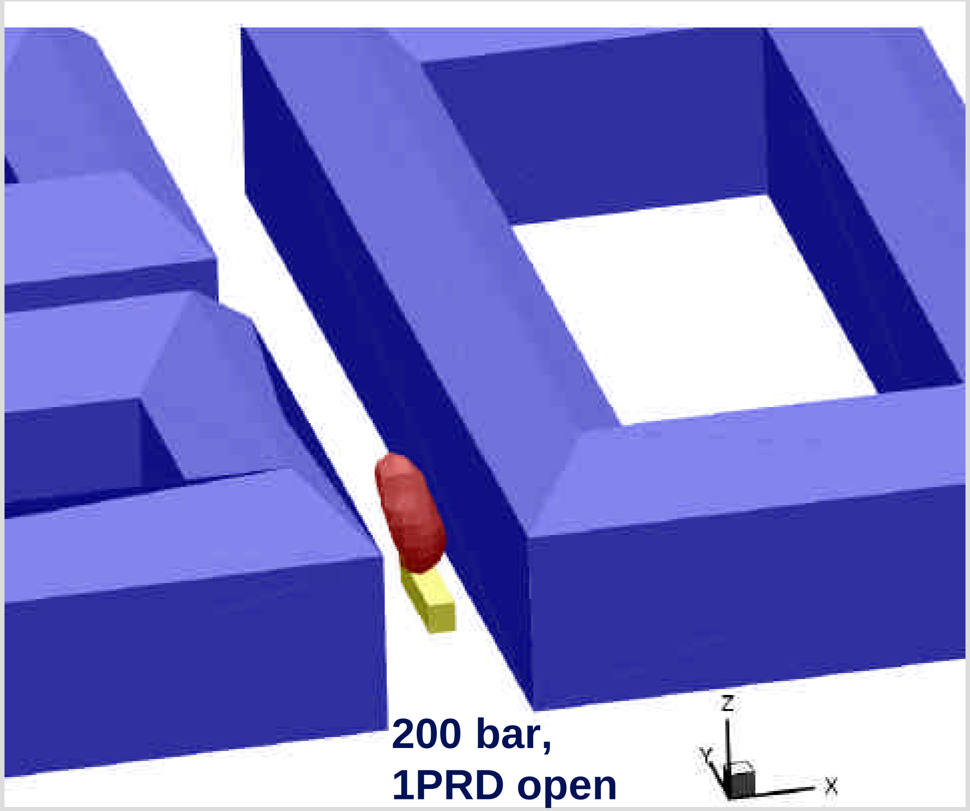
Predicted time history of the mass of hydrogen, above the lower flammability level (4% concentration)

Predicted time history of the volume of the hydrogen-air mixture, above the lower flammability level (4% concentration)

Comparison between different CGH2 release scenarios using ADREA-HF

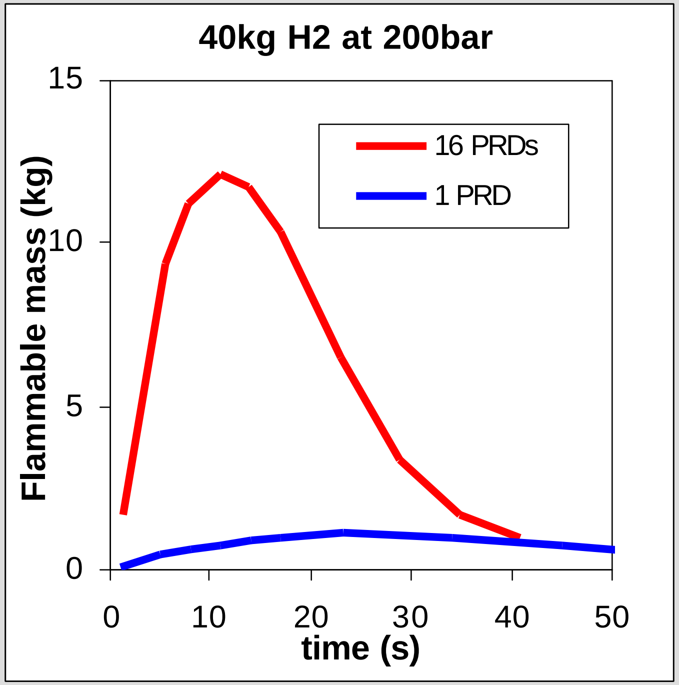


Predicted maximum flammable cloud (14 seconds after start of accident)

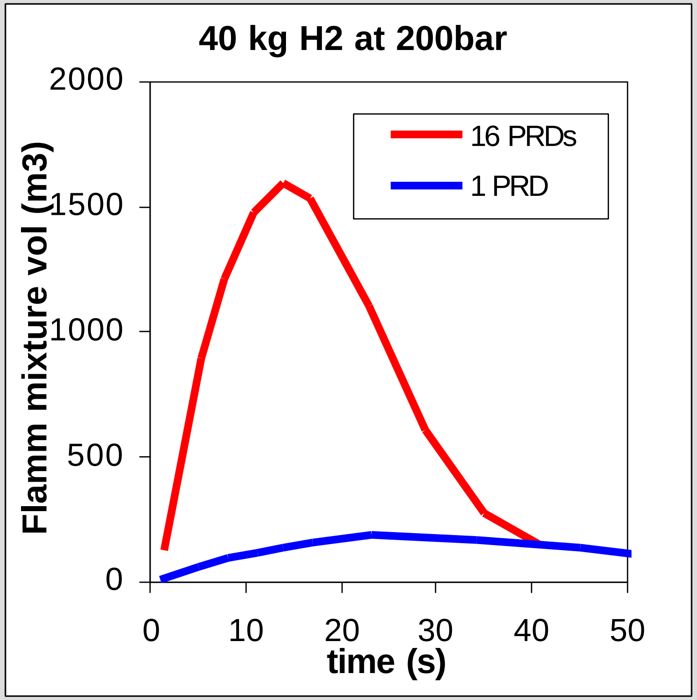


Predicted maximum flammable cloud (23 seconds after start of accident)

Comparison between different CGH2 release scenarios using ADREA-HF



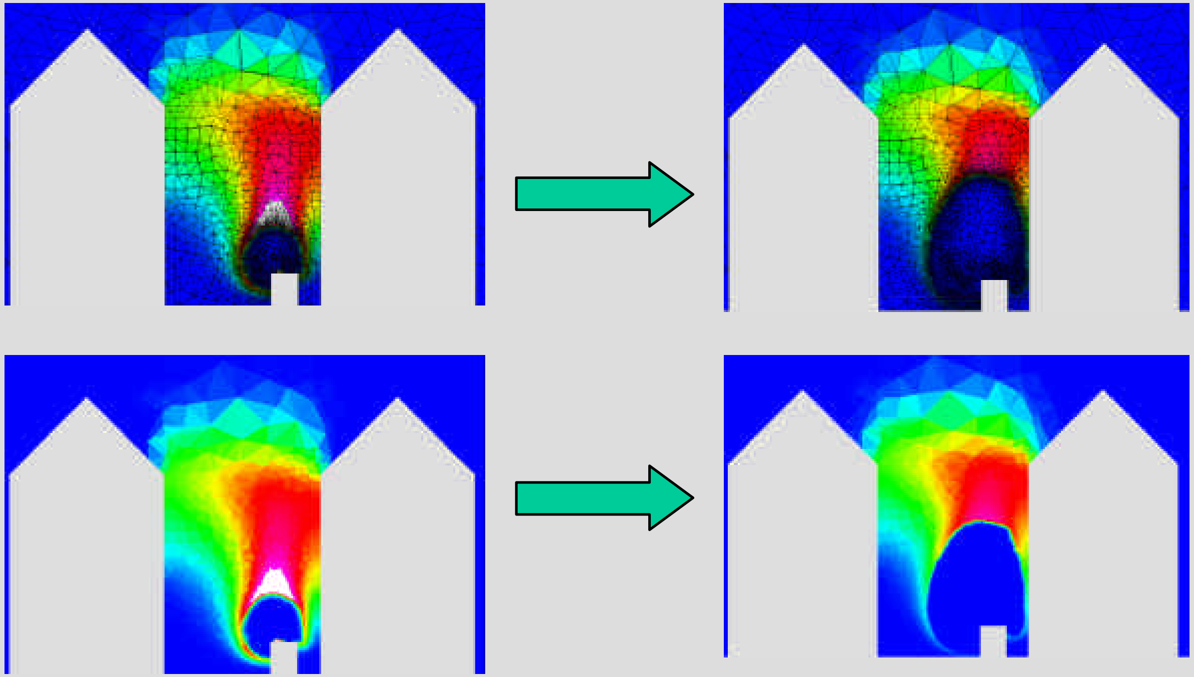
Predicted time history of the H2 mass above the lower flammability level



Predicted time history of the mixture volume above the lower flammability level

Bus Accident Simulations - ReacFlow

H2 Molar Fraction at 2 different times for Scenario 5



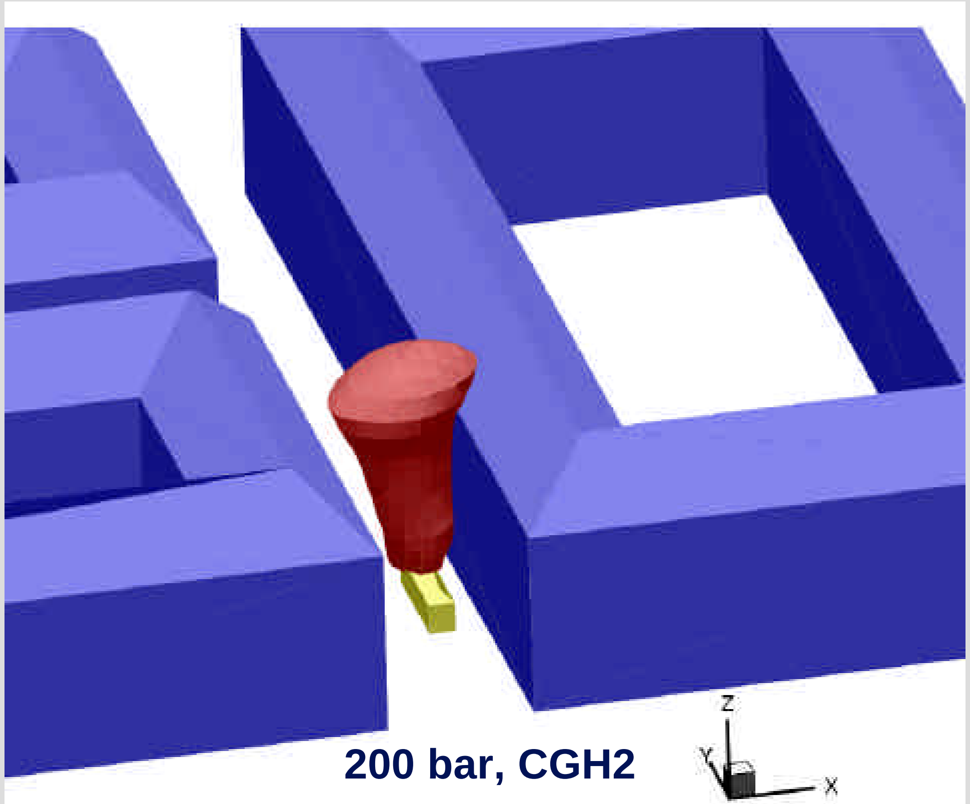
Time = 30 ms   Time = 150 ms

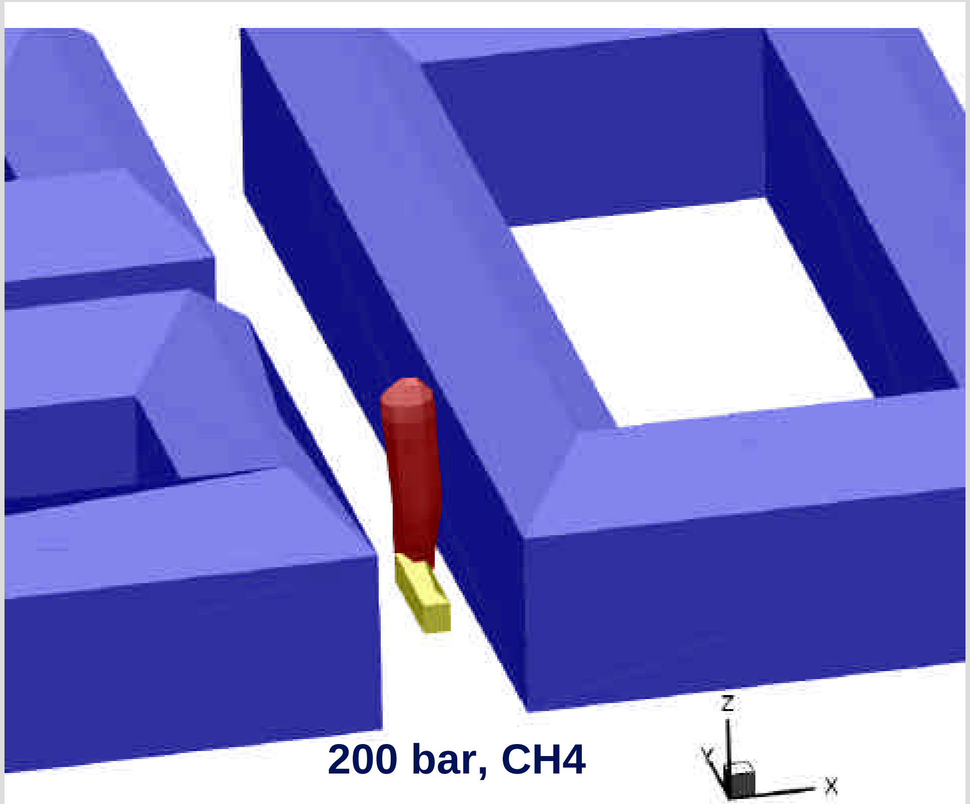
Scenario 2: 8x200lt cylinder system of CH2, 350 bar working pressure, 1 PRD open.

Scenario 5: 8x200lt cylinder system of CH2, 350 bar working pressure, 16 PRD open.

The maximum overpressure in a point on the wall of the building in front of the explosion location is about one order of magnitude larger in scenario 5 than in scenario 2.

Comparison between CGH2 and CNG (assumed CH4) using ADREA-HF

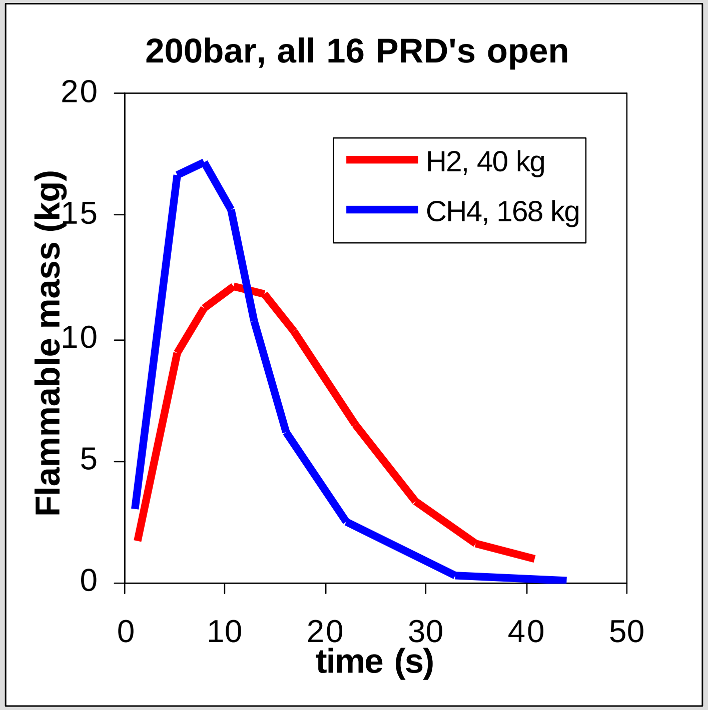


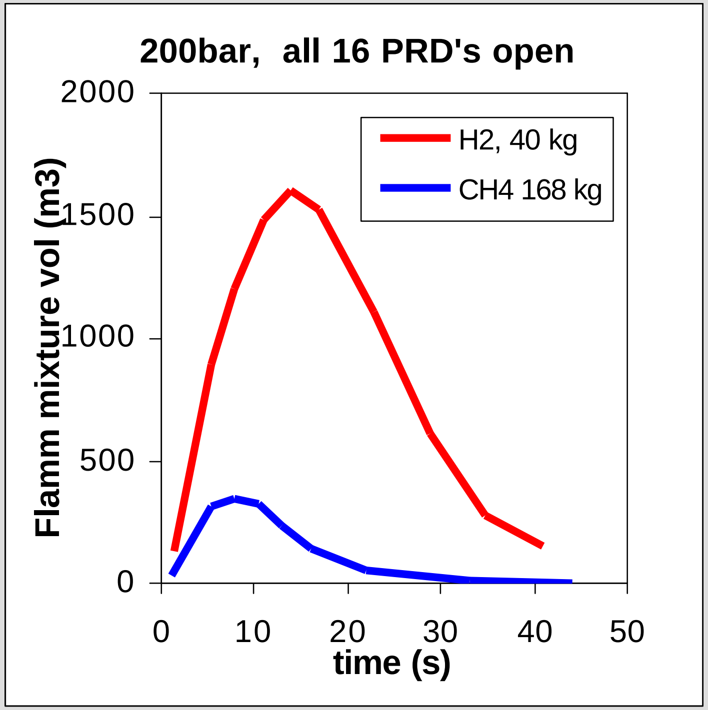


Predicted lower flammability clouds at 14 seconds for CGH2 (4% concentration) and 8 seconds for CH4 (5% concentration)

EIHP2, NCSR Demokritos, City bus Safety Analysis

Comparison between CGH2 and CNG (assumed CH4) using ADREA-HF

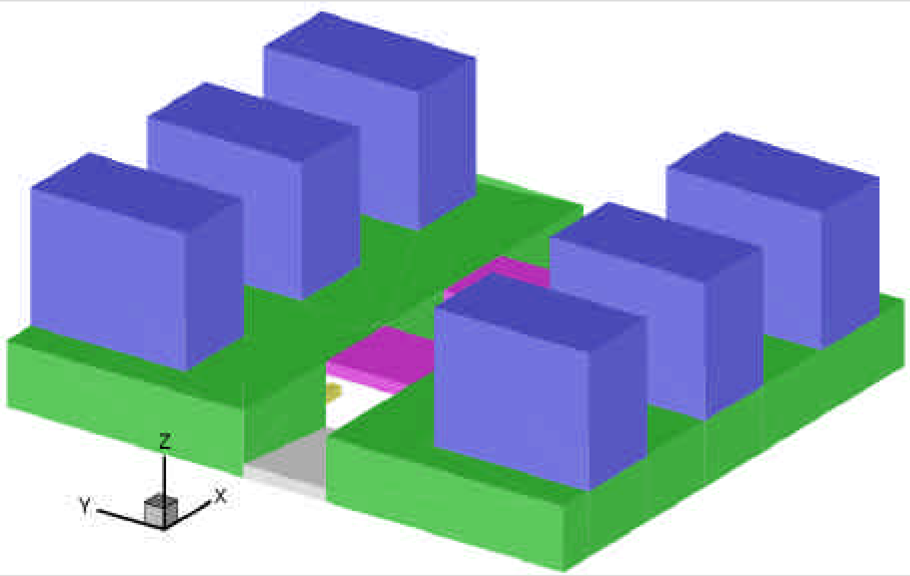




Predicted time history of the H2 or CH4 mass above the lower flammability level

Predicted time history of the mixture volume above the lower flammability level

Dispersion predictions using ADREA-HF



Modeled refueling site (buildings in blue, roads in green, bridges in purple, vehicle in yellow)

STATOIL site in Oslo

- **Conclusions**
  - **Task 5.3**
    - Predicted overpressures in reasonable agreement against the 1983 Stockholm hydrogen accident reported damage (Paper submitted to JHM)
    - City Bus Safety Analysis
      - **350bar H2 storage results in higher flammable masses and volumes than 200bar storage**
      - **Typical CNG storage results in higher flammable masses and lower flammable volumes than CGH2**
  - **Task 5.2**
    - No results yet

Evaluation of Hazards Associated with H_2 Combustion

Mid-Term Assessment Workshop

Brussels
02 October 2002

Presentation by
S. Dorofeev

FZK,
Germany

Hazards associated with H_2 combustion

Introduction

- For introduction of H_2 as a retail fuel quantitative safety and risk assessment is needed
- This requires quantitative methodology for evaluation of hazards associated with H_2 combustion or explosion
- The following issues should be addressed for hazard evaluation
  - Combustion regime (slow flames, fast supersonic flames, detonations)
  - Pressure and thermal loads inside the mixture
  - Air blast waves and thermal radiation outside
  - Missiles

Hazards associated with H_2 combustion

Background

- Straightforward solution - **fully resolved simulation of turbulent reactive flows with multi-species chemistry** – will stay out of reach for quite some time to come

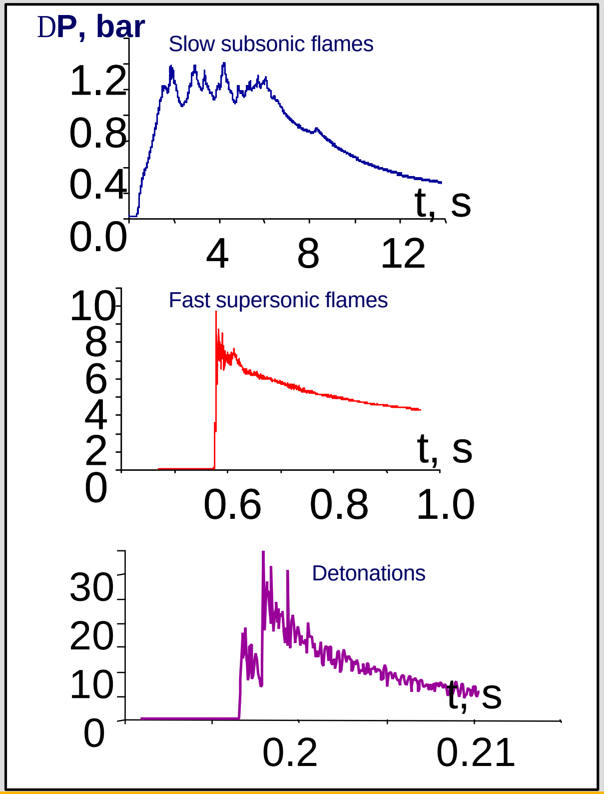
- Approach for evaluation of hazard potential from combustion events that has been explored so far is largely empirical
  - Address key issues experimentally
  - Develop analytical and engineering models for hazard evaluation
  - Validate “under-resolved” numerical tools for explosion simulation

- Most of activities have been focused on
  - Unconfined and confined explosion of CH fuels (chemical/fuel industry)
  - Hydrogen combustion behavior under confined conditions (nuclear energy)

Hazards associated with H_2 combustion

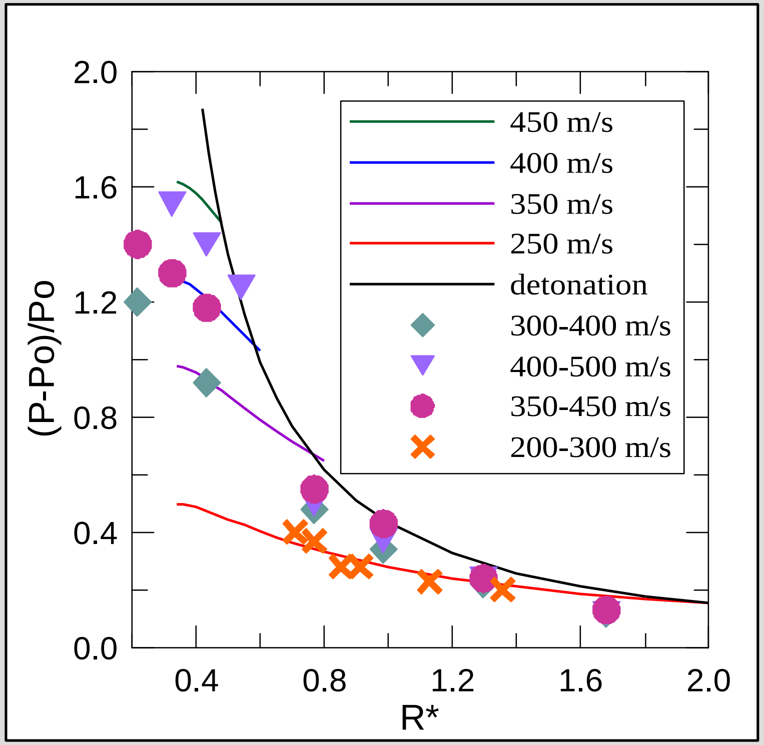
Key issue: How fast can it burn?

- Combustion regime is important. Hazards from various explosion events depends significantly on the flame speed



Pressure loads typical for various combustion regimes in confined explosions

Air blast overpressure as a function of flame speed

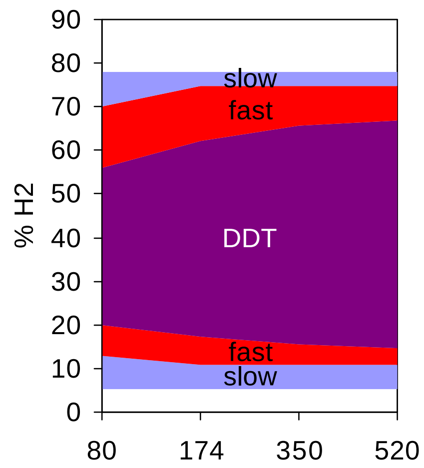


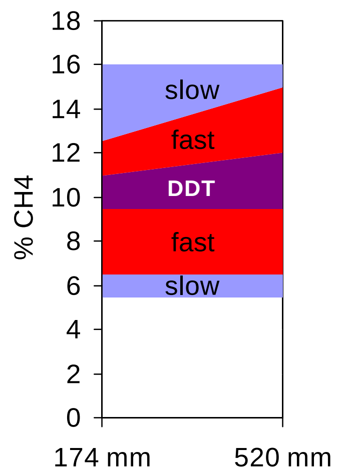
Hazards associated with H_2 combustion

Criteria for FA and DDT

- Critical conditions for strong FA and DDT were studied extensively, especially for **confined explosions**
- Limits for fast flames and DDT depend not only on composition but also on geometry, scale, and initial thermodynamic state
- Criteria were formulated for FA ($\sigma > \sigma^*$) and DDT ($L > \alpha\lambda$) and tested against wide variety of experimental data

Composition limits for fast flames and DDT in tubes (BR=0.6) versus tube diameter for H_2 and CH_4

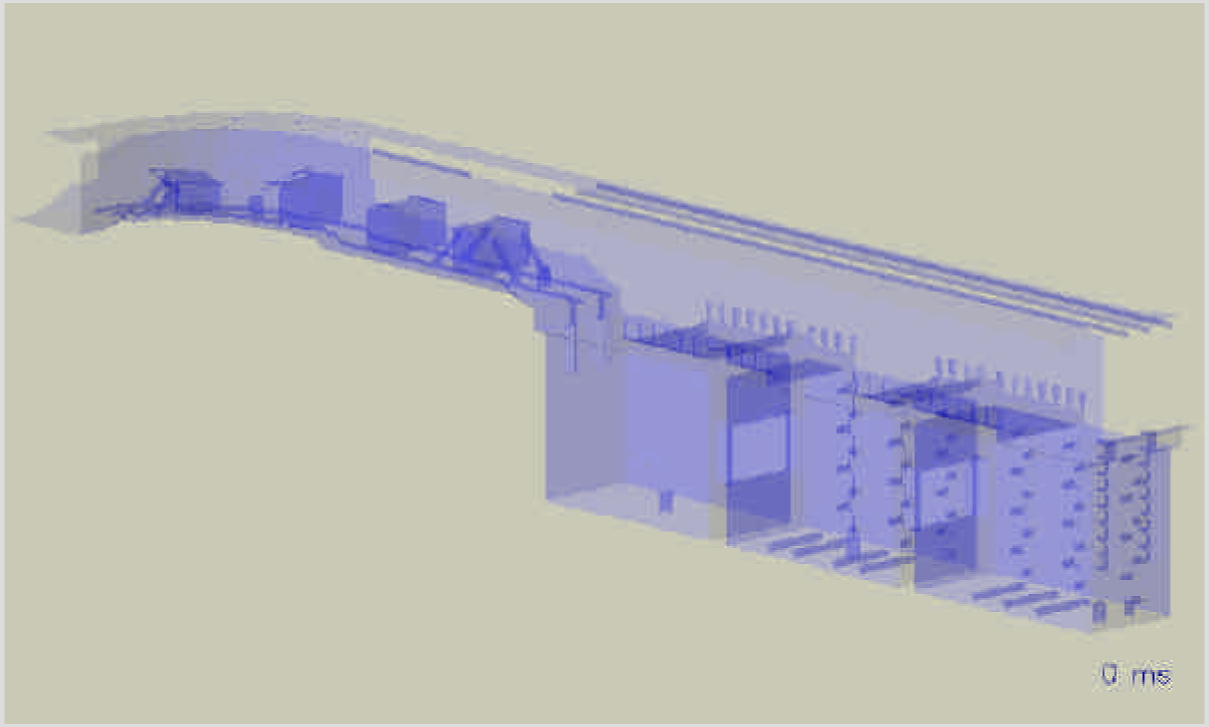


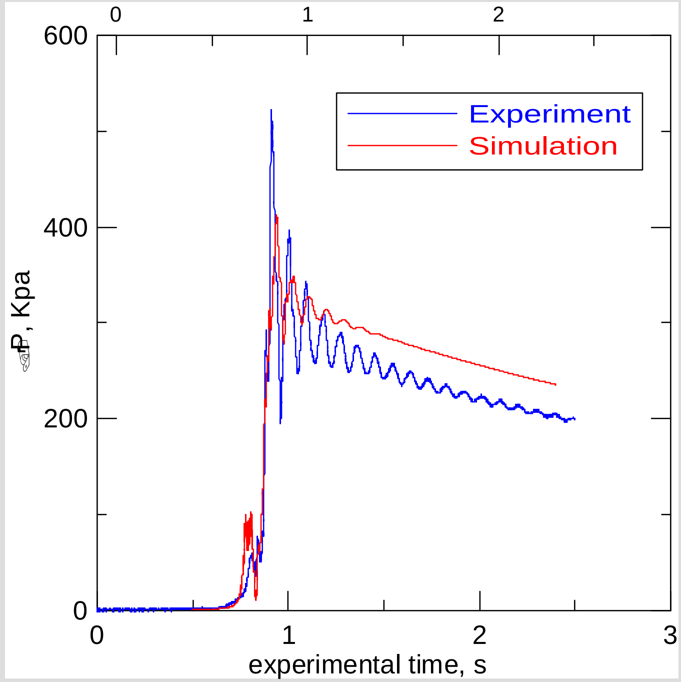


Hazards associated with H_2 combustion

Validation of combustion codes

- Example of code validation against large-scale experimental data (RUT facility). Blind simulation of H_2-air deflagration with B0X code (CREBCOM package, KI)





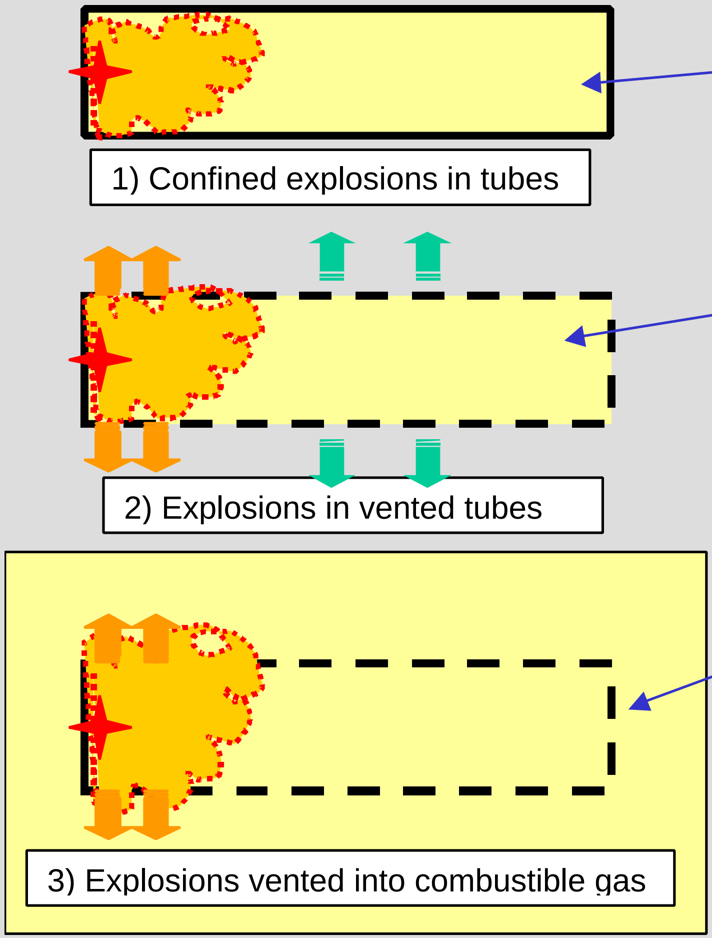
Hazards associated with H_2 combustion

Approach

- Safety and risk studies of H_2-fuel involve accidental releases of hydrogen into a partially vented, partially confined geometry
- These cases are relatively less understood compared to cases of confined geometry
- To take advantage of data and understanding available
- Experimental data should be useful to provide quantitative methodology for safety and risk studies

Hazards associated with H_2 combustion

Approach



- Case 1): relatively well understood
- Case 2): can be related to some accident situations, and serves as a bridge between case 1) and the main problem case 3)
- Case 3) is directly related to real applications involving the geometry of vehicles/infrastructure

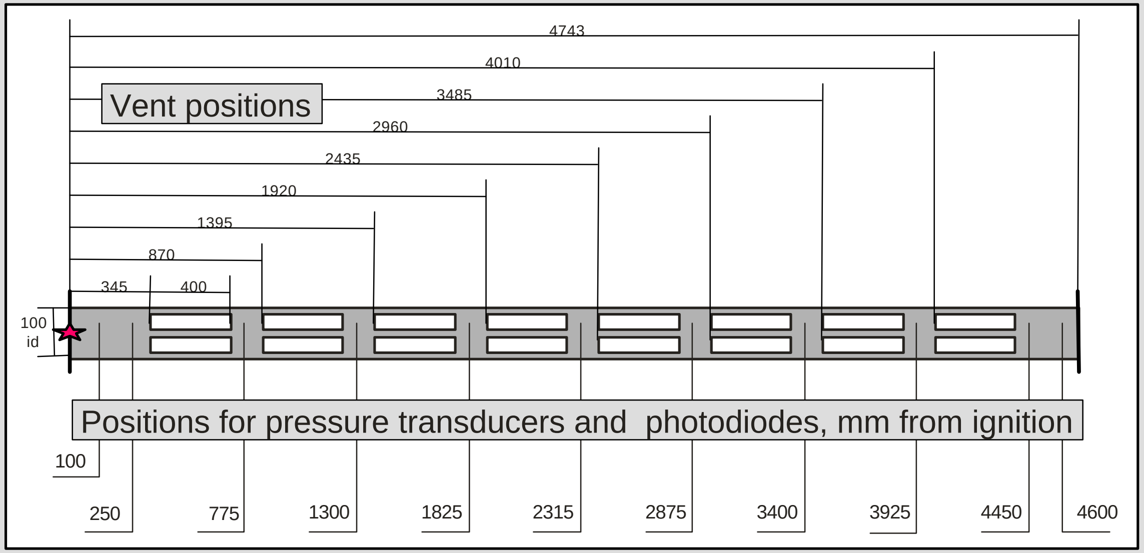
Hazards associated with H_2 combustion

Objectives of EIHP 2 experimental program

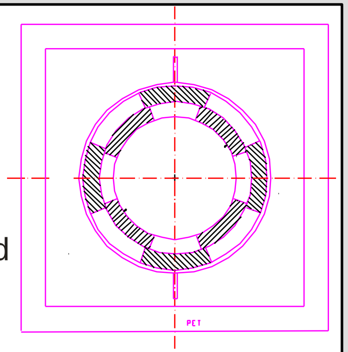
- Study of critical conditions for strong Flame Acceleration and DDT in vented tubes and semi-confined geometry;
- Comparison of explosion properties of hydrogen and typical hydrocarbon fuels in semi-confined geometry
- Generation of the data necessary for validation of computer codes for simulation of gaseous explosions in semi-confined geometry.

Hazards associated with H_2 combustion

Tests in vented tube



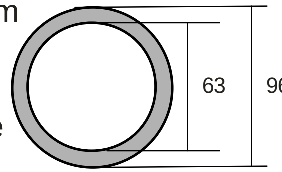
Mutual position of inner tube, outer tube, and frame



Orifice plate obstacles

Spacing: 100 mm

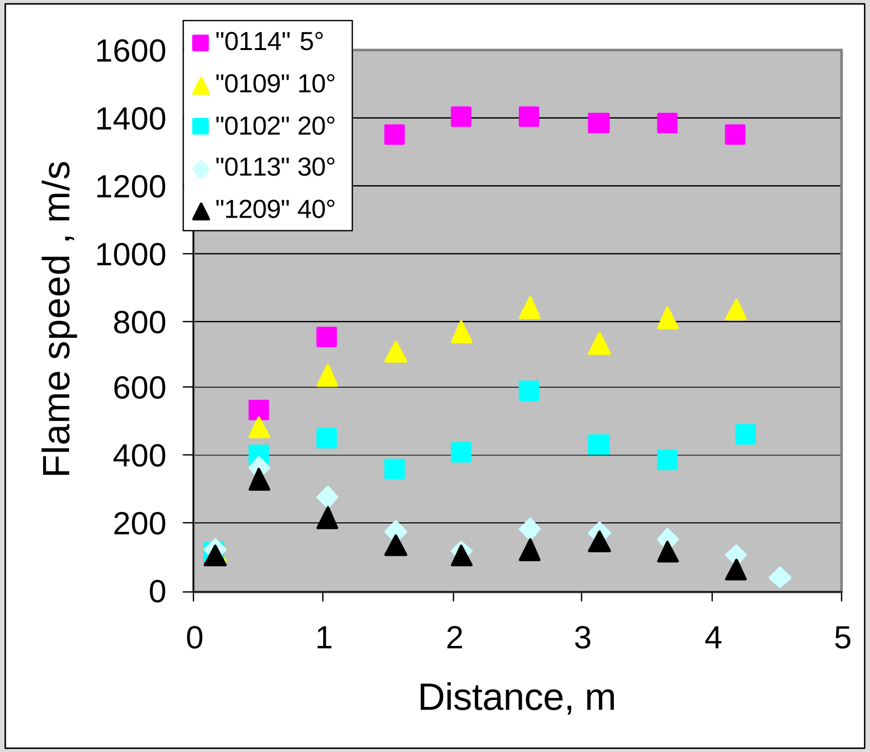
Thickness of the plates: 10 mm



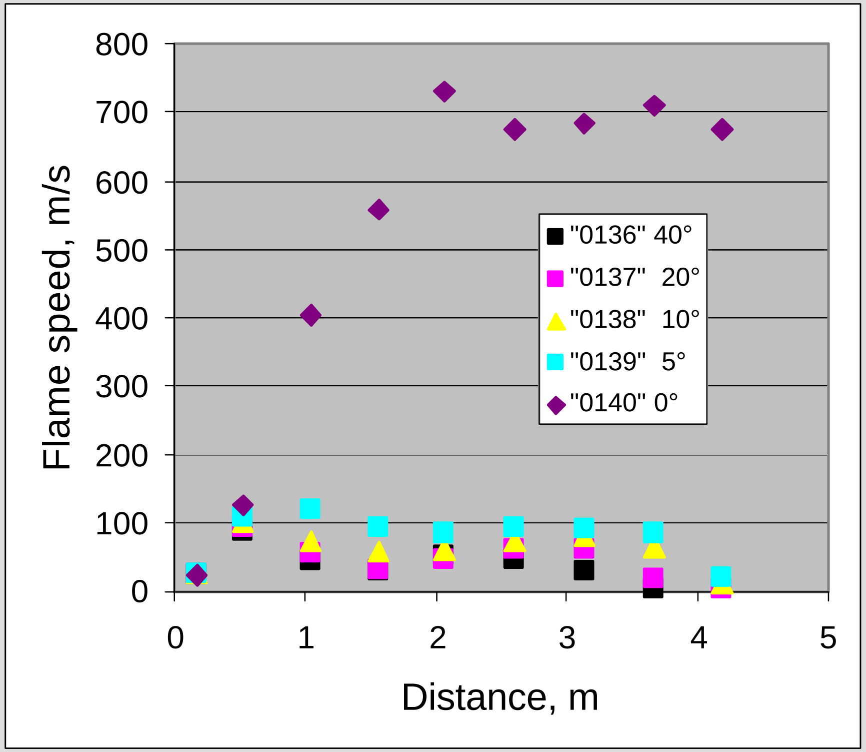
Hazards associated with H_2 combustion

Tests in vented tube

➢ Results: flame speeds versus distance



25% H_2

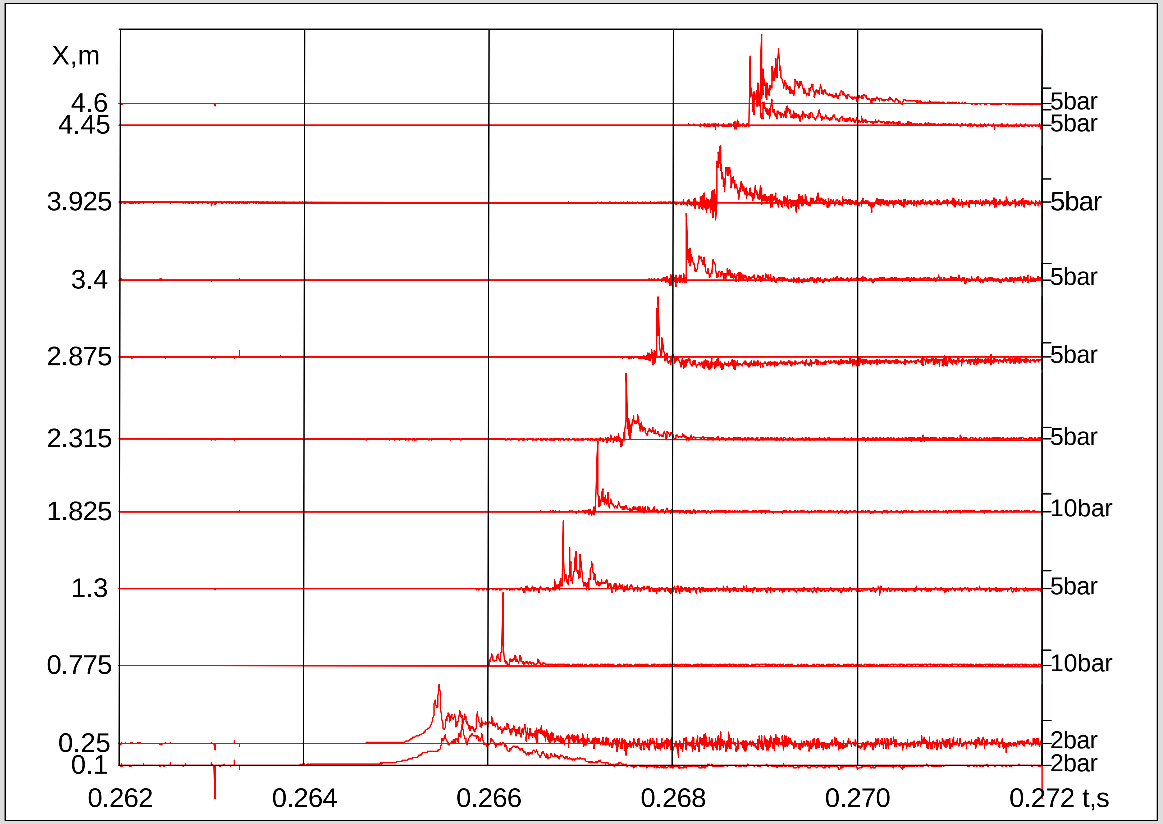


9.5% CH_4

Hazards associated with H_2 combustion

Tests in vented tube

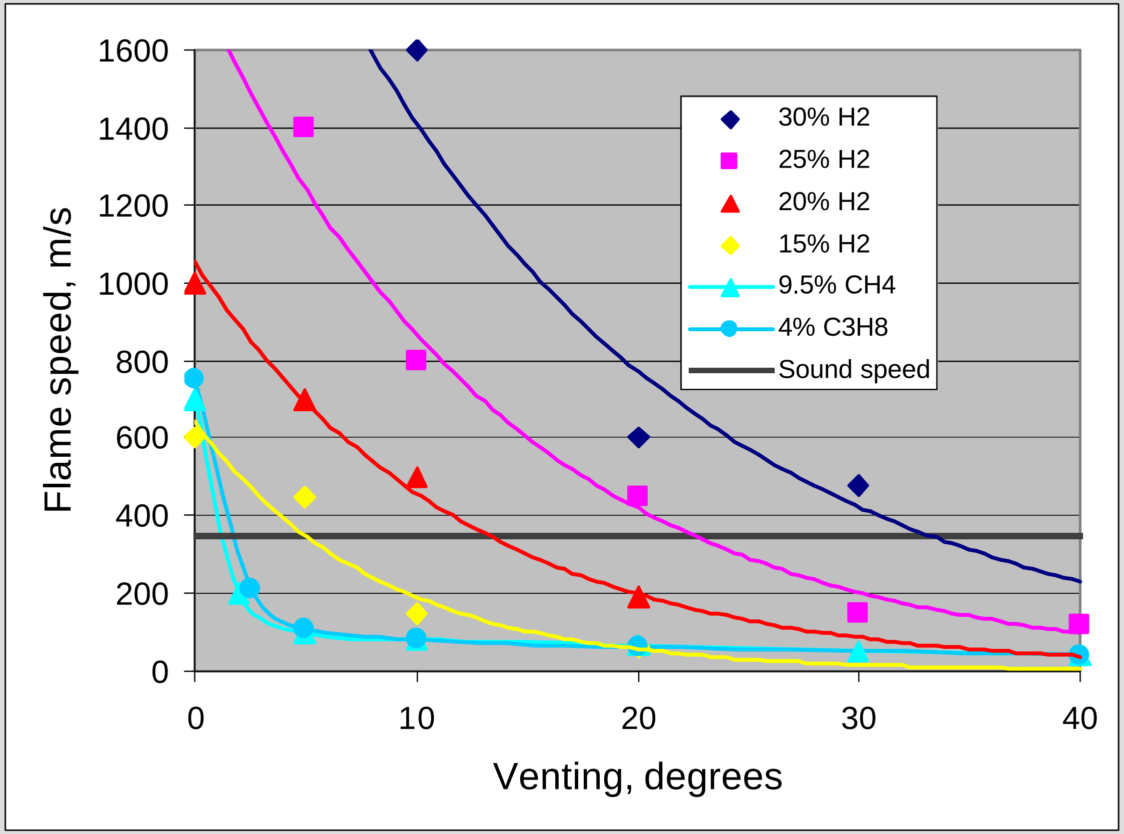
- Results:
  - pressure records inside the tube
  - data necessary for code validation



Hazards associated with H_2 combustion

Tests in vented tube

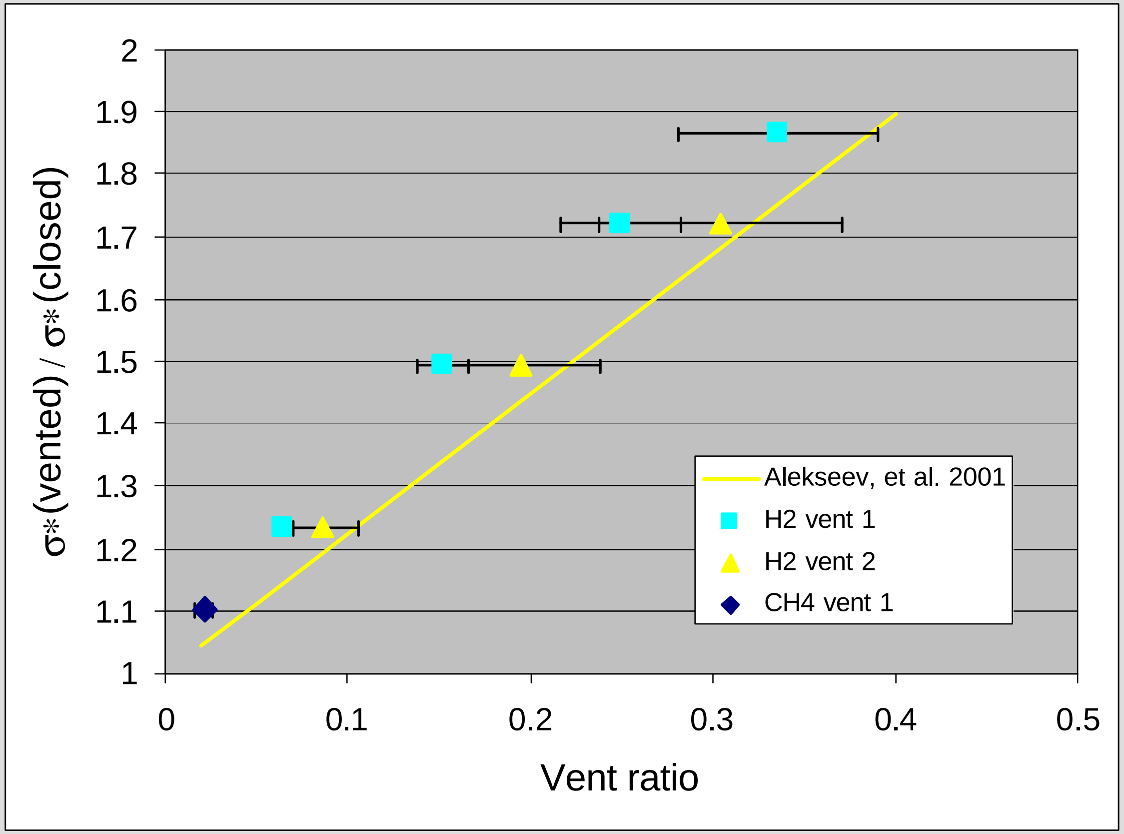
- Final flame speeds
  - effect of venting
  - effect of mixture composition
- H_2 shows wider range of compositions for fast flames
- Potential for H_2 –flames to accelerate is less affected by geometry constrains



Hazards associated with H_2 combustion

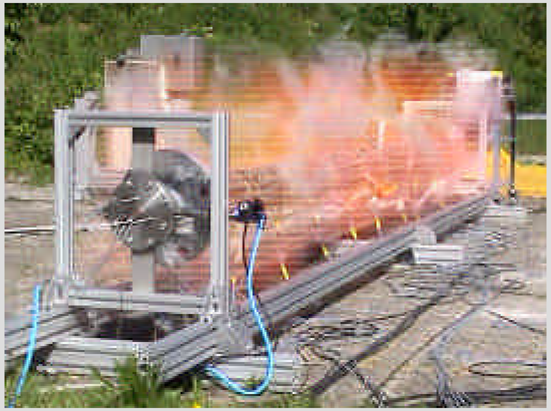
Tests in vented tube

- Critical conditions for strong FA
- Minimum expansion ratio of a mixture σ*, necessary for strong FA increases with venting

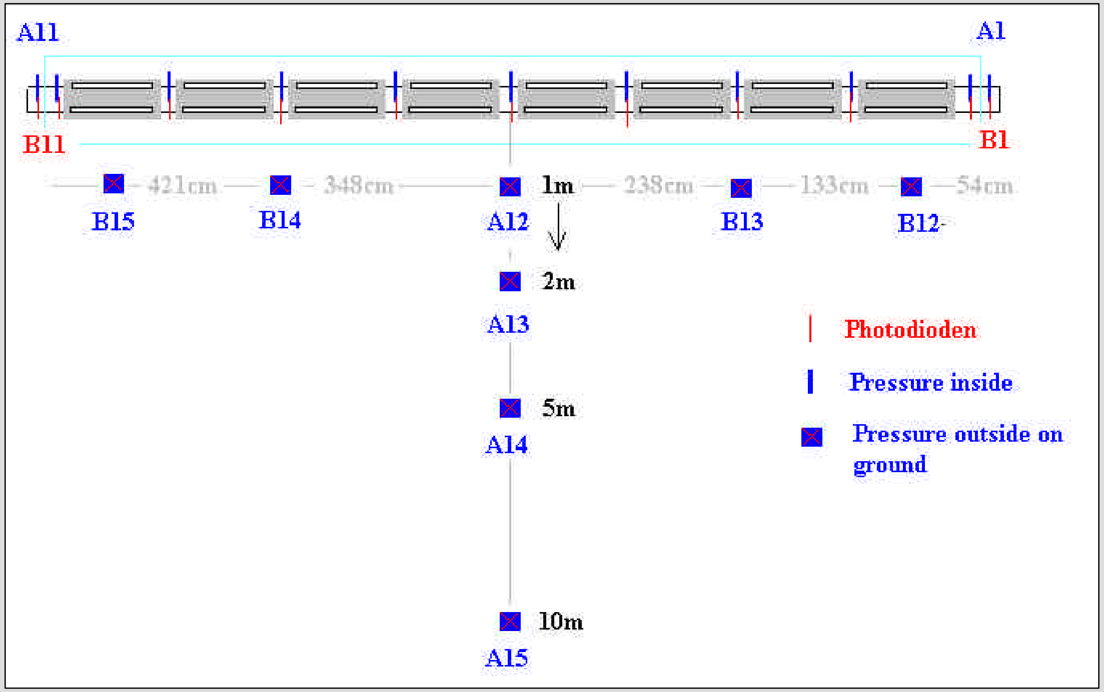


Hazards associated with H_2 combustion

Tests in semi-confined geometry



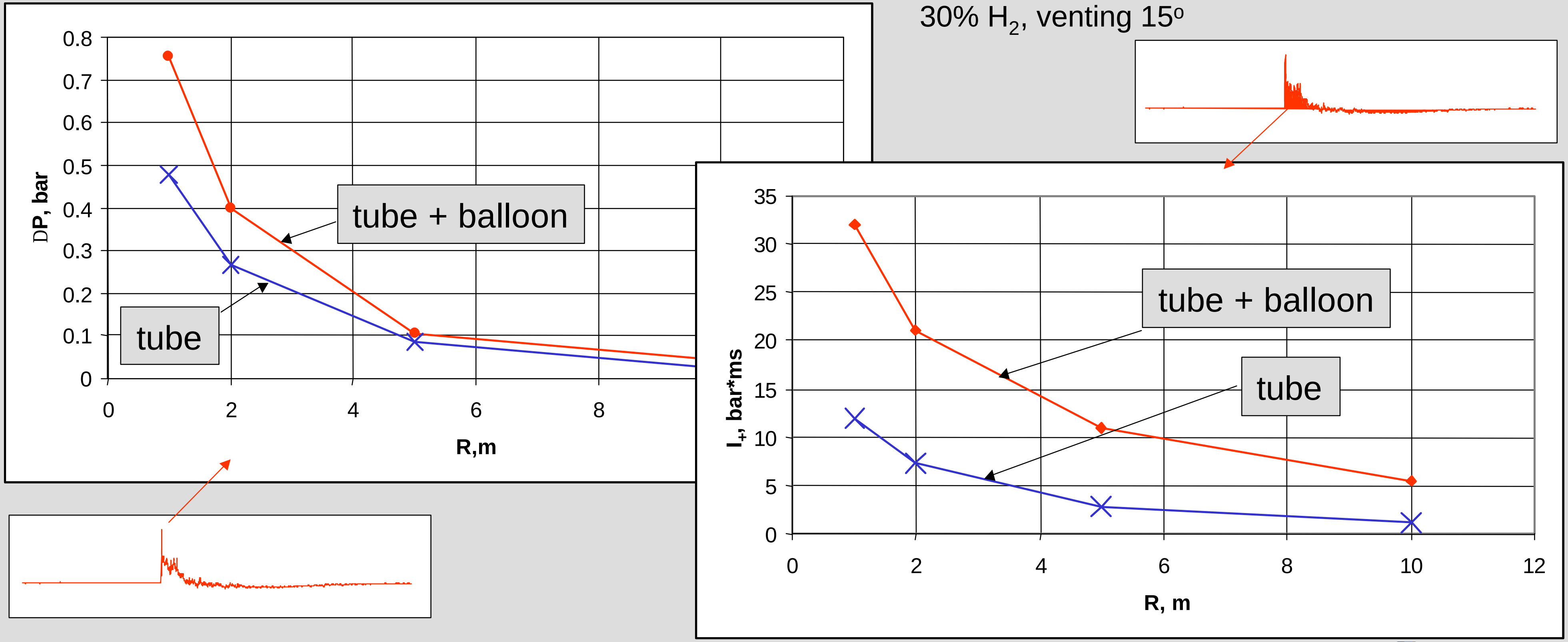
Positions for pressure transducers and photodiodes. Top view.



Hazards associated with H_2 combustion

Tests in semi-confined geometry

- Results: overpressure and impulse in air blast wave versus distance



Hazards associated with H_2 combustion

Summary

- Experimental data, models, and computer codes are available for evaluation of hazards associated with H_2 combustion
- Most of these tools are validated for confined hydrogen explosions
- EIHP experimental program have provided an important extension on the role of venting and semi-confined geometry on FA and DDT
- Tests on semi-confined H_2 explosions are in progress to provide data for code validation

Hazards associated with H_2 combustion

Issues

- More experimental data are necessary to cover wider variety of applications
  - Free plums and jets
  - Stratified layers
  - …
- All these should give a basis for development of methodology for evaluation of hazards from hydrogen explosions
- Extensive code development and validation work should be made to provide reliable input for quantitative safety and risk studies

WP 5.2
Risk analysis of refueling infrastructure

Brussels
02 October 2002

Presentation by
Det Norske Veritas and Norsk Hydro.

Status - Work Completed

- ✓ Established Rapid Risk Ranking (RRR) method for H_2 filling stations
- ✓ Development of risk acceptance criteria for HGV filling stations
- ✓ RRR analyses of 6 HGV filling station concepts, including H_2 production
- ✓ Hazop analysis of HGV filling station based on hydrogen production by water electrolysis
- ✓ Input to NCSRD for CFD H_2 gas dispersion calculations
  - Filling station layout and design geometry
  - H2 release scenario input
- ✓ CFD calculations of H_2 dispersion and explosion inside electrolysis container

RRR methodology

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- ✓ Method to identify hazardous incidents at a facility when information is limited
- ✓ Identified incidents rated with regard to probability and consequences
- ✓ Results are compared to a risk matrix
  - High or medium risk incidents should be examined further
  - Incidents with low risk are acceptable
- ✓ Risk reducing measures can be identified and incorporated in design
- ✓ Participants:
  - Group of experts with relevant experience from similar installations; process, mechanics, electrical engineering

Concepts analysed

Refuelling station concept	*Participants*
GH_2, production by water electrolysis	Hydrogen Systems, Shell, Air Liquid, DNV
GH_2, production by Methanol Steam Reforming	BP, Volvo, Norsk Hydro, Haldor Topsoe, Methanex, DNV
GH_2, production by Ammonia splitting	Norsk Hydro, DNV
GH_2, production by Natural Gas Steam Methane Reforming	Norsk Hydro, DNV
CGH_2, supplied from pipeline or truck	Air Liquid, Air Products, Volvo, BP, Hydrogen Systems, DNV, Norsk Hydro
Liquefied H_2, supplied from truck	Air Liquid, Air Products, Volvo, BP, Hydrogen Systems, DNV, Norsk Hydro

Observations from RRR

- ✓ Results very dependent on participants
- ✓ Unsuitable for direct comparison of concepts
- ✓ Very sparse technical input due to
  - Confidentiality aspects related to accident statistics and technical input
  - Concepts are still not finally designed
  - Still some way to go until technical information is ready
- ✓ Transport of hydrogen or hazardous feed stock (ammonia, natural gas, methanol) should also be examined
- ✓ LH2 not covered as well as gaseous hydrogen
- ✓ Purification (PSA) not yet analysed

System breakdown

Supply and Production:

- Storage of raw materials
- H2 generation,
- Compression/ Cooling

→ **Storage** →

Filling:

- Dispenser
- Filling device/hose
- Connector

Refuelling station layout

Results and findings from RRR

✓General:

- Hydrogen gas releases is a main hazard coupled to
  - high pressures (large release rates)
  - confined areas, explosion risk
- Relief of hot/flammable/toxic/acid exhaust gases/liquids to atmosphere
- Safety valves – ventilation to safe location
- Grounding of equipment during refuelling
- Location – Safety distances – Area limitations – Fire walls/protection
- Access for 3 party/ Sabotage???
  - Protection, enclosures

Results, aspects that should be addressed

✓ H_2 supply, supply of feed stock, feed stock storage

- Leak of flammable or toxic materials during transport or discharge at filling station
- Methanol: Environmental problems with regard to drinking water
- Ammonia: Toxicity, smell problems
- Purging system, coupled to startup and shutdown
- For all concepts the risk of releases of flammable gases inside confined areas should be addressed. Prevention of backflow from high pressure side is a critical aspect, back flow must be prevented

Results, aspects that should be addressed, cont.

✓ **Dispenser**

- **Physical protection against collisions**
- **Leak detection system**
- **Ventilation system**
- **Cascade filling imply a lot of opening/closure of many valves – Strict requirements to correct operation of these systems**
- **Fast filling time require strong control of max. and min. temperatures/pressures in filling hoses, connectors and tanks**

Risk reduction, possible input to requirements

Releases/ignition in confined areas(containers):

- High quality materials and equipment
- Leak testing requirements
- Grounding system requirements
- Gas, smoke, fire detection coupled to
  - Emergency purging and shut down of process
  - Emergency ventilation systems
  - Segmentation valves, activation time
  - Explosion relief areas
  - Opening of roof/walls
- Design against high explosion blast?

Risk reductions, possible input to requirements

Safe refuelling of vehicles

- Grounding of dispenser, vehicle and driver
- Secure that connection is tight before refuelling can start
- Break away couplings
- Secure against vehicle drive away
- Purging and cooling of filling hose before filling (liq.)
- Correct measurement of amount of gas inside vehicle fuel tank
- No smoking, electronics such
  as mobile telephones, open fire

Further work in WP5.2

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- ✓ **Hazop analysis of non electrolyser concept**
- ✓ **Quantitative risk assessment as input to**
  - **Safety distances**
  - **Classification of explosive zones**
  - **Acceptable risk outside refuelling station**
- ✓ **The quality/success of a QRA depends on technical information**
  - **Technical information for a generic refuelling station should be established within WP2**