Dealing with hydrogen explosions

Dealing with hydrogen explosions

Content

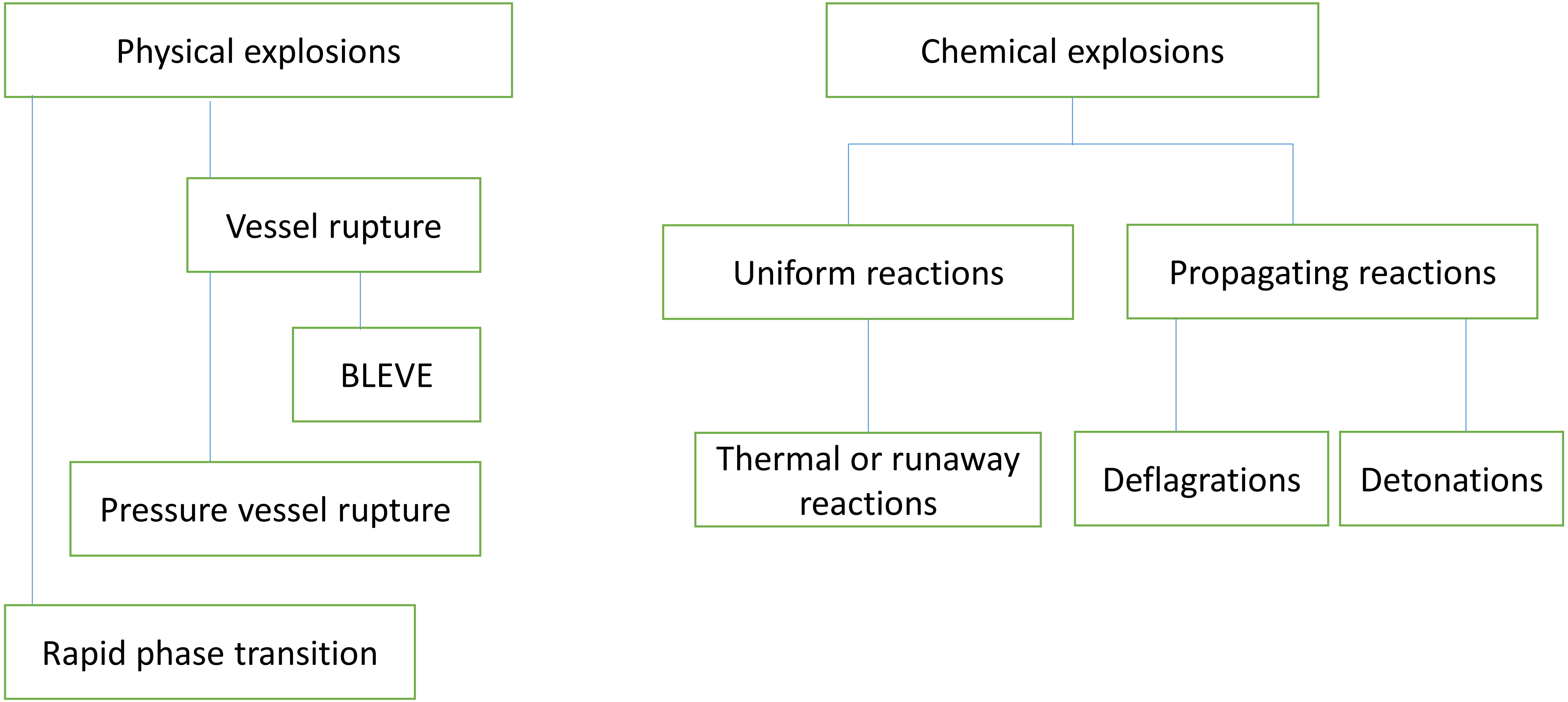
- Objectives
- Classification of explosions
- Terminology
- Deflagrations
- Deflagration-to-detonation transition (DDT)
- Detonations
- The effects of blast waves on people and buildings
- Explosion prevention and mitigation

Dealing with hydrogen explosions

Objectives of the lecture

- Distinguish between deflagrations and detonations
- Recognise the severe consequences of deflagrations and detonations
- Point out the main features of deflagrations and detonations
- Make a distinction between deflagrations in the open and in confined spaces
- Explain deflagration-to-detonation transition (DDT) phenomenon
- Evaluate the effect of blast waves caused by a rupture of a storage tank (in afire) on people and building structures with the use of nomograms
- Explain the vented deflagration as a main mitigation technique
- Recognise the effects of missiles and debris from explosions
- State the main prevention and suggest possible mitigation measures for explosion events.

Classification of explosions (Crowl, 2003)



Physical explosions

Vessel rupture

BLEVE

Pressure vessel rupture

Rapid phase transition

Chemical explosions

Uniform reactions

Propagating reactions

Thermal or runaway reactions

Deflagrations

Detonations

Source: Crowl, DA (2003). Understanding explosions.

Terminology

- ‘Chemical’ explosions: deflagrations and detonations
- ‘Physical’ explosions: occur on vessels rupture due to a sudden release of mechanical energy.
- **Deflagration** is the phenomenon of a combustion zone propagation at the velocity lower than the speed of sound (sub-sonic) into a fresh, unburned mixture.
- **Detonation** is the process of combustion zone propagating at the velocity higher than the speed of sound (supersonic) in the unreacted mixture.
- Detonation propagates 2-3 order of magnitudes faster than deflagration and results in pressures at the detonation front 15-20 times higher than initial pressure.

Dealing with hydrogen explosions

Backdraft

https://www.youtube.com/watch?v=c4yH9s6OW1s&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=7

Deflagrations and detonations

- Deflagrations in the open, in the absence of any obstacles, could generate overpressures (pressure above atmospheric pressure) of about 10 kPa.
- Deflagrations in the enclosures and/or confined spaces could lead to more significant overpressures. During deflagration the pressure grows practically uniformly within an enclosure.
- Deflagration in an enclosure can be mitigated by **venting**, the most cost-effective and widespread explosion mitigation technique.
- Detonation is a coupled shock and flame front structure which propagates with supersonic velocity. The speed of detonation wave depends on the stoichiometry of hydrogen-air mixture and ranges from **1,600 to 2,000 m/s**. The overpressures also much higher: **1,000-1,500 kPa.**
- Venting technique is not applicable to detonations as the pressure arrives to any location and affects a system and/or structural elements simultaneously with the detonation wave, i.e. there is no time to “release” the pressure.

General features of deflagrations and detonations

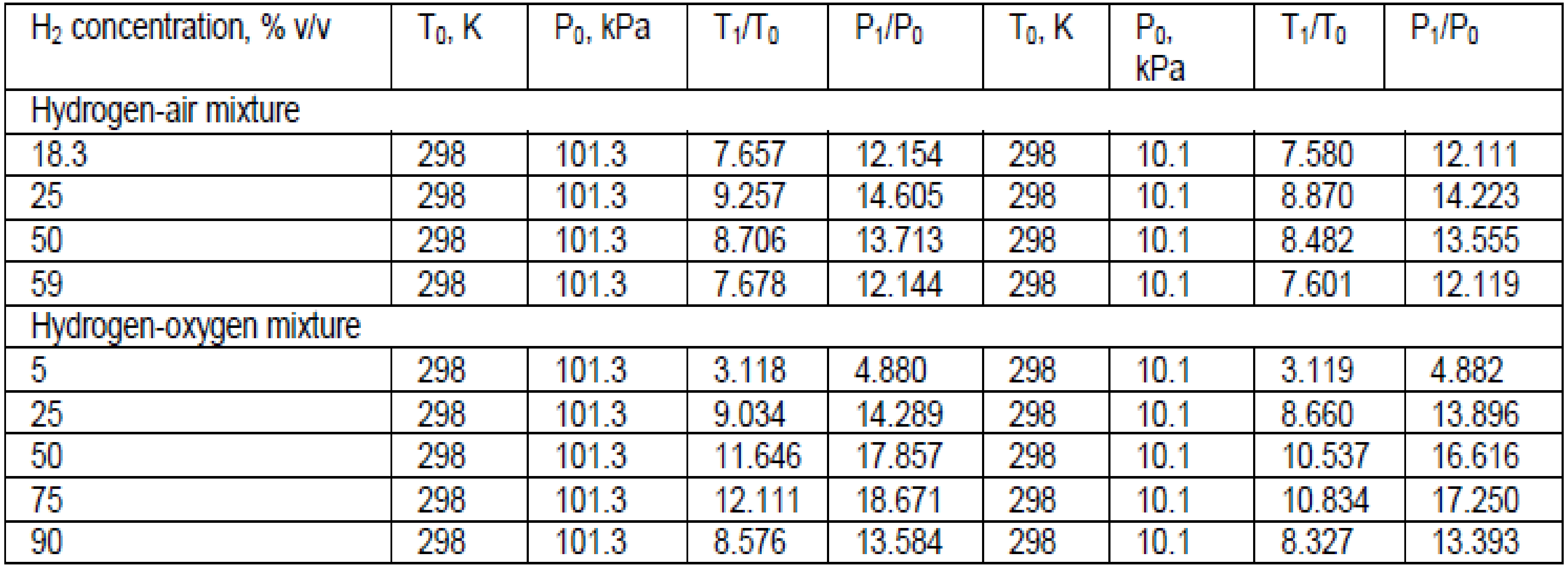
- The stoichiometric hydrogen-air mixture, flame propagation velocity during deflagration in the open quiescent atmosphere in a 20 m diameter: hemi-spherical flame propagation speed increased up to its maximum velocity of **84 m/s**, and an explosion overpressure is of the order of **0.1 atm** in the near field. Then, pressure in a blast wave decays inversely proportional to the radius (for high explosives the pressure decays inversely proportional to radius squared).
- The maximum deflagration pressure in a closed vessel may reach approximately 8.0 atm depending on hydrogen fraction in the flammable composition. It is essentially higher than typical overpressure for open atmosphere deflagration 0.1 atm.
- Detonation front propagation velocity and pressure - often called Chapman-Jouguet (CJ) velocity and the CJ pressure – reach for stoichiometric hydrogen-air mixture **1,968 m/s** (about 6 times faster than speed of sound in air) and **1.56 MPa,** respectively.

Factors affecting the severity of deflagrations

- The composition of hydrogen-oxidizer mixture
- The uniformity of hydrogen-oxidizer mixture (for the same hydrogen inventory)
- The level of confinement (walls and ceiling)
- The presence of obstacles

Detonation parameters

- Dimensionless detonation pressure (P_1/P_0, equilibrium CJ values) and temperature (T_1/T_0) for hydrogen-air and hydrogen-oxygen mixtures are given in the Table below. The P_1/P_0 and T_1/T_0 ratios give the pressure and temperature rise across the detonation shock .



H_2 concentration, % v/v	T_0, K	P_0, kPa	T_1/T_0	P_1/P_0	T_0, K	P_0, kPa	T_1/T_0	P_1/P_0
Hydrogen-air mixture								
18.3	298	101.3	7.657	12.154	298	10.1	7.580	12.111
25	298	101.3	9.257	14.605	298	10.1	8.870	14.223
50	298	101.3	8.706	13.713	298	10.1	8.482	13.555
59	298	101.3	7.678	12.144	298	10.1	7.601	12.119
Hydrogen-oxygen mixture								
5	298	101.3	3.118	4.880	298	10.1	3.119	4.882
25	298	101.3	9.034	14.289	298	10.1	8.660	13.896
50	298	101.3	11.646	17.857	298	10.1	10.537	16.616
75	298	101.3	12.111	18.671	298	10.1	10.834	17.250
90	298	101.3	8.576	13.584	298	10.1	8.327	13.393

Source: NASA Guidelines for hydrogen system design, materials selection, operations, storage, and transportation ”Safety standard for hydrogen and hydrogen systems”, NSS 1740.16, Office of safety and mission assurance, Washington, DC 20546, USA.

Dealing with hydrogen explosions

Consequences of explosions

- Propane fire and explosions, Dallas

  https://www.youtube.com/watch?v=n85R3OXK3bs
- Explosion at a chemical plant producing rocket fuel, Nevada

  https://www.youtube.com/watch?v=_KuGizBjDXo
- Massive explosion at a polyethylene production plant (23rd October 1989, Pasedena, Texas, USA)

  https://www.youtube.com/watch?v=3I2PQEjMnnM


Source : Presse Paris Normandie


Source: www.H2tools.org


Source : SDIS

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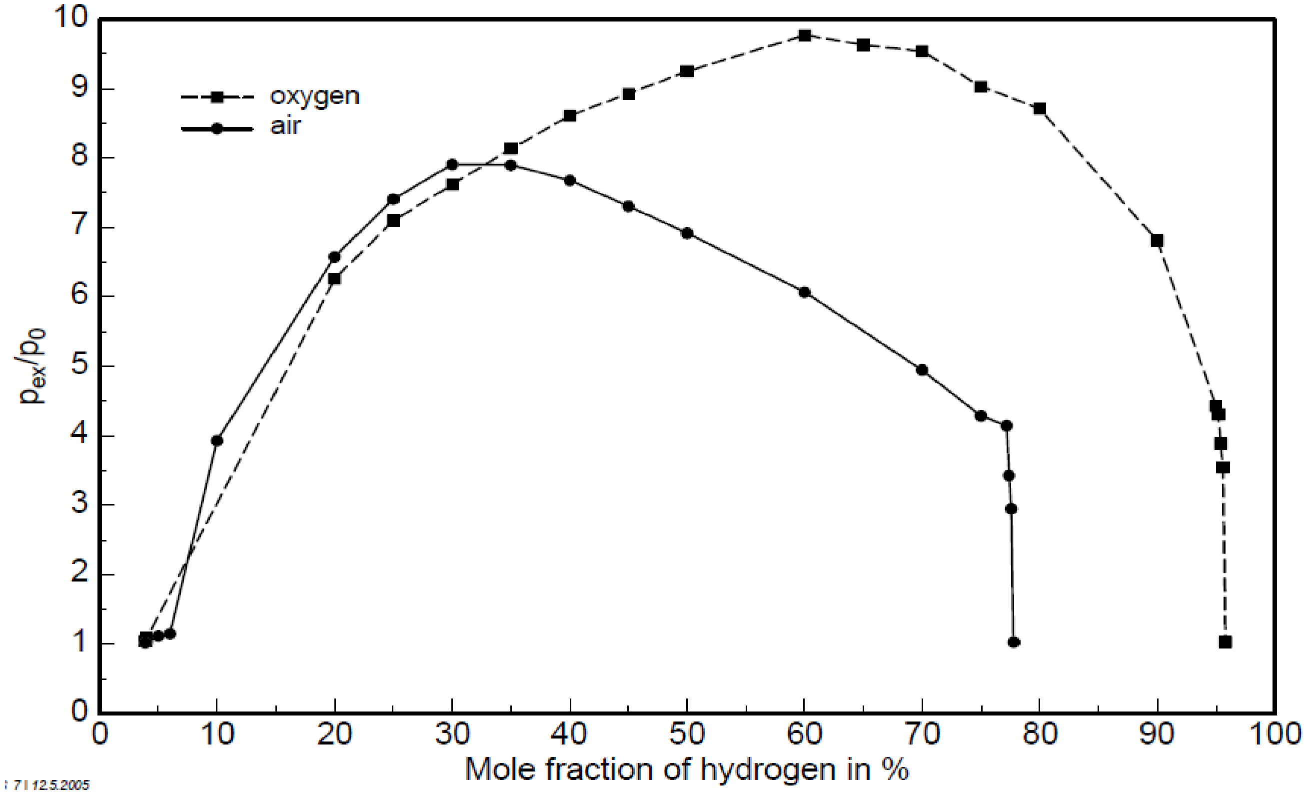
Closed vessel deflagrations

Deflagration pressure ratio of hydrogen-air and hydrogen-oxygen in a closed vessel at NTP



Source: Jordan, T. Overview of hydrogen and fuel cell technologies. 1st ISCARW “Progress in Hydrogen Safety”, September 2008, University of Ulster, Belfast

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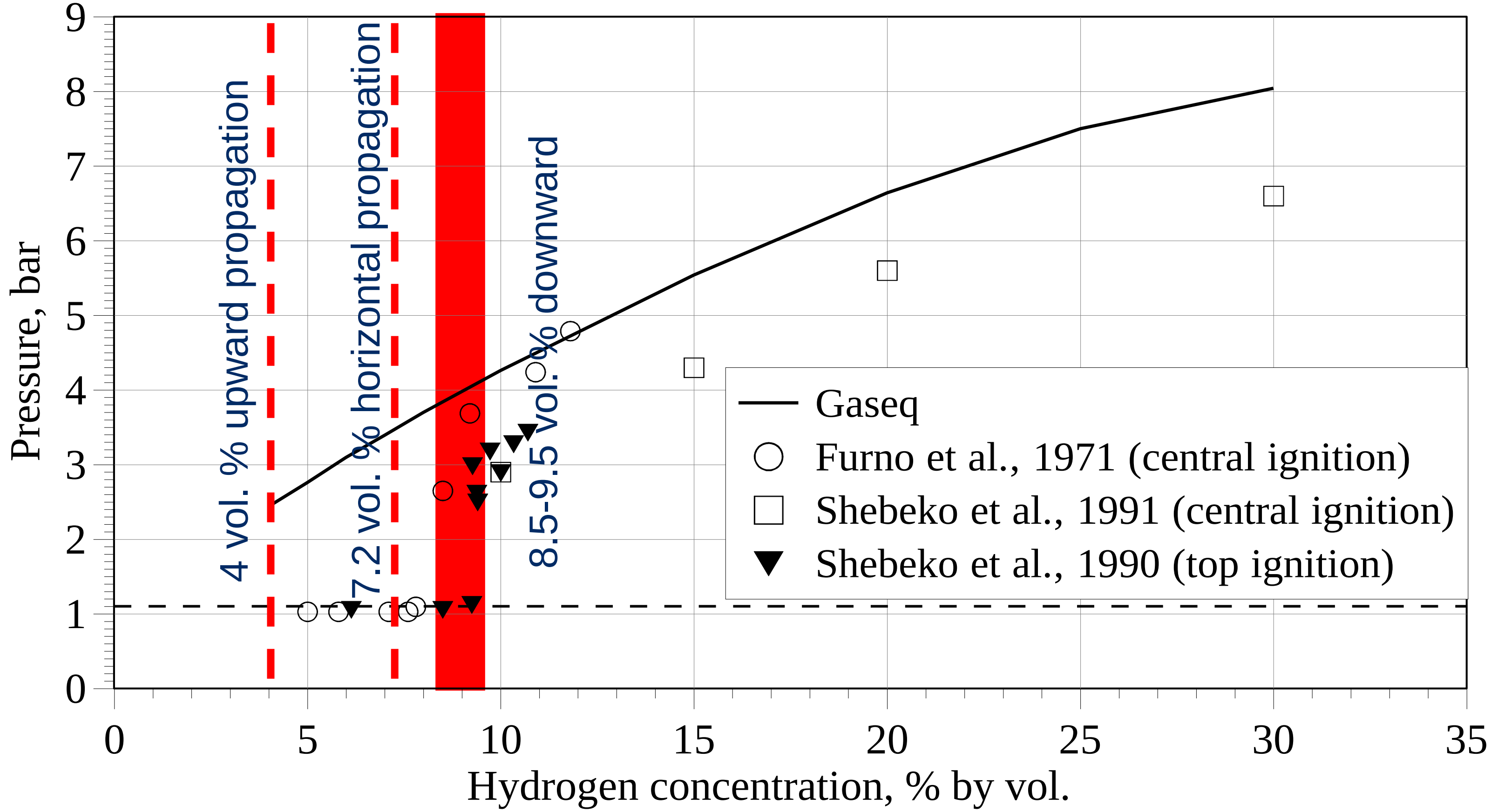
Closed vessel – quiescent mixture

- Quiescent mixtures < 8 vol. % generate no pressure



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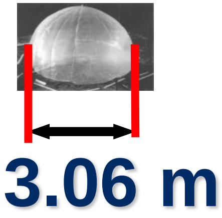
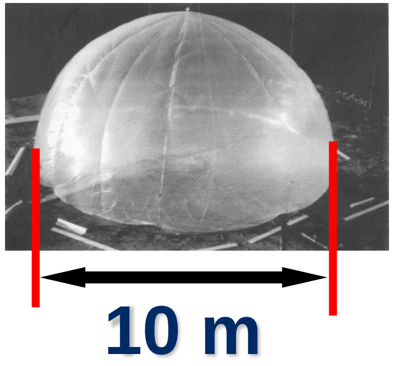
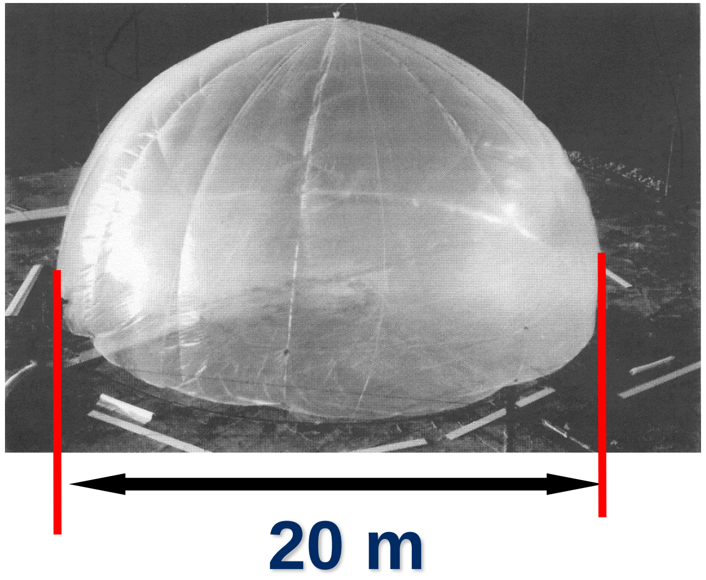
Hydrogen-air deflagrations in the open atmosphere

A series of experiments with near stoichiometric hydrogen-air deflagrations in unconfined hemispherical volumes was performed by Pförtner and Schneider (1983) in the Fraunhofer Institute for Fuels and Explosive Materials.





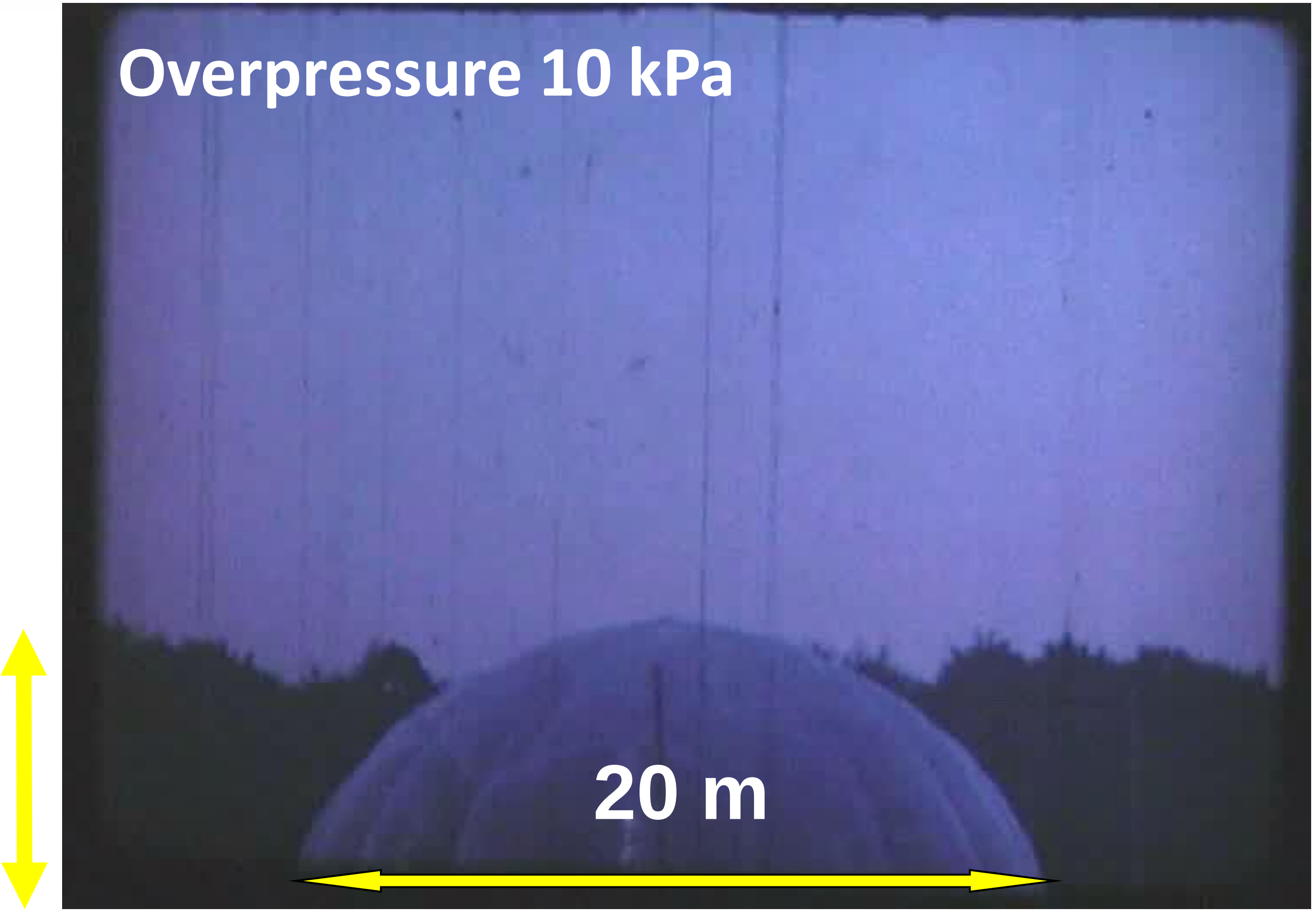


* - Experiments with wire net over the hemispherical balloon.

Test No.	D_b, m	V, m^3	C, % vol.	T_i, K	p_i, kPa	E_{ign}, J	S_{ui}^{exp}, m/s	χ_{max}^{exp}, m/s	w_{max}^{exp}, m/s
GHT 26	3.06	**7.5**	**29.2**	**281**	**99.06**	**1000**	**2.32**	**2.55**	**43**
GHT 11	10.00	**262**	**31.0**	**281**	**100.66**	**314**	**2.50**	**3.32**	**60**
GHT 34*	20.00	**2094**	**29.7**	**283**	**98.93**	**150**	**2.39**	**4.84**	**84**

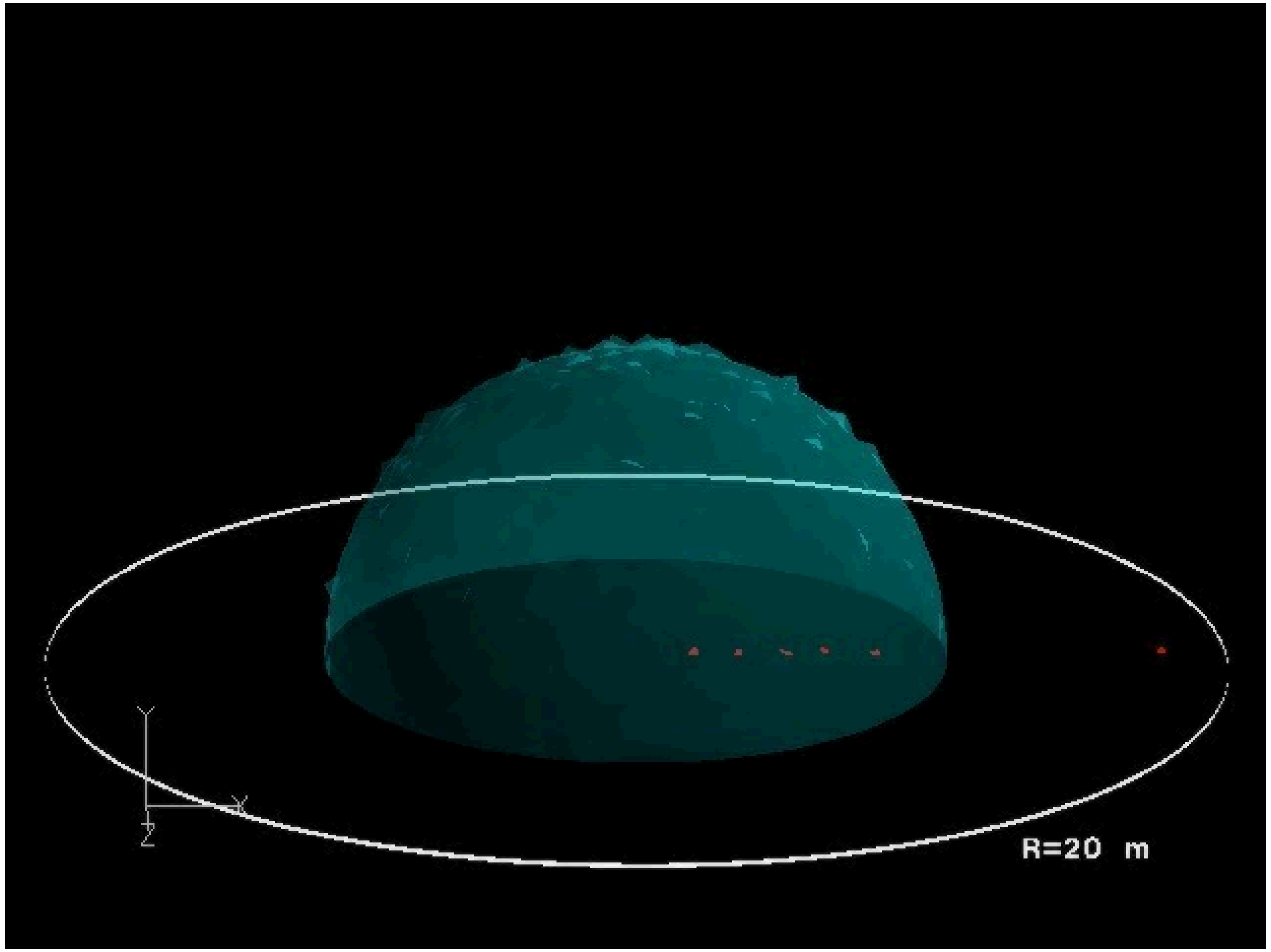
Dealing with hydrogen explosions

The largest hydrogen-air deflagration test



https://www.youtube.com/watch?v=z8jowE7HP1U&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=3

LES of the open atmosphere test



https://www.youtube.com/watch?v=UEh2eRe_dJI&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=6

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The open atmosphere

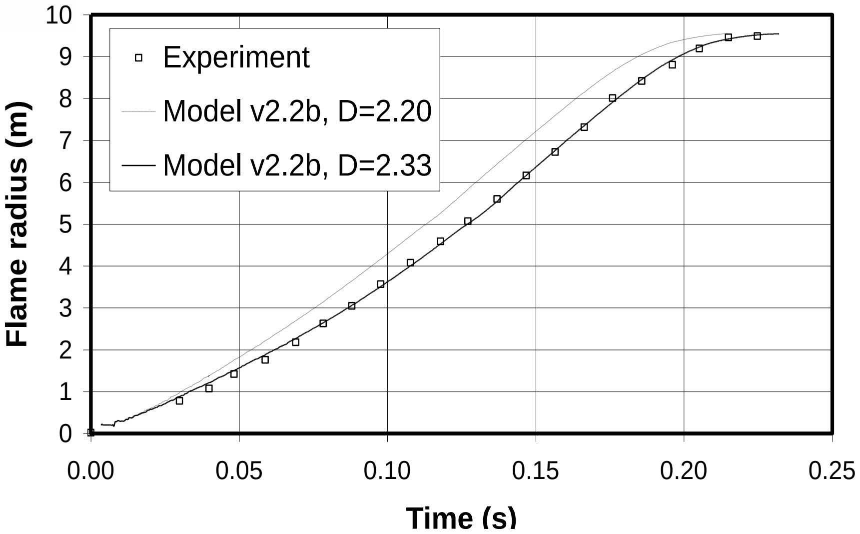
Hemisphere

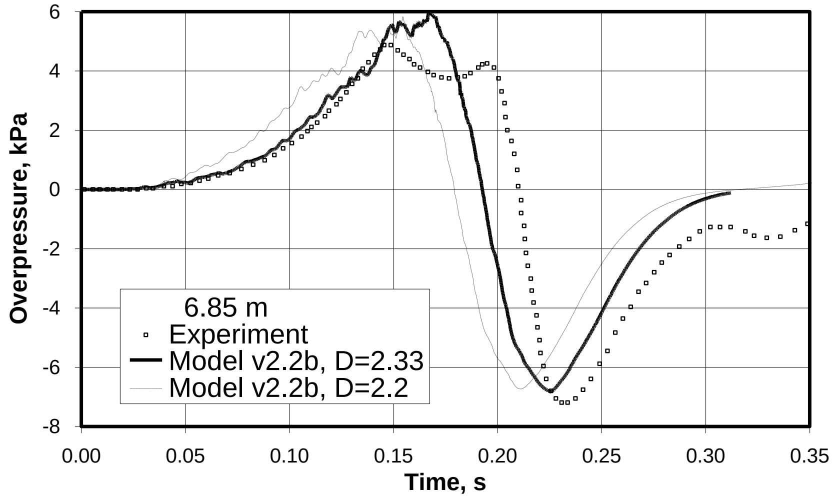
10 m

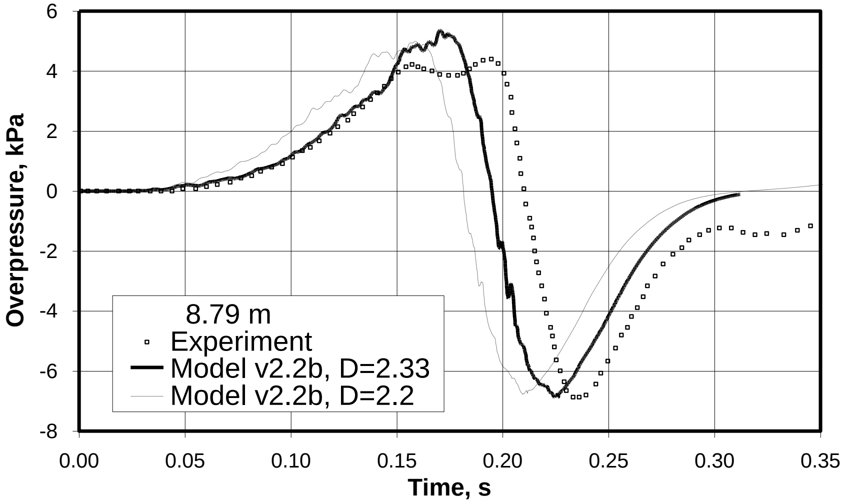
diameter

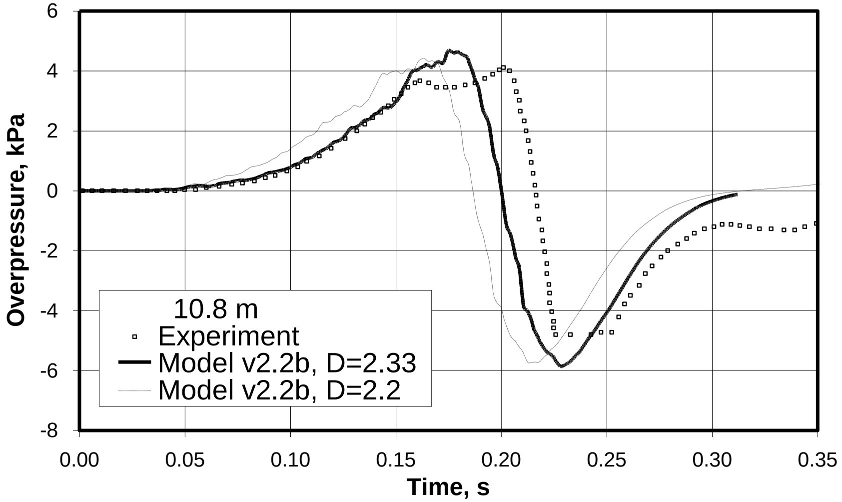
(Fraunhofer

ICT)









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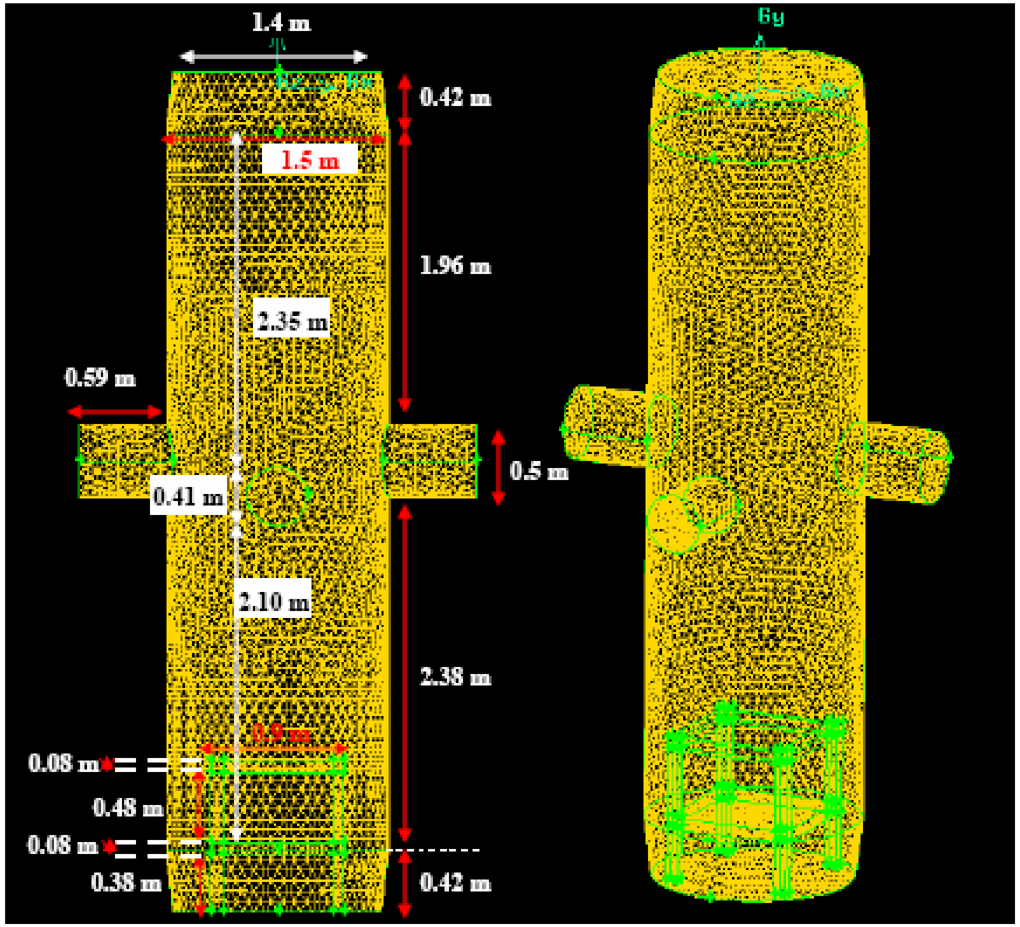
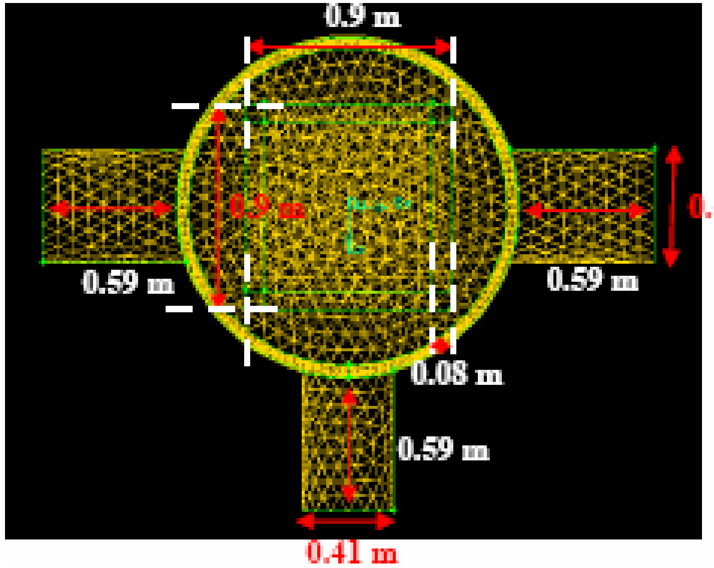
Lean and non-uniform hydrogen-air deflagrations

Calculation domain



5.7 m height cylinder



Δ_{CV}= 0.08 m;
157,352 CVs in total;

Experiment: Whitehouse et al., Nuclear Engineering and Design, 1996, Vol.166, pp.453-462

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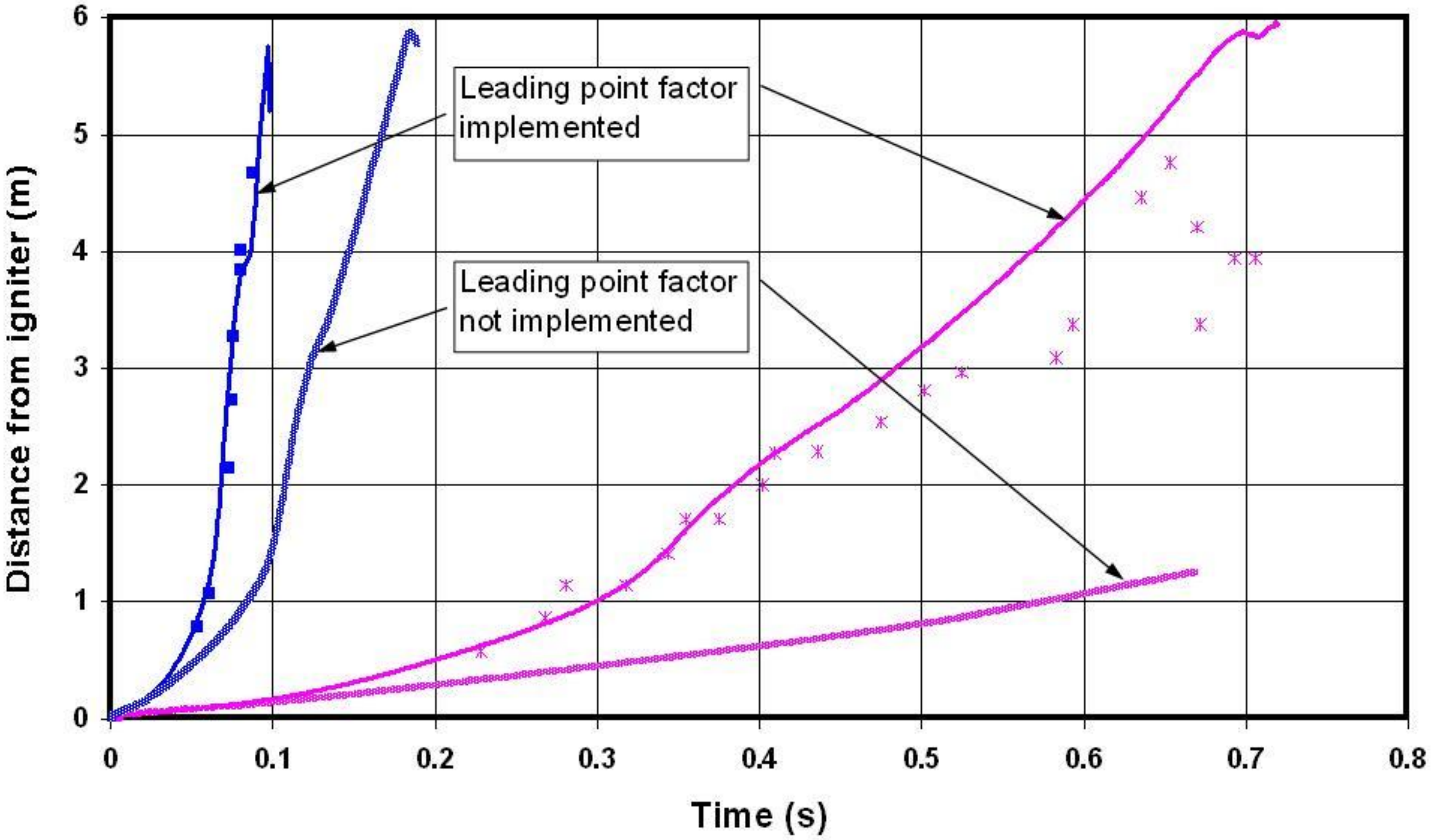
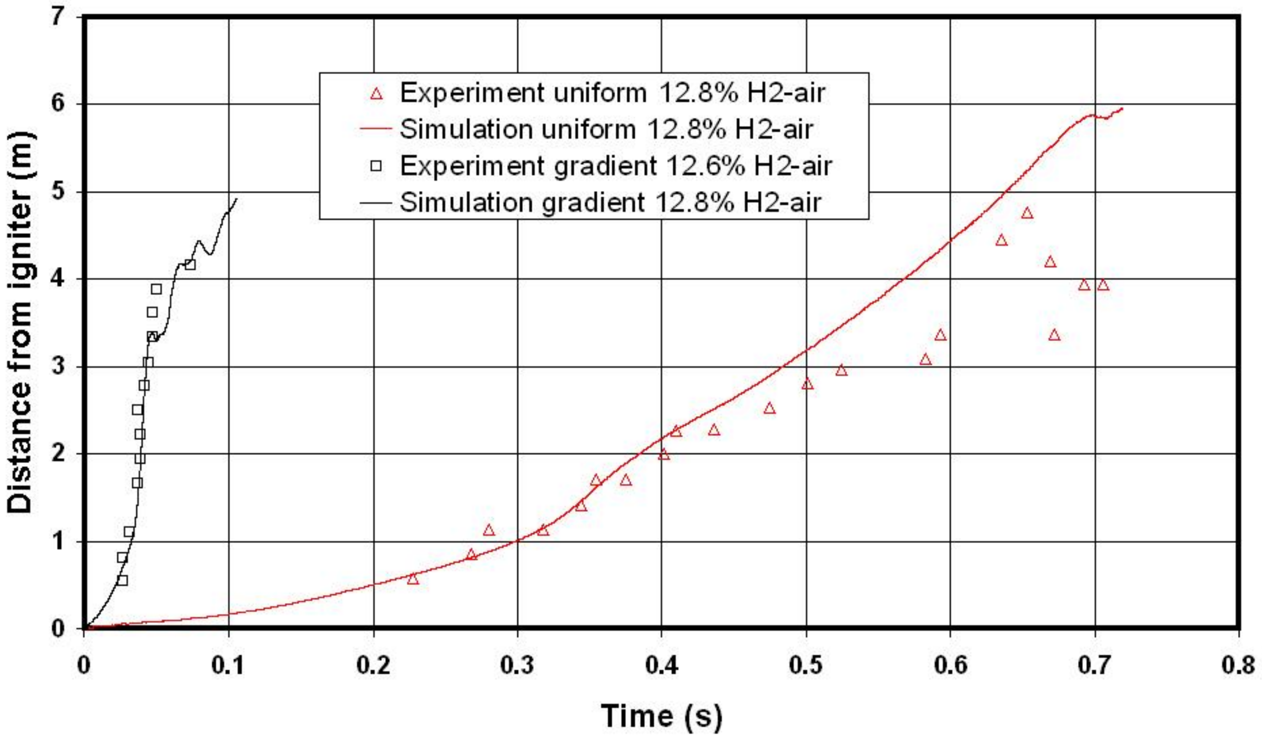
Effect of preferential diffusion

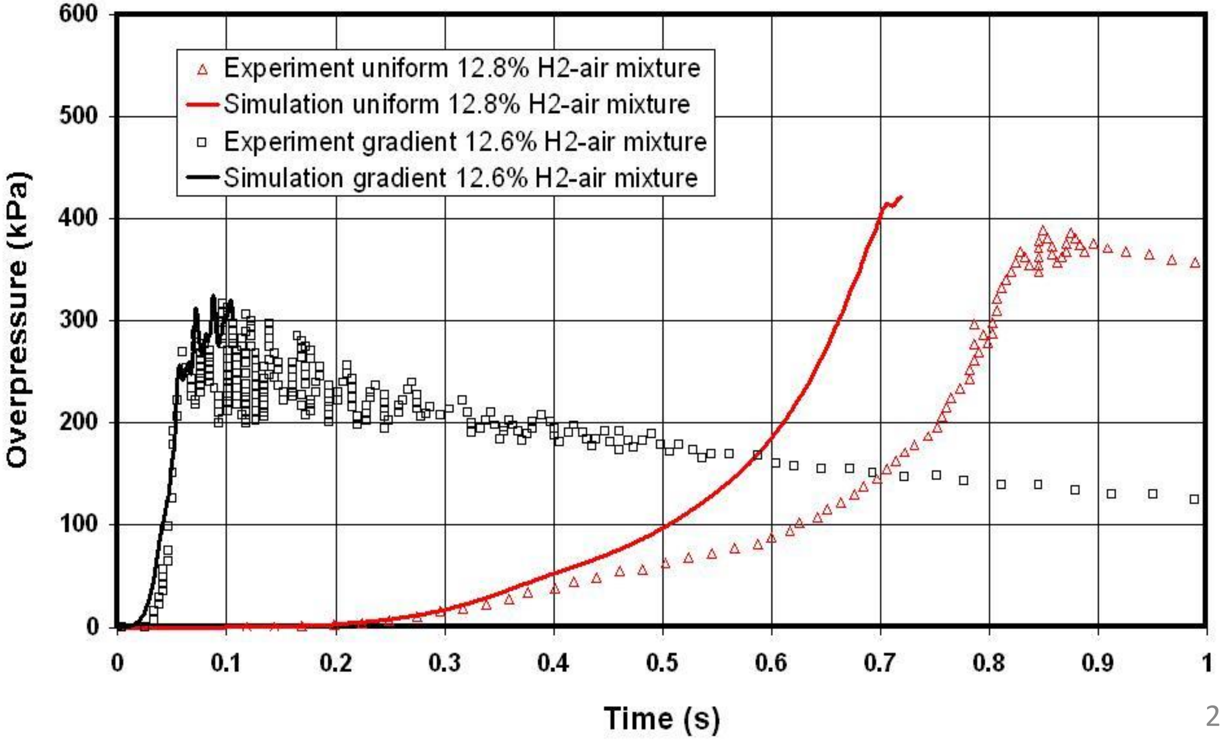


Effect of mixture non-uniformity on deflagration dynamics

Closed vessel: Whitehouse et al., 1996): L=5.7 m; D=1.5 m (V=10.1 m^3),

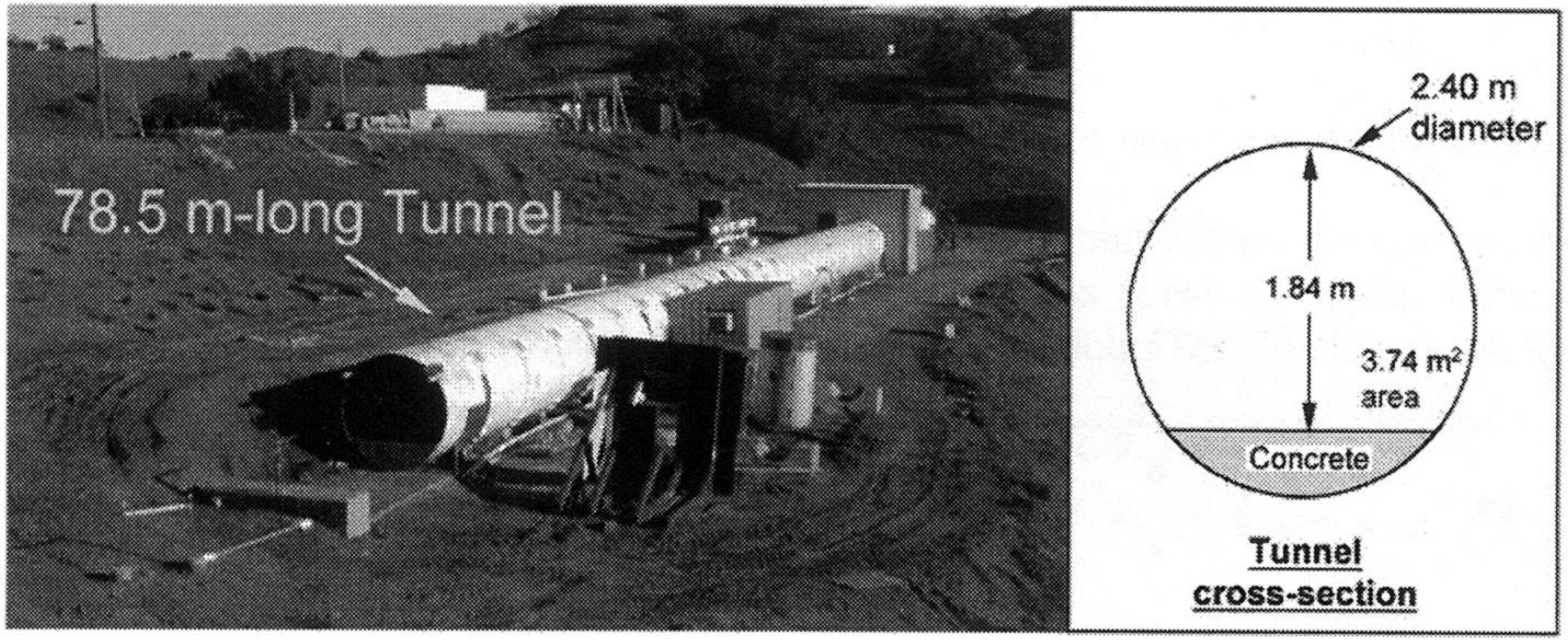
uniform (12.8 vol. %) vs. non-uniform (average 12.6%, 2.5-27%)





Hydrogen-air deflagrations in a tunnel (1/6)

- **SRI Tunnel** (1/5 scale), Groethe et al. (2005): 78.5 m length
- Horse-shoe cross section: 3.74 m²
- Hydrogen-air mixture: 30 and 20% by volume
- Vehicle size: L × H × W = 0.94 × 0.362 × 0.343 m (BR = 0.05)
- Distance between vehicles: 0.940 m



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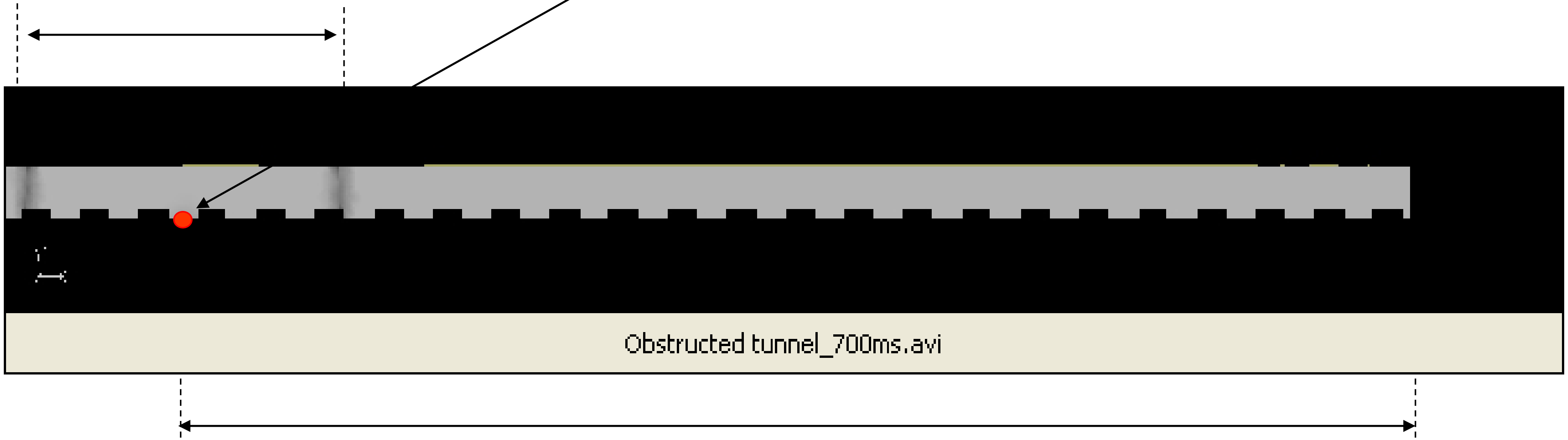
Hydrogen-air deflagrations in a tunnel (2/6)

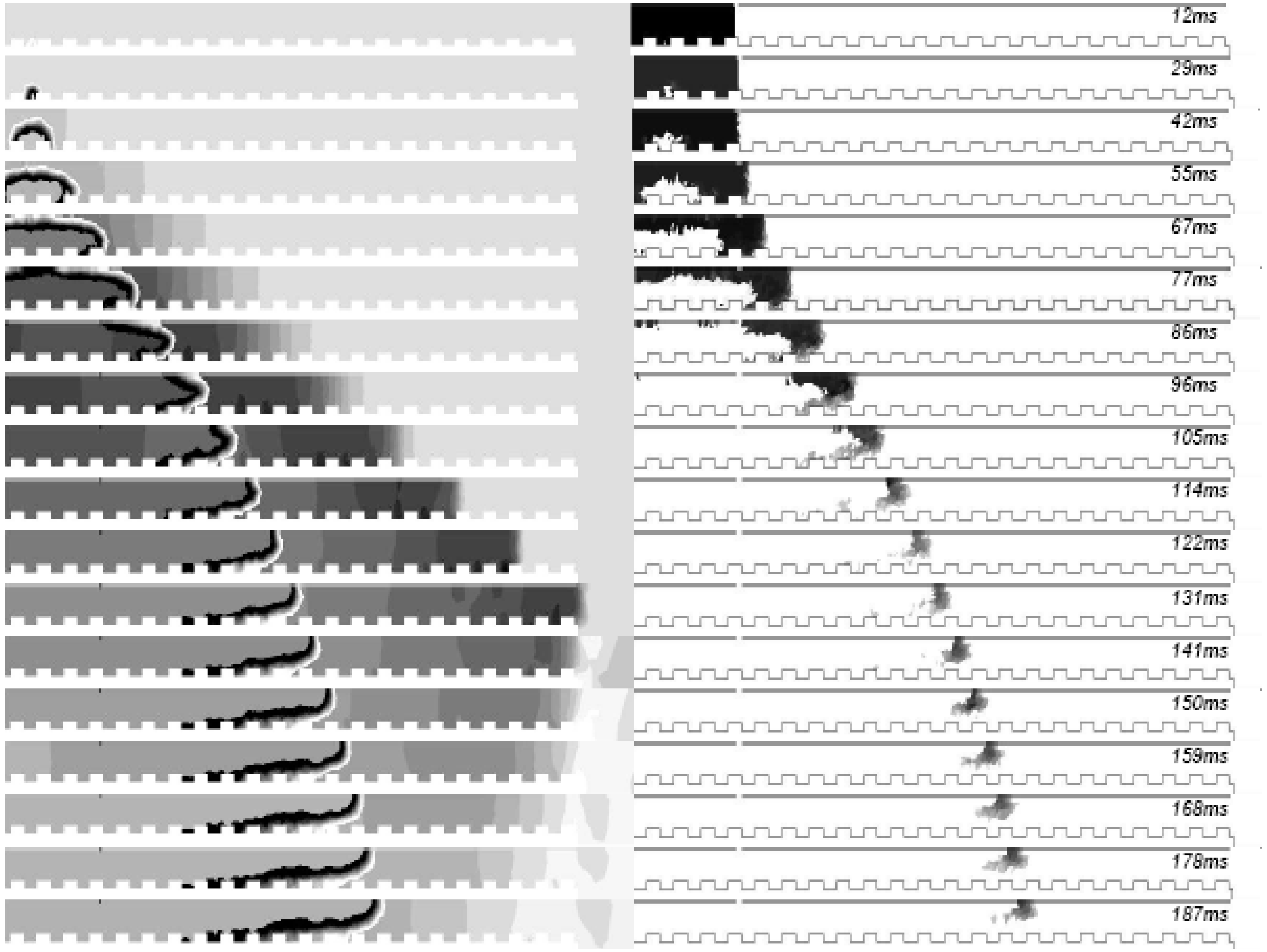
Ignition at the centre of the tunnel

H_2-air mixture



39.25 m (half of the tunnel)

Hydrogen-air deflagrations in a tunnel (3/6)



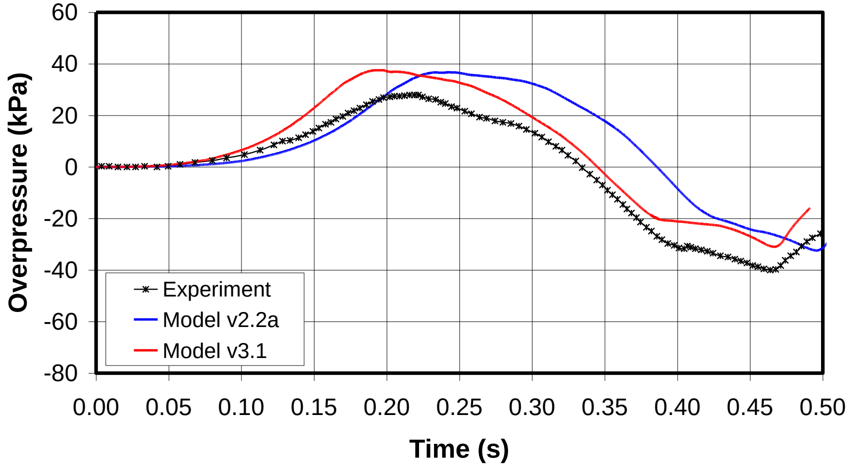
Dealing with hydrogen explosions

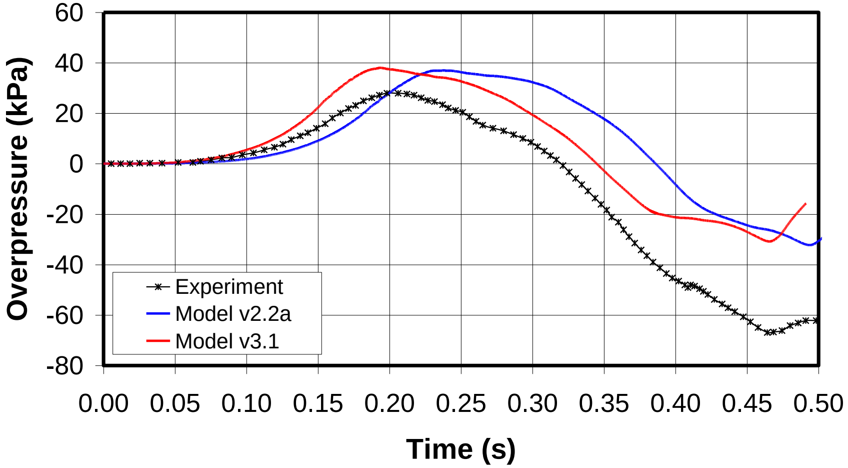
Hydrogen-air deflagrations in a tunnel (4/6)

Hydrogen-air deflagrations in a tunnel (5/6)

Example: uniform **20 vol. %** hydrogen-air mixtures of 37.4 m^3 volume (10 m long cloud)

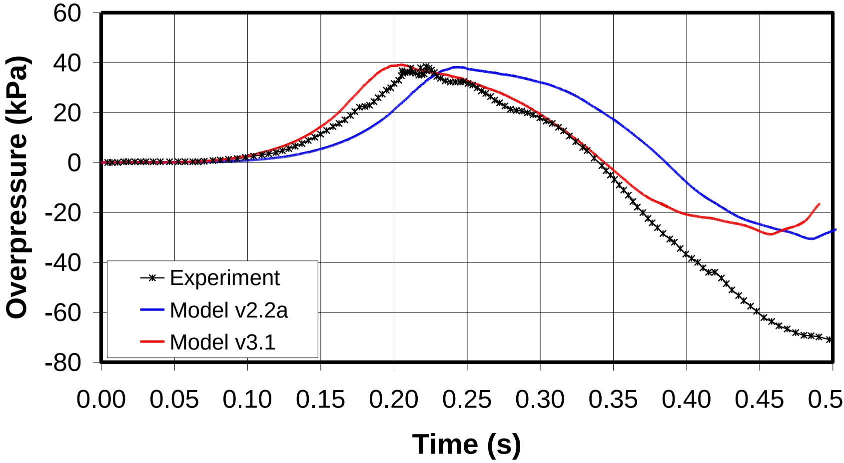
R = 1.00 m

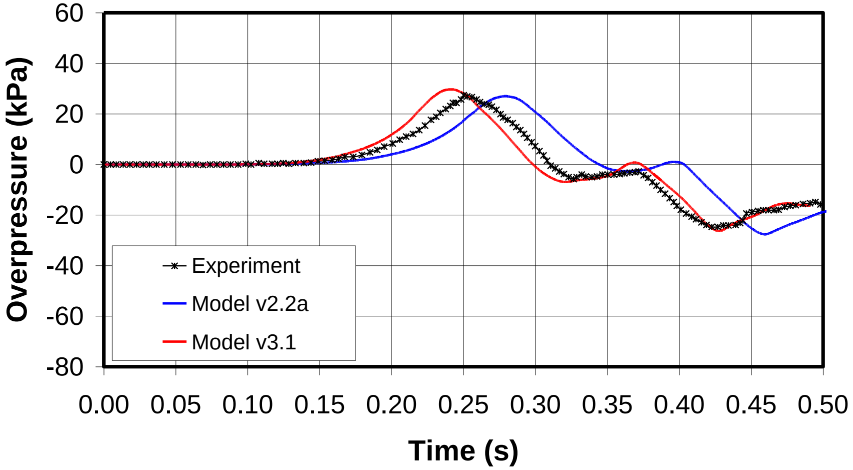




R = 3.61 m

R = 10.61 m





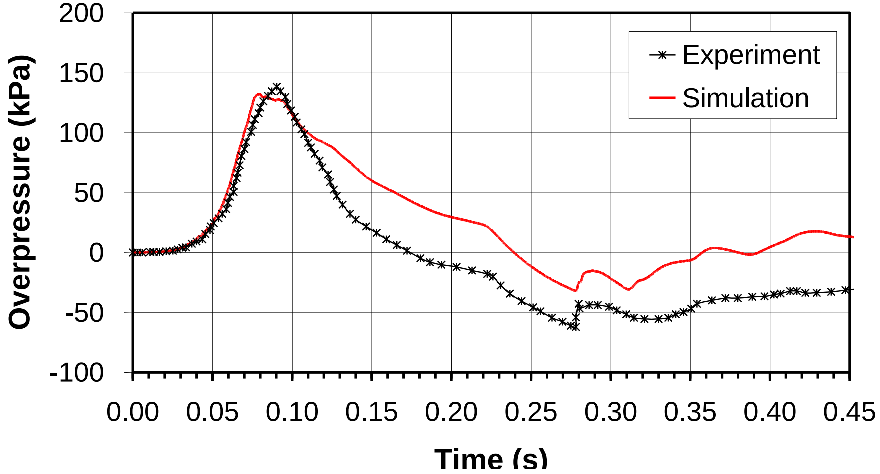
R = 30.40 m

Dealing with hydrogen explosions

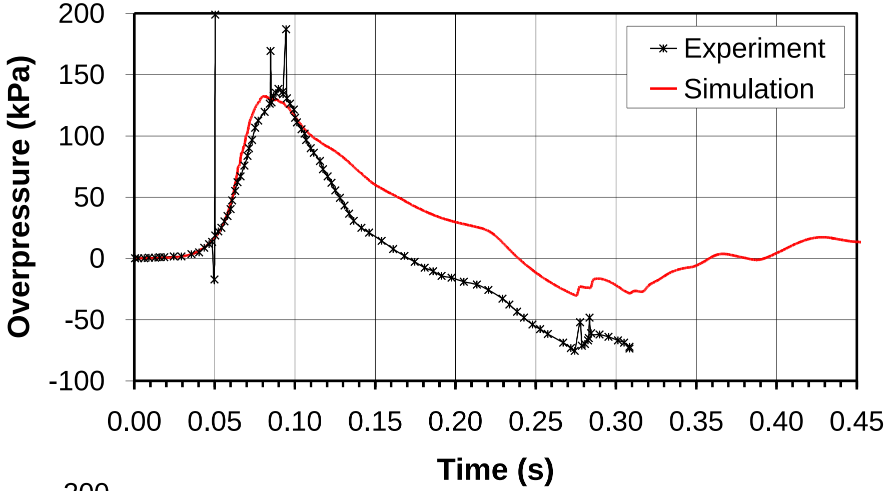
Hydrogen-air deflagrations in a tunnel (6/6)

30 vol. % hydrogen-air mixture deflagration, with obstacles

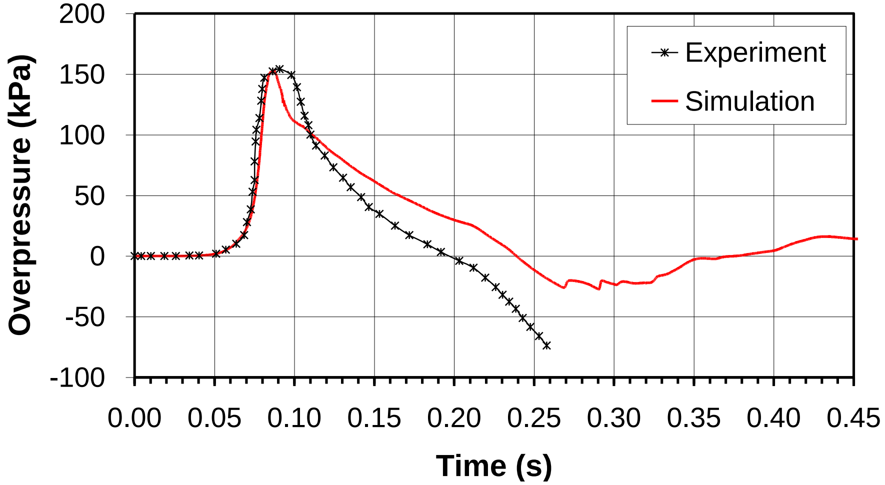
R = 1.00 m



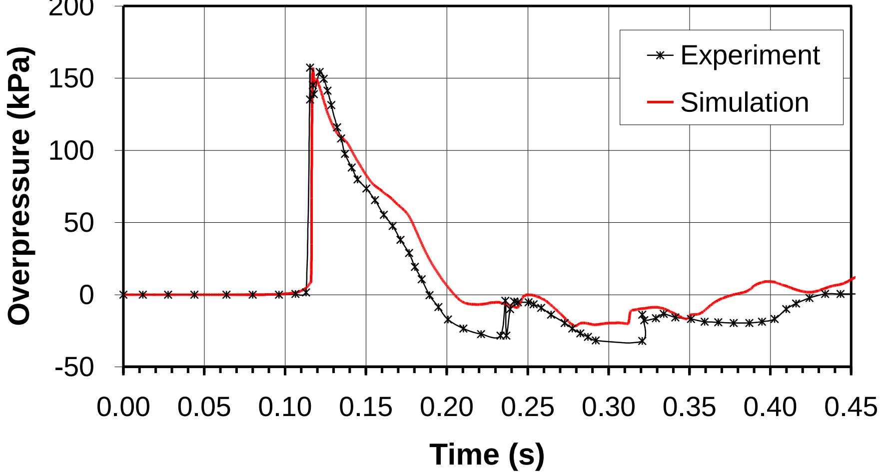
R = 3.61 m



R = 10.61 m



R = 30.40 m

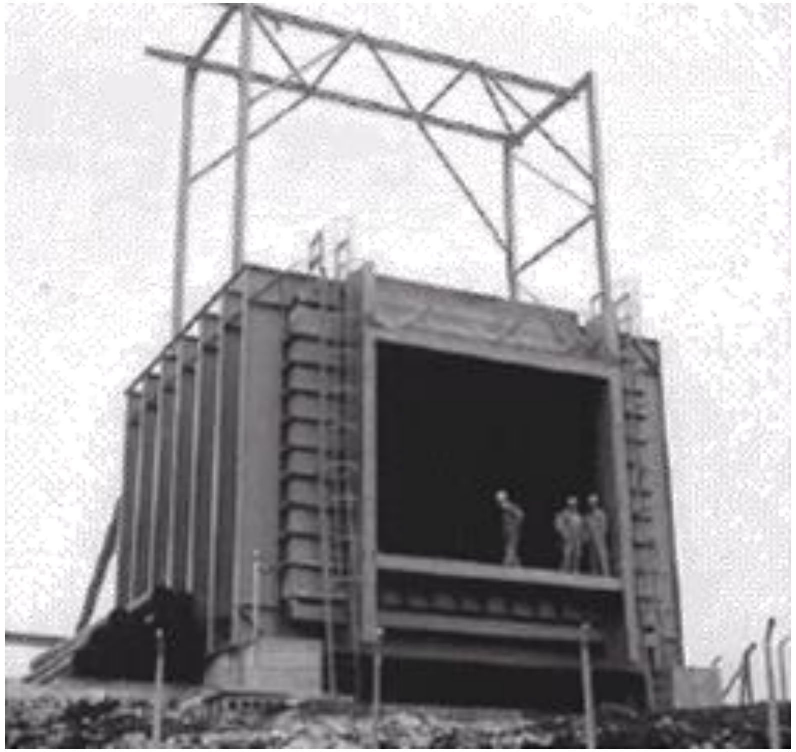


Dealing with hydrogen explosions

Deflagration venting

- Deflagration venting is the most widespread and cost-effective “explosion” mitigation technique.
- It reduces deflagration-incurred pressure to an acceptable level by venting gases out of an enclosure through a vent or number of vents of sufficient area during the deflagration. Design of explosion vents may be based on the vent sizing correlations or application of the computational fluid dynamics (CFD).

SOLVEX methane-air deflagration



- Puttock et al., 1996

- The 547-m^3 volume SOLVEX facility
  - Vessel size H × W × L = 6.25 × 8.75 × 10.0 m
  - Vent size H × W = 4.66 × 5.86 m in the centre of the wall
- 10.5% methane-air mixture
- Ignition at the centre of the rear wall
- Initially quiescent mixture, no special agitation of air in the surrounding atmosphere before ignition
- The repeatability of experiments was excellent

Dealing with hydrogen explosions

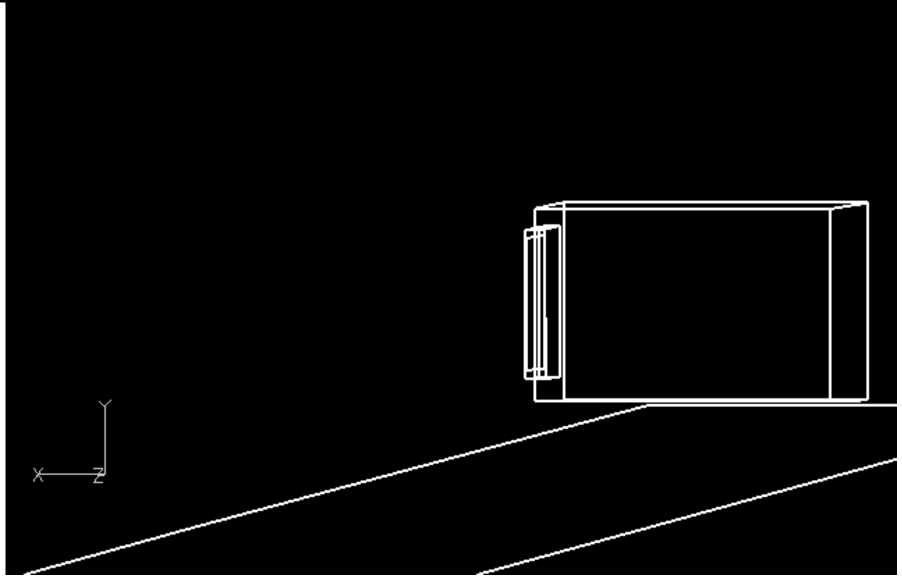
The nature of coherent deflagrations (1/2)

Shell 3

Shell 4

Ulster LES model

LES of SOLVEX



https://www.youtube.com/watch?v=HAGz636uWRw&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=5

https://www.youtube.com/watch?v=wivmrxetAvQ&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=4

https://www.youtube.com/watch?v=Q2wCXfvNr9Y&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=2

The nature of coherent deflagrations (2/2)

- The **formation of the starting turbulent vortex** in the flammable mixture outside the enclosure is a **prerequisite** for a turbulent combustion intensification outside the enclosure.
- The **rapid** increase of the burning rate outside the enclosure commences after the flame front reaches the **edges** of the vent.
- The coherent steep pressure rise is observed both inside and outside the enclosure. The pressure rise in the atmosphere is a direct consequence of the highly turbulent deflagration outside the enclosure. At the same time there is **no** increase of the burning rate **inside** the enclosure.
- The pressure rise **inside** the enclosure is **caused** by the decrease of **mass flow rate** from the enclosure to the atmosphere due to the decrease of pressure drop at the vent as a result of intensive combustion of emerged flammable mixture in the atmosphere in front of the vent.

Vented deflagration (1/3)

Experiment:

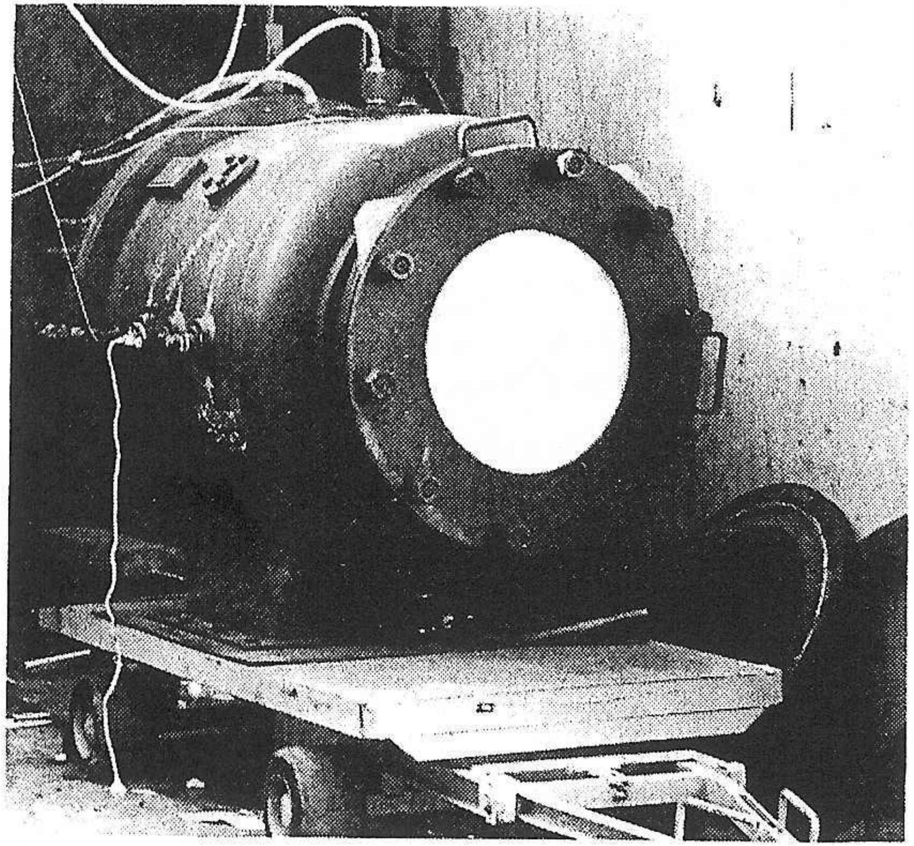
Pasman H.J., et al (1974) Design of Pressure Relief Vents, pp.185-189.

Cylindrical vessel: L×D=1.50×0.97 m, 0.95 m^3

Vents: 0.3 m^2 (∅=0.62 m) and 0.2 m^2 (∅=0.50 m)

Vent relief overpressure: 13.5 kPa (∅=0.62 m),
7.5 kPa (∅=0.5 m)

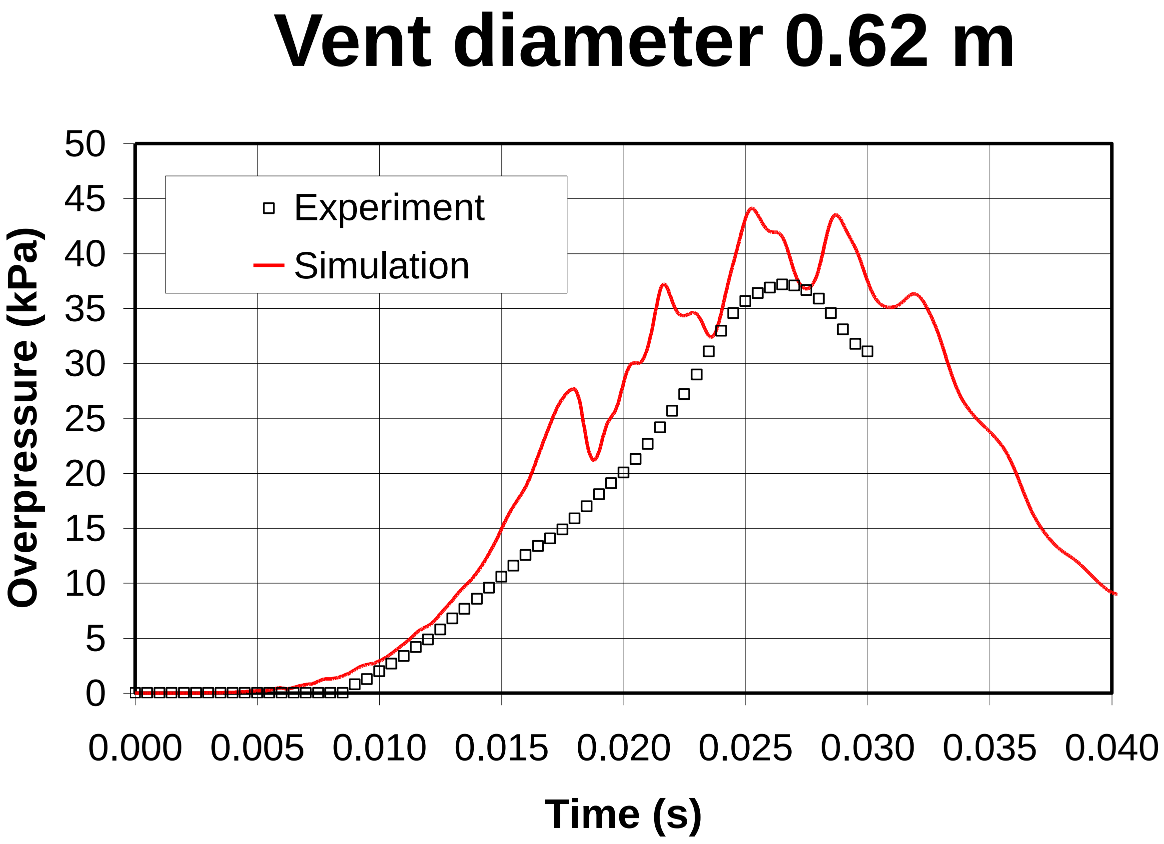
C_{H2}=29.6% (vol.), central ignition,
quiescent mixture,
p_0=101.8 kPa, T_{u0}=281 K.



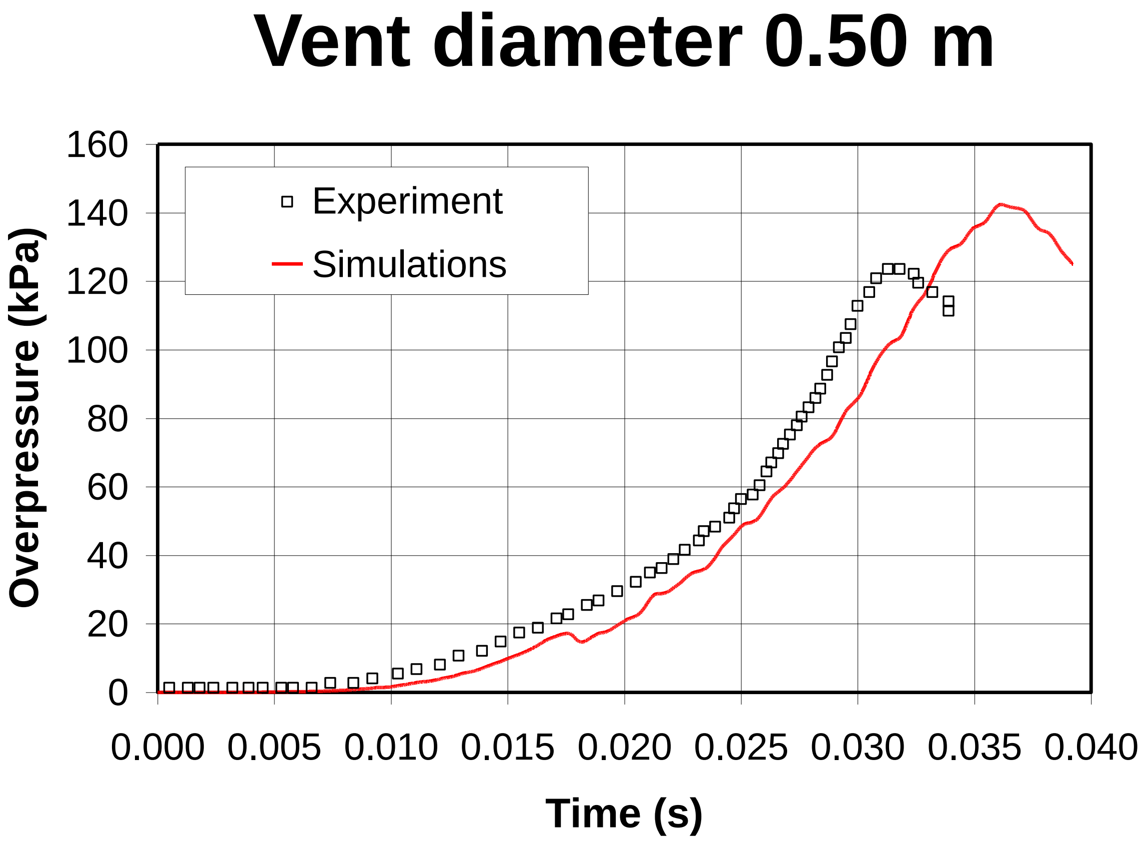
Simulations:
S_{ui}=1.73 m/s, m_0=1.7, e=0.57
ψ=0.5, R^*=1.2 m, Ξ_K=1.7, Ξ_{lp}=1.28
$\Delta x_{CV} \approx$0.045 m, total CV number 159,000

Dealing with hydrogen explosions

Vented deflagration (2/3)



Vent diameter 0.62 m



Vent diameter 0.50 m

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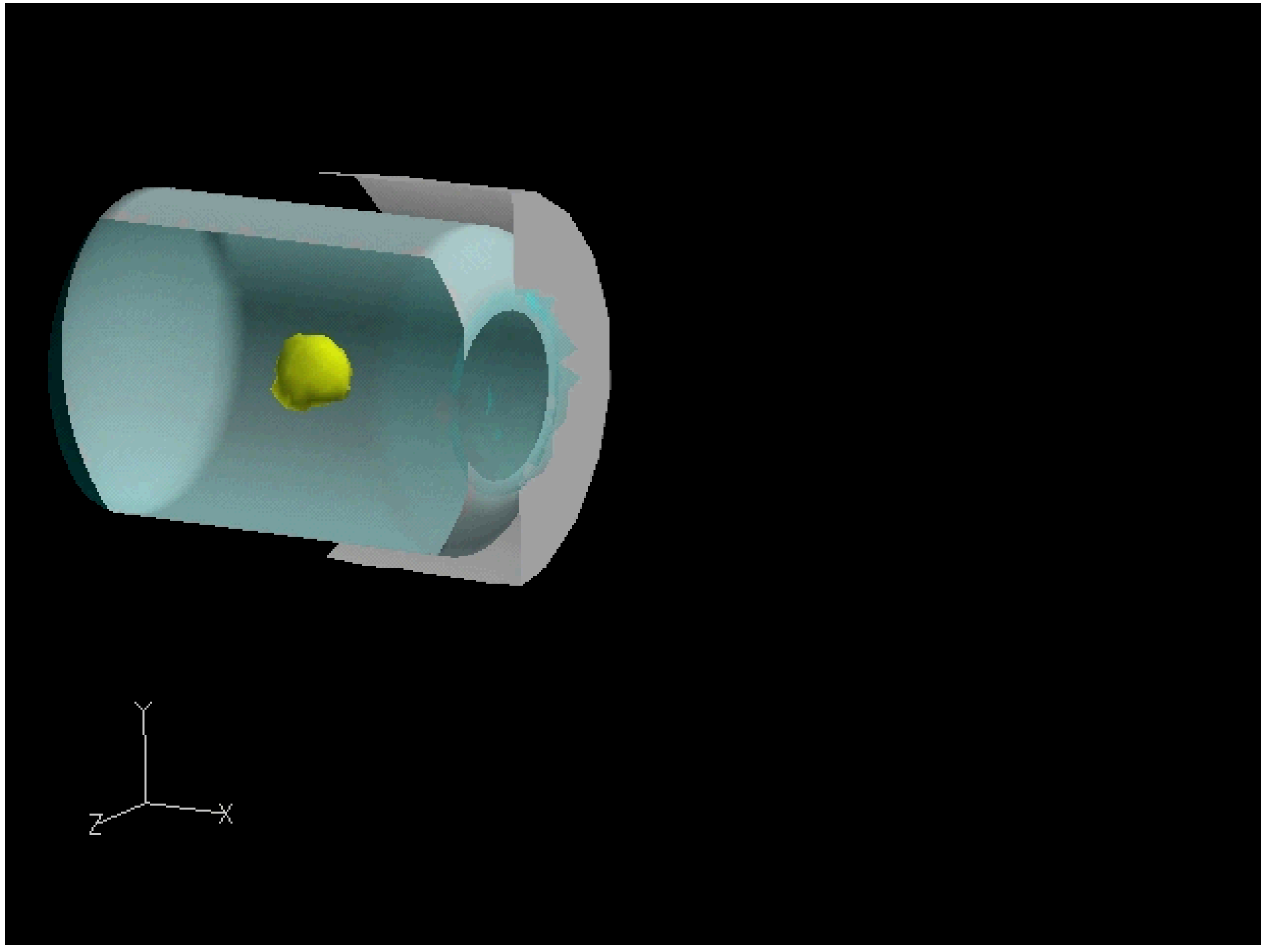
Vented deflagration (3/3)

Simulation, vent diameter 0.50 m



https://www.youtube.com/watch?v=F8fW3Oz_Ke0&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=1

Dealing with hydrogen explosions

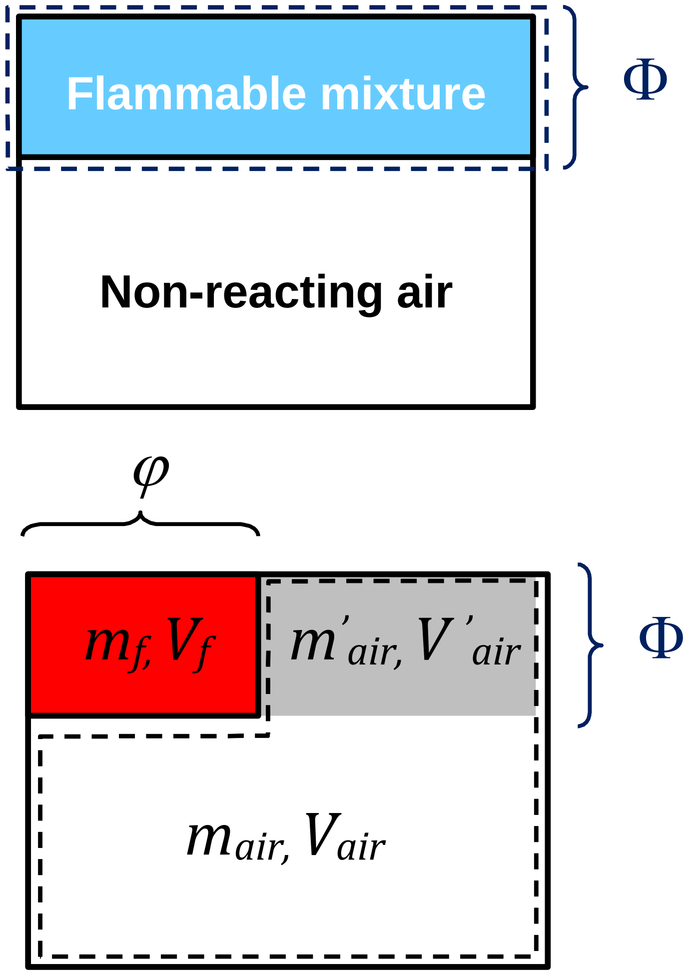
Localised hydrogen-air deflagration (1/3)

- **Closed vessel deflagration**

○ **Limitation of hydrogen inventory** (stored hydrogen mass) is one of safety strategies for indoor use of hydrogen.

○ Upper limit of hydrogen inventory may be defined using 10 kPa overpressure as a criterion for minor damage (such as windows breakage, etc.).

○ A model to find the hydrogen inventory limit for use in poorly ventilated enclosures was developed and validated against HyIndoor project.



Localised hydrogen-air deflagration (2/3)

- **Closed vessel deflagration**

○ The lowest hydrogen inventory, which provided 0.1 atm overpressure, was obtained for H_2 vol. fraction in the mixture (LFL) $\varphi=0.04$ and vol. fraction of mixture in enclosure $\Phi=0.0786$, giving total H_2 vol. fraction in a sealed enclosure $(\Phi \cdot \varphi) = 3.14 \times 10^{-3}$ - smaller than LFL of 0.04! – or 0.261 g of hydrogen per 1 m^3 of enclosure volume

○ **Safety strategy example:** for 10,000 m^3 warehouse allowable H_2 mass not to exceed 10 kPa overpressure is $m_{H2}=2.62$ kg

Dealing with hydrogen explosions

Localised hydrogen-air deflagration (3/3)

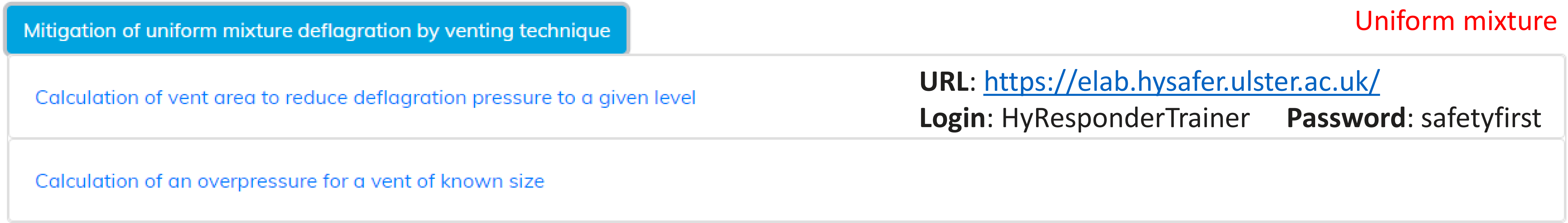
- **Vented deflagration**

- Where inventory is larger than the specified limit 0.261 g H_2/m^3, the use of other mitigation techniques should be considered (natural/forced ventilation to exclude flammable mixture formation, deflagration venting, etc.).
- It is expected that venting of partial-volume or stratified mixture deflagrations should be easier than that of full-volume explosions due to lower amount of hydrogen.
- For the same amount of hydrogen deflagrations of non-uniform layered mixtures can generate overpressure above that for uniform mixture deflagration: maximum overpressure depends strongly on portion of mixture with largest burning velocity (i.e. largest hydrogen concentration in case of lean mixtures).
- Method to calculate the vent area to avoid destructive overpressure in case of localized mixture deflagration was described and validated within HyIndoor project.

Dealing with hydrogen explosions

Venting of deflagration – e-Laboratory (1/2)

Uniform mixture



Mitigation of uniform mixture deflagration by venting technique

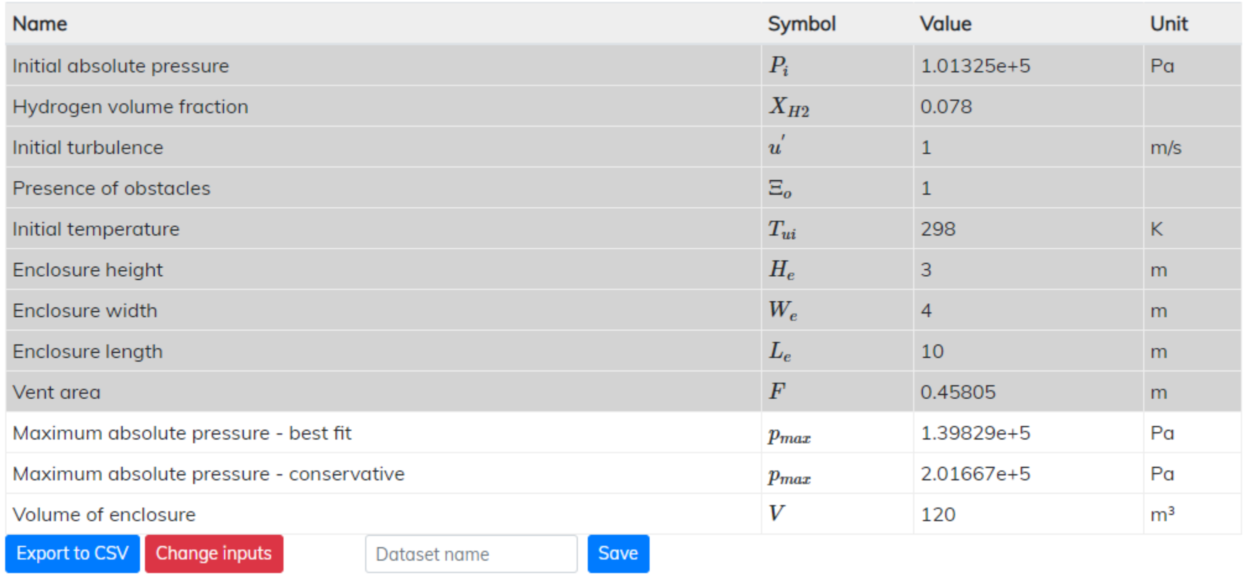
Calculation of vent area to reduce deflagration pressure to a given level

Calculation of an overpressure for a vent of known size

URL: https://elab.hysafer.ulster.ac.uk/

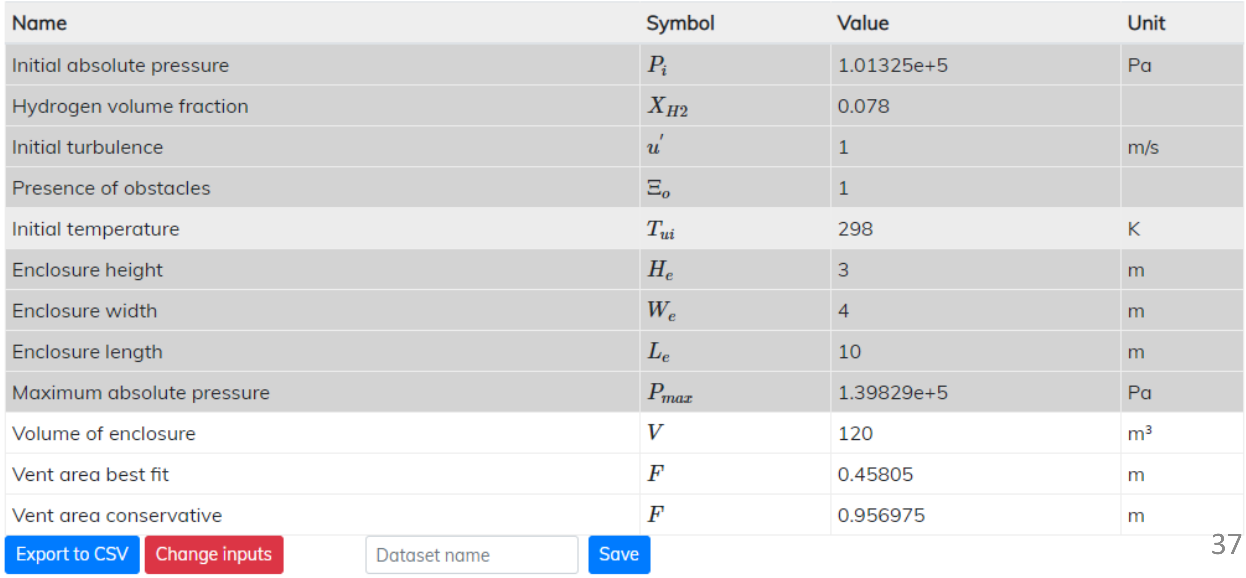
Login: HyResponderTrainer **Password**: safetyfirst

Maximum pressure for a given vent area



Name	Symbol	Value	Unit
Initial absolute pressure	P_i	1.01325e+5	Pa
Hydrogen volume fraction	X_{H2}	0.078	
Initial turbulence	u'	1	m/s
Presence of obstacles	Ξ_o	1	
Initial temperature	T_{ui}	298	K
Enclosure height	H_e	3	m
Enclosure width	W_e	4	m
Enclosure length	L_e	10	m
Vent area	F	0.45805	m
Maximum absolute pressure - best fit	p_{max}	1.39829e+5	Pa
Maximum absolute pressure - conservative	p_{max}	2.01667e+5	Pa
Volume of enclosure	V	120	m³

Required vent area to a given pressure

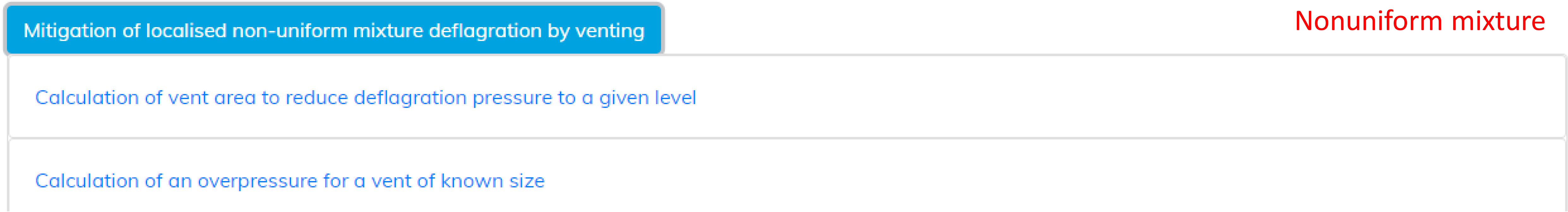


Name	Symbol	Value	Unit
Initial absolute pressure	P_i	1.01325e+5	Pa
Hydrogen volume fraction	X_{H2}	0.078	
Initial turbulence	u'	1	m/s
Presence of obstacles	Ξ_o	1	
Initial temperature	T_{ui}	298	K
Enclosure height	H_e	3	m
Enclosure width	W_e	4	m
Enclosure length	L_e	10	m
Maximum absolute pressure	P_{max}	1.39829e+5	Pa
Volume of enclosure	V	120	m³
Vent area best fit	F	0.45805	m
Vent area conservative	F	0.956975	m

Dealing with hydrogen explosions

Venting of deflagration – e-Laboratory (2/2)

Nonuniform mixture

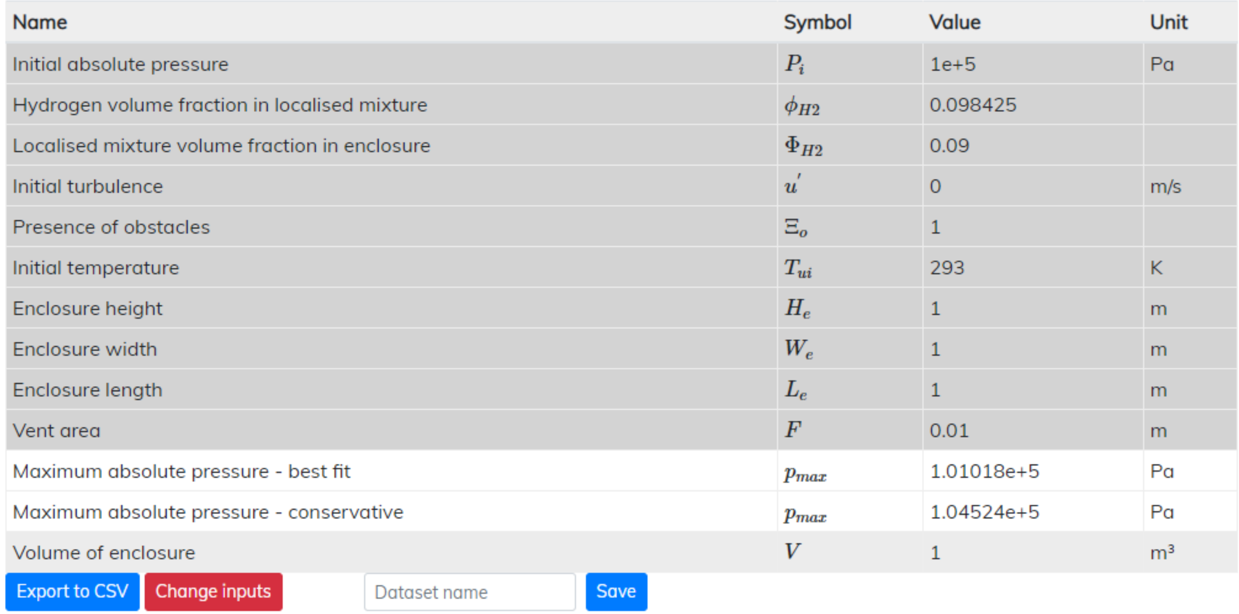


Mitigation of localised non-uniform mixture deflagration by venting

Calculation of vent area to reduce deflagration pressure to a given level

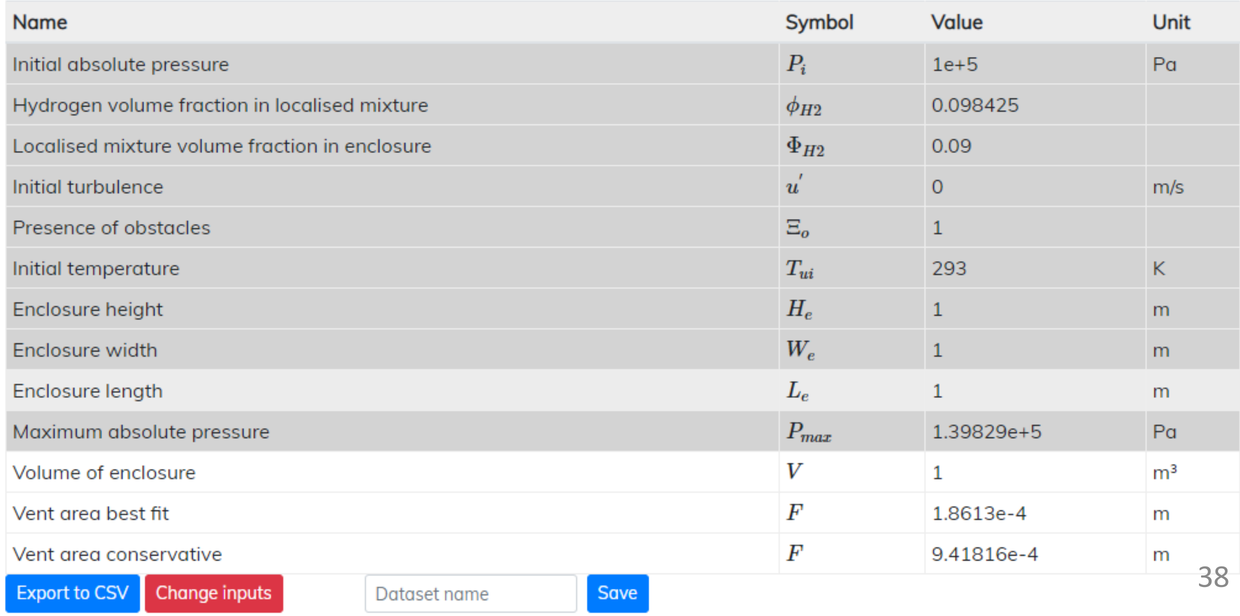
Calculation of an overpressure for a vent of known size

Maximum pressure for a given vent area



Name	Symbol	Value	Unit
Initial absolute pressure	P_i	1e+5	Pa
Hydrogen volume fraction in localised mixture	ϕ_{H2}	0.098425	
Localised mixture volume fraction in enclosure	Φ_{H2}	0.09	
Initial turbulence	u'	0	m/s
Presence of obstacles	Ξ_o	1	
Initial temperature	T_{ui}	293	K
Enclosure height	H_e	1	m
Enclosure width	W_e	1	m
Enclosure length	L_e	1	m
Vent area	F	0.01	m
Maximum absolute pressure - best fit	p_{max}	1.01018e+5	Pa
Maximum absolute pressure - conservative	p_{max}	1.04524e+5	Pa
Volume of enclosure	V	1	m³

Required vent area to a given pressure



Name	Symbol	Value	Unit
Initial absolute pressure	P_i	1e+5	Pa
Hydrogen volume fraction in localised mixture	ϕ_{H2}	0.098425	
Localised mixture volume fraction in enclosure	Φ_{H2}	0.09	
Initial turbulence	u'	0	m/s
Presence of obstacles	Ξ_o	1	
Initial temperature	T_{ui}	293	K
Enclosure height	H_e	1	m
Enclosure width	W_e	1	m
Enclosure length	L_e	1	m
Maximum absolute pressure	P_{max}	1.39829e+5	Pa
Volume of enclosure	V	1	m³
Vent area best fit	F	1.8613e-4	m
Vent area conservative	F	9.41816e-4	m

Dealing with hydrogen explosions

Deflagration-to-Detonation Transition (DDT)

- Hydrogen is prone to the deflagration-to-detonation transition (DDT). DDT can happen in different environments, including tubes, enclosures, etc.
- The experimentally observed run-up distance for transition from deflagration-to-detonation (DDT) in stoichiometric hydrogen-air mixture in a tube has typical length to diameter ratio of approximately 100.
- The presence of obstacles in a tube increases a flame front area and reduces run-up distance for DDT.
- The DDT phenomenon is still one of the challenging subjects for combustion research.
- The initiation of detonation during DDT is thought to happen in a so-called hot spot(s), which potentially could be located within the turbulent flame brush or ahead of it, e.g. in a focus of a strong shock reflection

DDT in hydrogen-air mixtures

- DDT was observed in a large-scale test carried out by Pfortner and Schneider (1984) in Fraunhofer ICT (see **video in slide 44**). The experimental set up included a “lane” (2 parallel walls 3 m apart with height 3 m and length 12 m) and an enclosure (driver section) of sizes L × W × H = 3.0 × 1.5 × 1.5 m (6.75 m^3 volume) with an initially open to the “lane” vent of 0.82 × 0.82 m.

- The “lane” and the enclosure were filled with the mixture kept under a plastic film. Venting of hydrogen-air deflagration (initiated at the rear wall of the enclosure by five ignitors) into the partially confined space simulating a “lane” resulted in DDT.

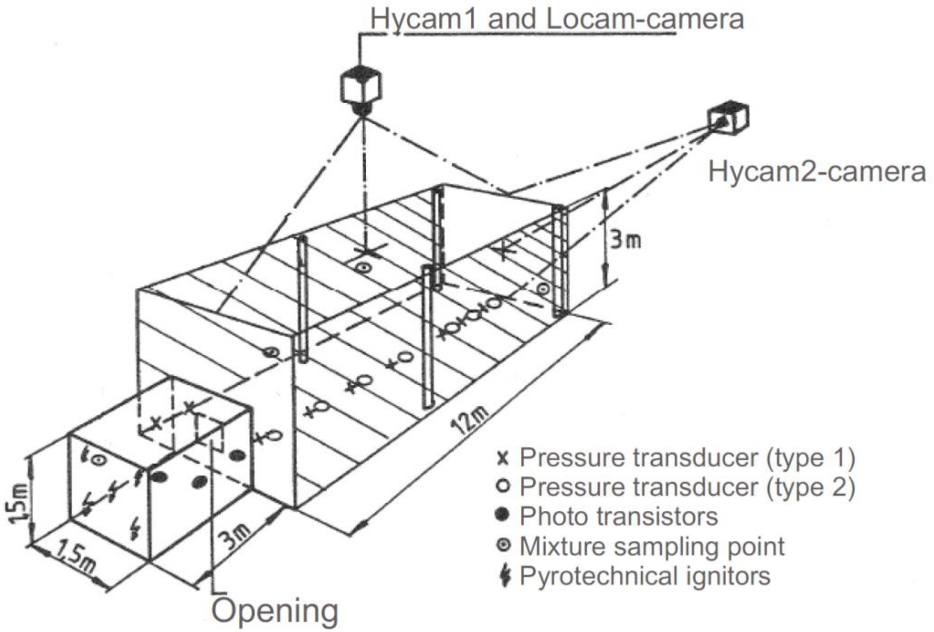
- DDT occurred 54.61 ms after ignition in the “lane” when the accelerated flame from the driver touched the ground.

Dealing with hydrogen explosions

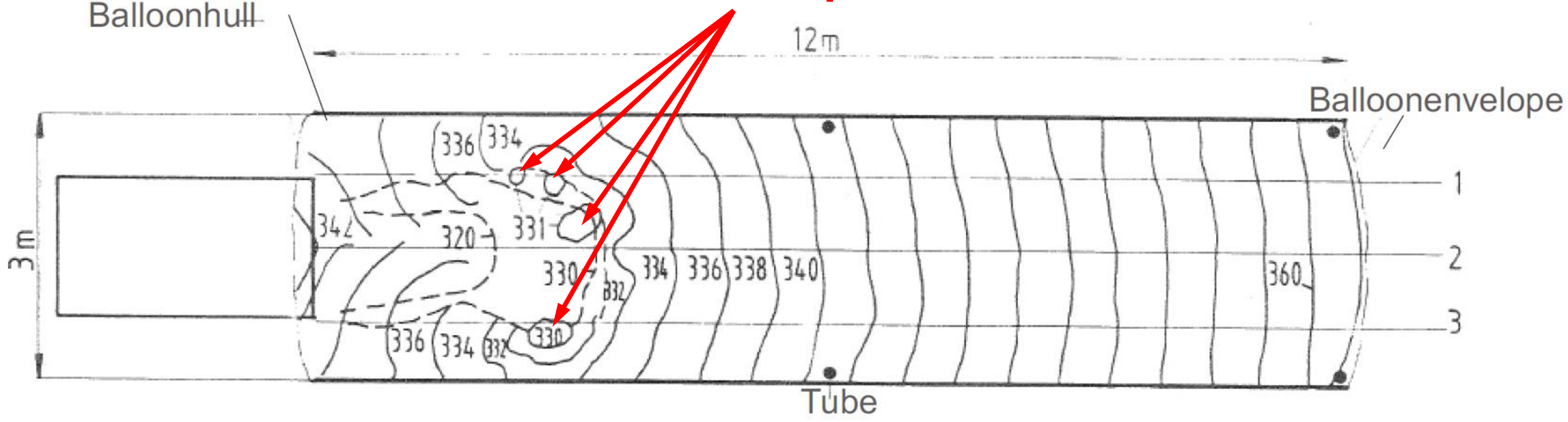
DDT in a “lane”

- Fh-ICT experiment IA4 (1984)

- 22% hydrogen-air mixture
- 3.0 × 1.5 × 1.5 m “driver” section
- 12.0 × 3.0 × 3.0 m “lane”

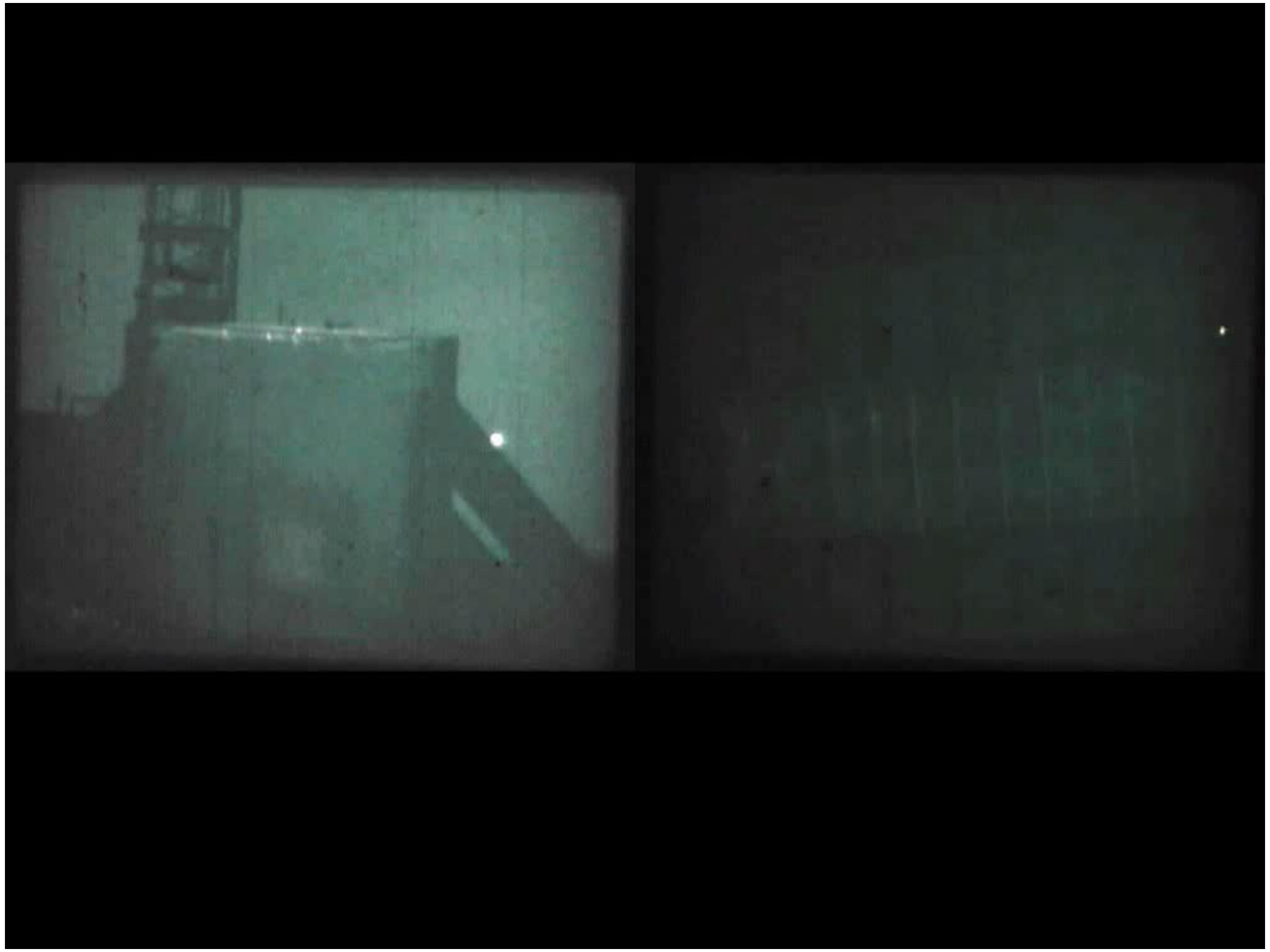


DDT in hot spots



Dealing with hydrogen explosions

Video of DDT in a “lane”



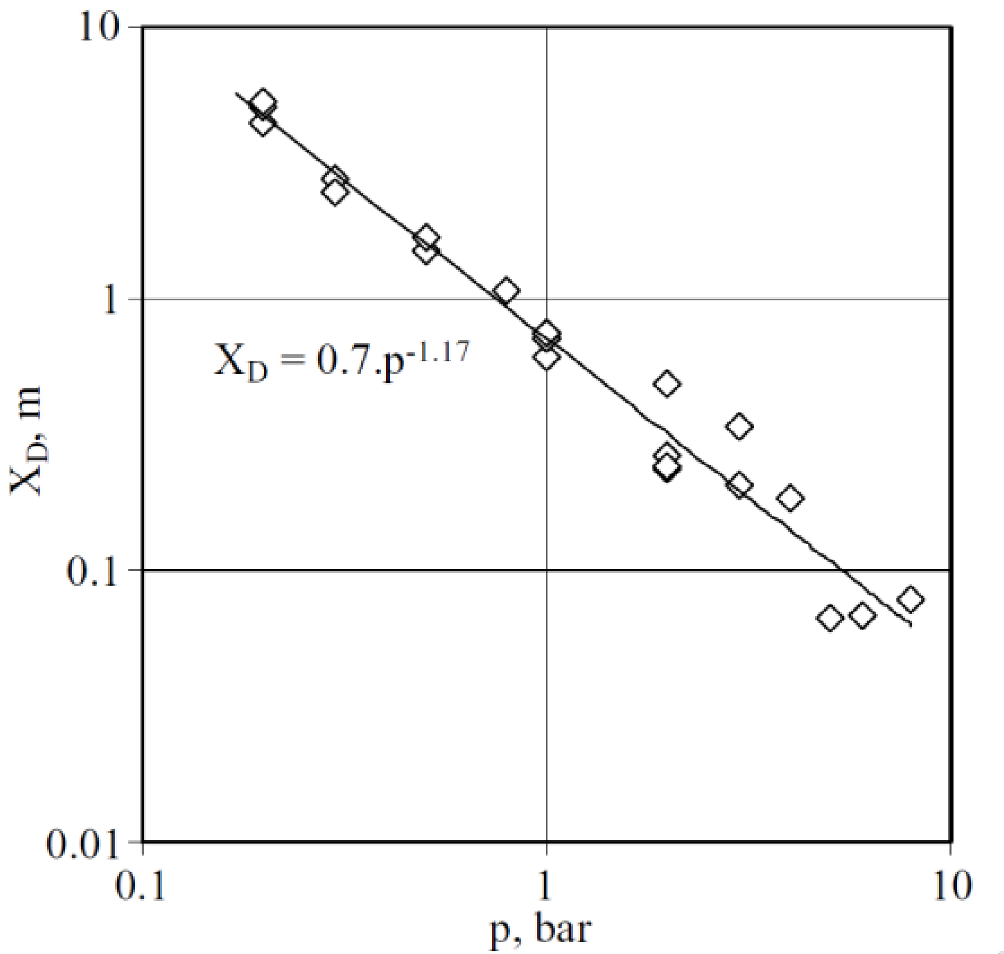
https://www.youtube.com/watch?v=f54TxnwFlcY&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=8

Deflagration-to-Detonation Transition (DDT)

- Deflagration can transit to detonation after a flame travelled some time and some distance.
- Flame speed exceeds the speed of sound at the onset of DDT.
- Generates a large pressure spike at DDT somewhere in the region of 3.0 MPa.
- DDT can occur in:
  - Highly-confined regions
  - Highly-congested regions
- Different physical mechanism involved for a high speed flame.
- DDT is not a continuous process but rather a step-wise change.

The run-up distance to DDT (smooth tubes)

- The distance from the ignition point to the location of DDT, i.e. **run-up distance** X_D, decreases with the increase of pressure. At the initial pressure of 1 bar it is about 70 cm and at pressure of 5 bar it is about 7 cm (correlation for X_D is applicable to empty tubes with internal diameter more than 20 detonation cell sizes, *d* > 20λ).

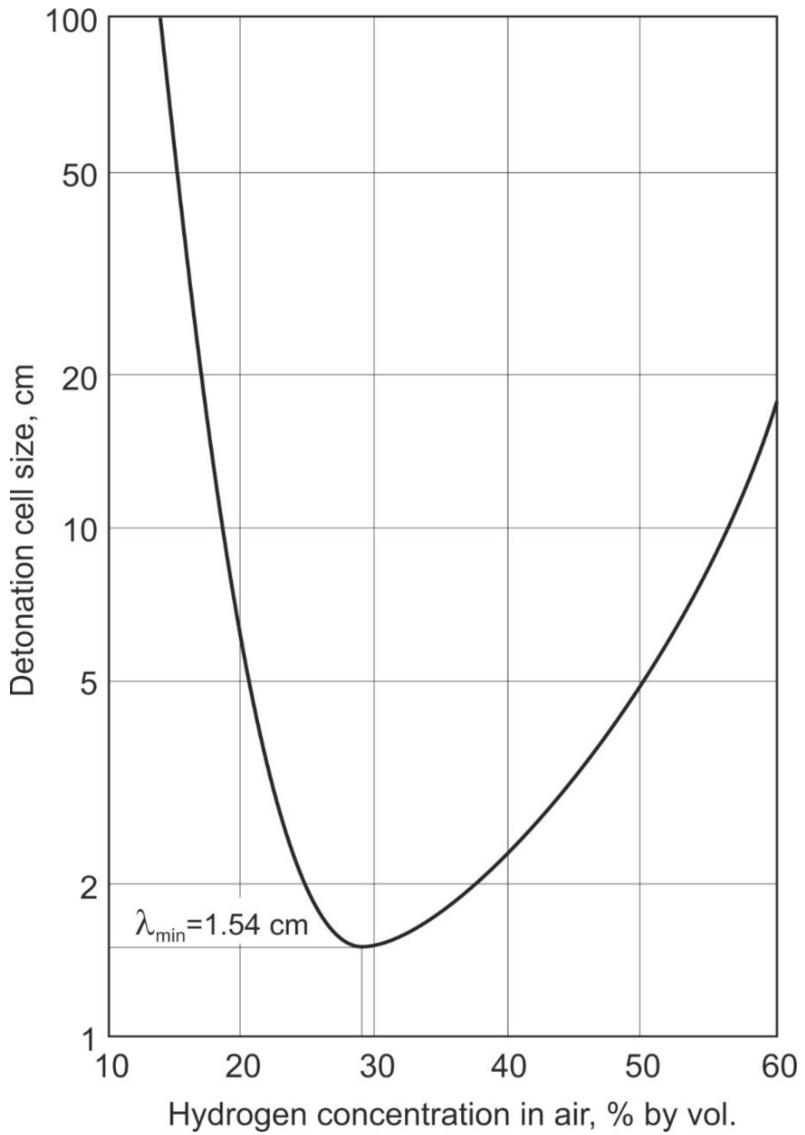


Source: Kuznetsov, M. et al . (2005). DDT in a smooth tube filled with a hydrogen-oxygen mixture. Shock Waves, 14(3):205-215.

Dealing with hydrogen explosions

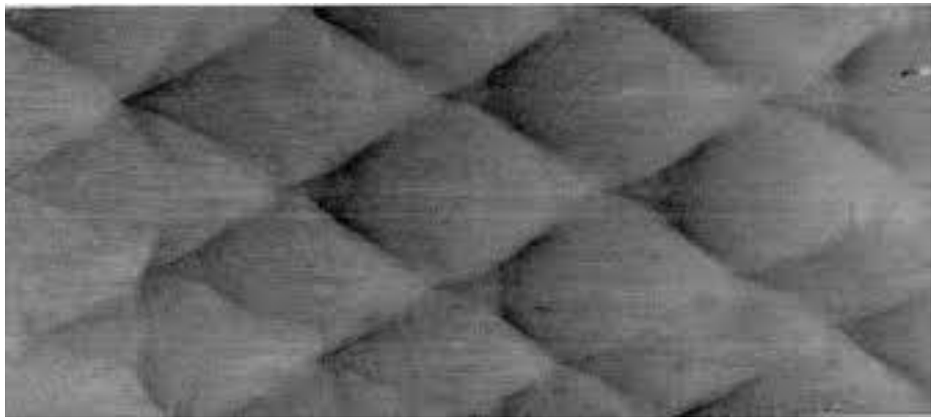
Detonation cell size

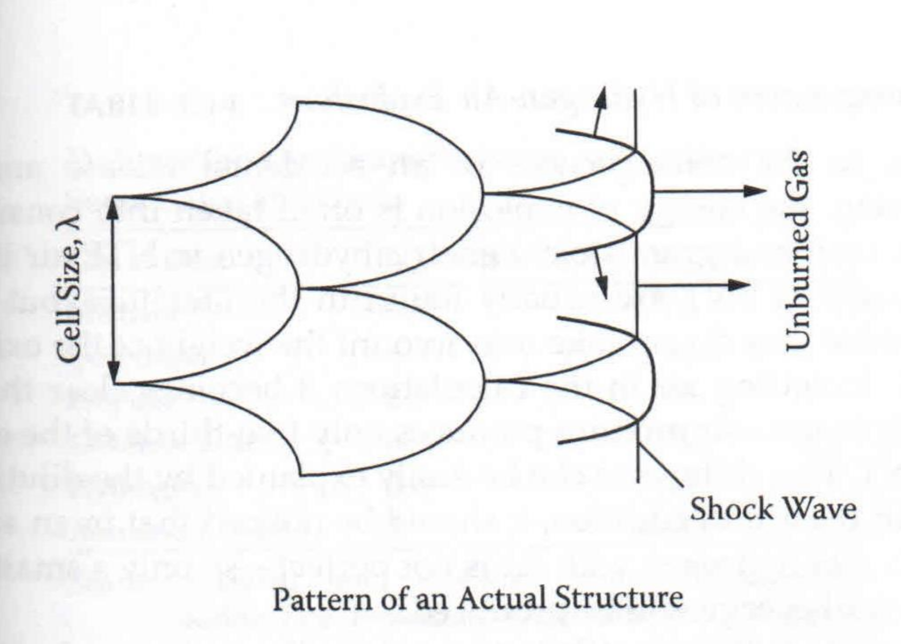
- The **detonation cell size**, λ, is a measure of reactivity of a fuel-oxidizer mixture. The wave front is not planar and composed of reaction cells (see next slide).
- A detonation wave has a complex 3D structure with a characteristic fish-scale pattern.
- Highly reactive mixtures such as acetylene-air or hydrogen-oxygen have very small cell sizes (about 1 mm).
- Cell lengths for stoichiometric hydrogen-air and hydrogen-oxygen mixtures at 101.3 kPa are 15.4 mm and 0.6 mm, respectively.



Structure of a detonation front

- 2D illustration of the detonation front structure is given below according to Zeldovich, von Neumann and Doring (ZND) model.
- Cell size decreases with pressure increase for hydrogen-air mixtures.
- The cell width of hydrogen-air detonations increases significantly with the concentration of diluents (carbon dioxide or water).





Pattern of an Actual Structure

Source: Rigas and Amyotte, 2013

Critical tube diameter for detonation onset

Detonation may only occur if the size of a duct or mixture volume is sufficiently higher compared to λ (if supersonic flow regime is developed)

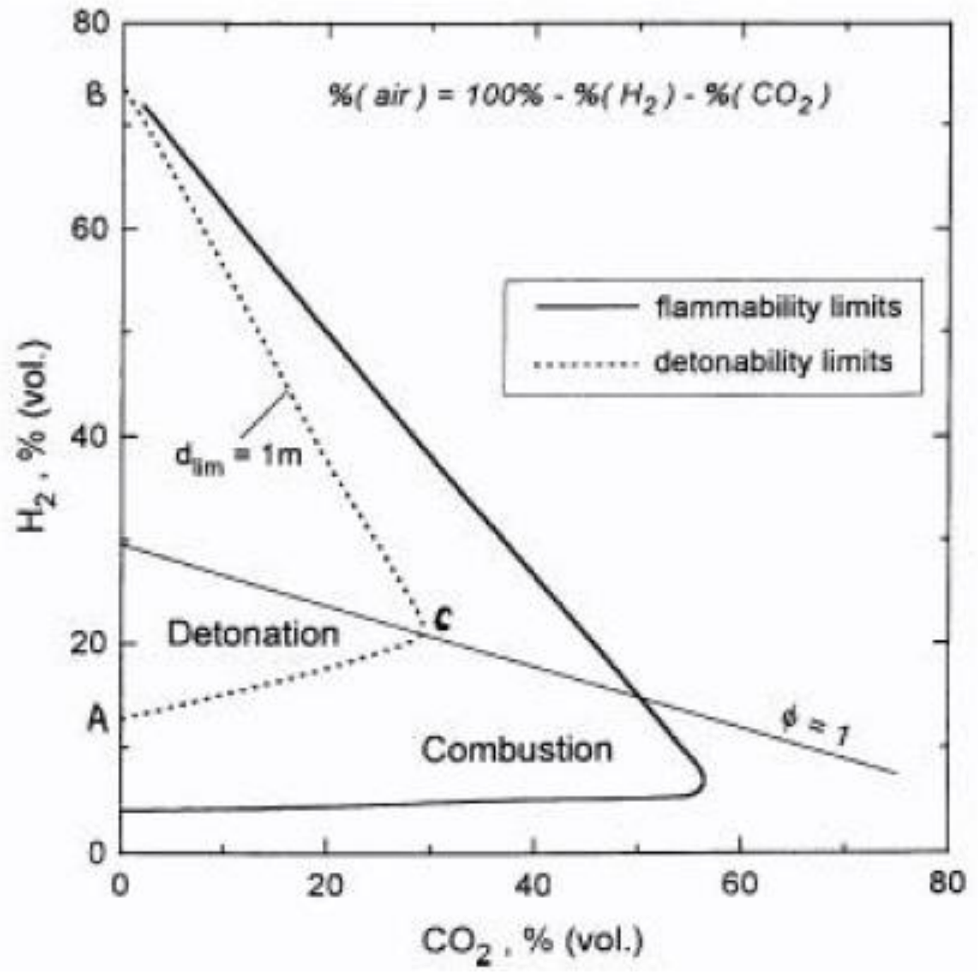
- $D>\lambda/\pi$, where D is a smooth tube internal diameter
- $d>\lambda$, where d is the transverse dimension of the unobstructed passage in a channel with obstacles
- $L>7\lambda$, where L is a more general characteristic size defined for rooms or channels
- $D_{jet}>(14\text{-}24)\lambda$, where D_{jet} refers to the jet exit diameter
- **Congested area: with stoichiometric hydrogen-air mixture DDT observed in cloud containing 4 g of hydrogen**

Factors affecting the detonability range

- The widest reported detonability range for **hydrogen-air mixtures**: 11-58.9 vol. % (Alcock et al, 2001)
- Narrower detonability limits - LDL between 13.5 and 19.0 vol. % and UDL between 61 and 70 vol. % - reflect effect of the **size of the experimental rig** where they were obtained.
- **Effect of temperature**: increase of T from 293 to 373 K leads to a **widening of detonability range**. LDL is reduced from 11.6 to 9.4 vol. %; UDL – increased from 74 to 76.9 vol.% for hydrogen-air mixtures.

Effect of diluents on detonability limits (1/3)

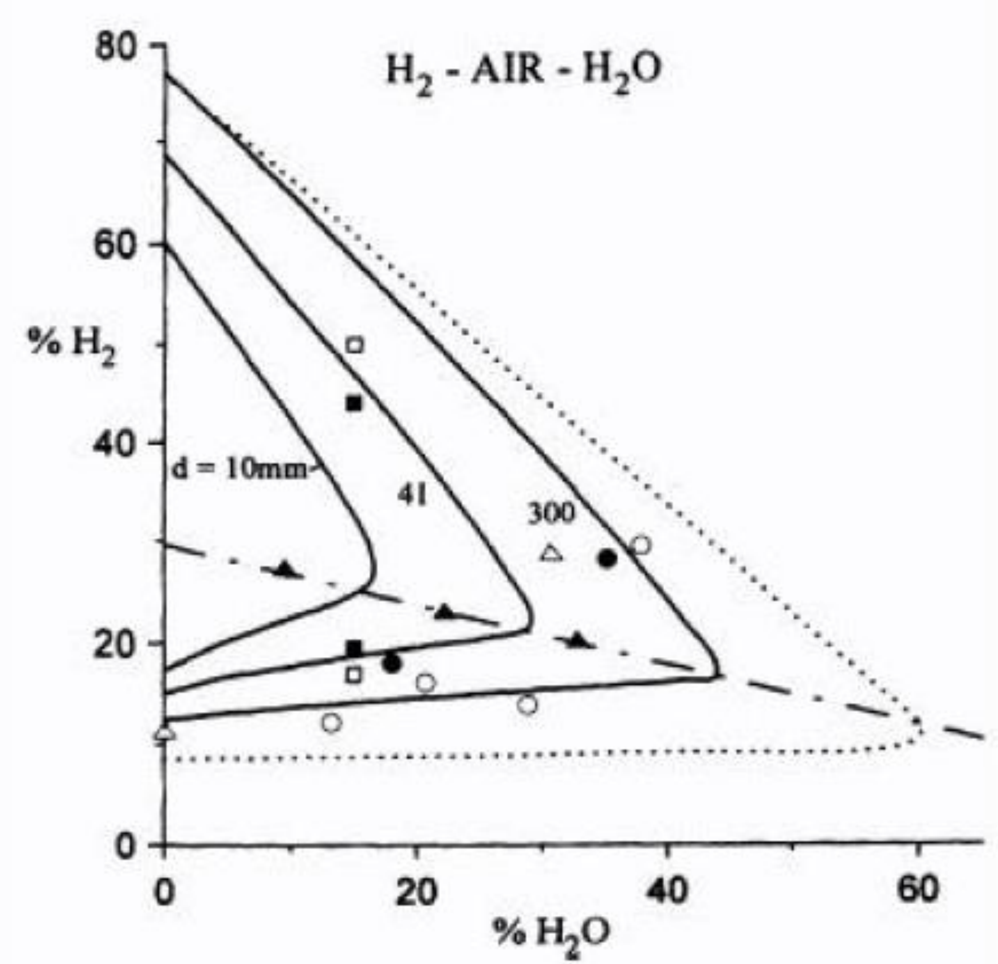
- Carbon dioxide significantly changes detonability range: it is marginally reduced in the presence of this diluent.



Source: Breitung, W et al. (2000) Flame acceleration and deflagration-to-detonation transition in nuclear society. NEA/CSNI Report No. NEA/CSNI/R(2000)7.

Effect of diluents on detonability limits (2/3)

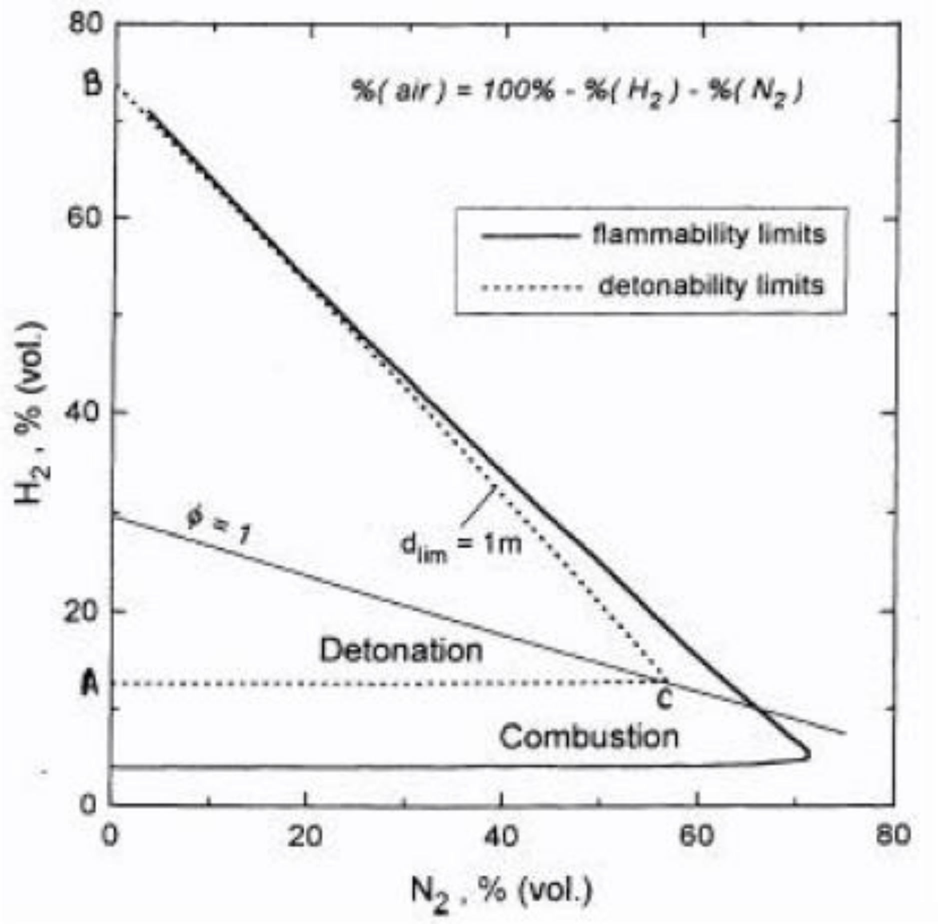
- Detonability range significantly reduced in the presence of water.
- A size of a pipe diameter also affects the detonability range.



Source: Breitung, W et al. (2000) Flame acceleration and deflagration-to-detonation transition in nuclear society. NEA/CSNI Report No. NEA/CSNI/R(2000)7.

Effect of diluents on detonability limits (3/3)

- In the presence of nitrogen upper detonability limit greatly reduces as the concentration of diluent increases.
- Both LFL and LDL remain unchanged.



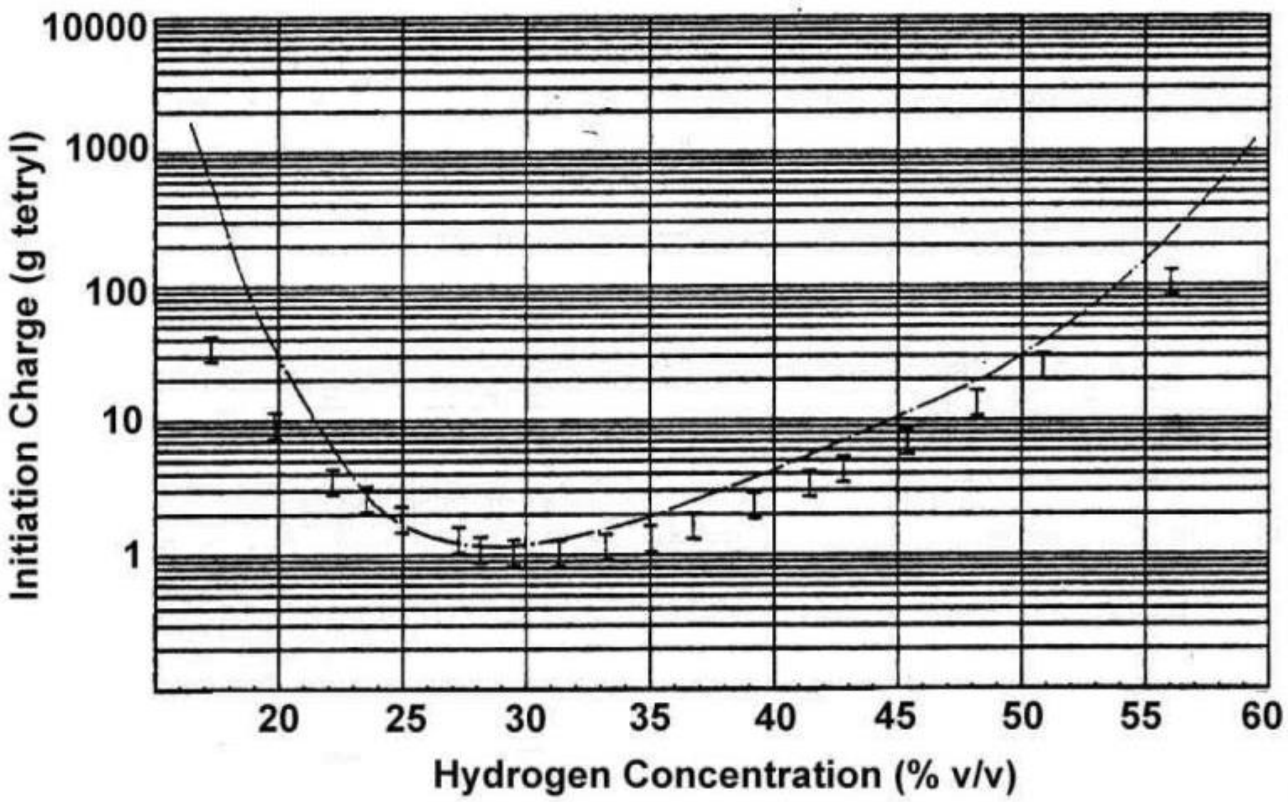
Source: Breitung, W et al. (2000) Flame acceleration and deflagration-to-detonation transition in nuclear society. NEA/CSNI Report No. NEA/CSNI/R(2000)7.

Direct initiation of detonations

- The potential for direct initiation of detonation in a hydrogen-air mixture is greater than that for hydrocarbons. The direct initiation of hydrogen-air mixture detonation is possible by 1.1 g of high explosive tetryl (BRHS, 2009). Only 1.86 g of high explosive TNT (trinitrotoluene) is needed to initiate detonation in 34.7 vol. % hydrogen-air mixture in the open atmosphere. However, for 20 vol. % hydrogen-air mixture the critical TNT charge increases significantly to 190 g (BRHS, 2009).
- For comparison, the release of energy during explosive reaction of 1 g TNT is arbitrarily standardized as 4.184 kJ (a gram of TNT releases 4.1-4.602 kJ upon explosion), and the lower heat of combustion of 1 g of hydrogen is equal to (241.7 kJ/mol / 2.016 g/mol) = 119.89 kJ. Thus, the TNT equivalent of hydrogen is high: 28.65, i.e. 28.65 g of TNT is energetic equivalent of 1 g of hydrogen (BRHS, 2009).

Initiation of detonation

- For many hydrogen-oxygen compositions with no dilution, initiation by a spark (for example,1-5 mJ) or flame source can produce a full detonation. In comparison, hydrogen-air mixture detonation requires essentially stronger initiation by at least a 1-2 g explosive charge.



Dealing with hydrogen explosions

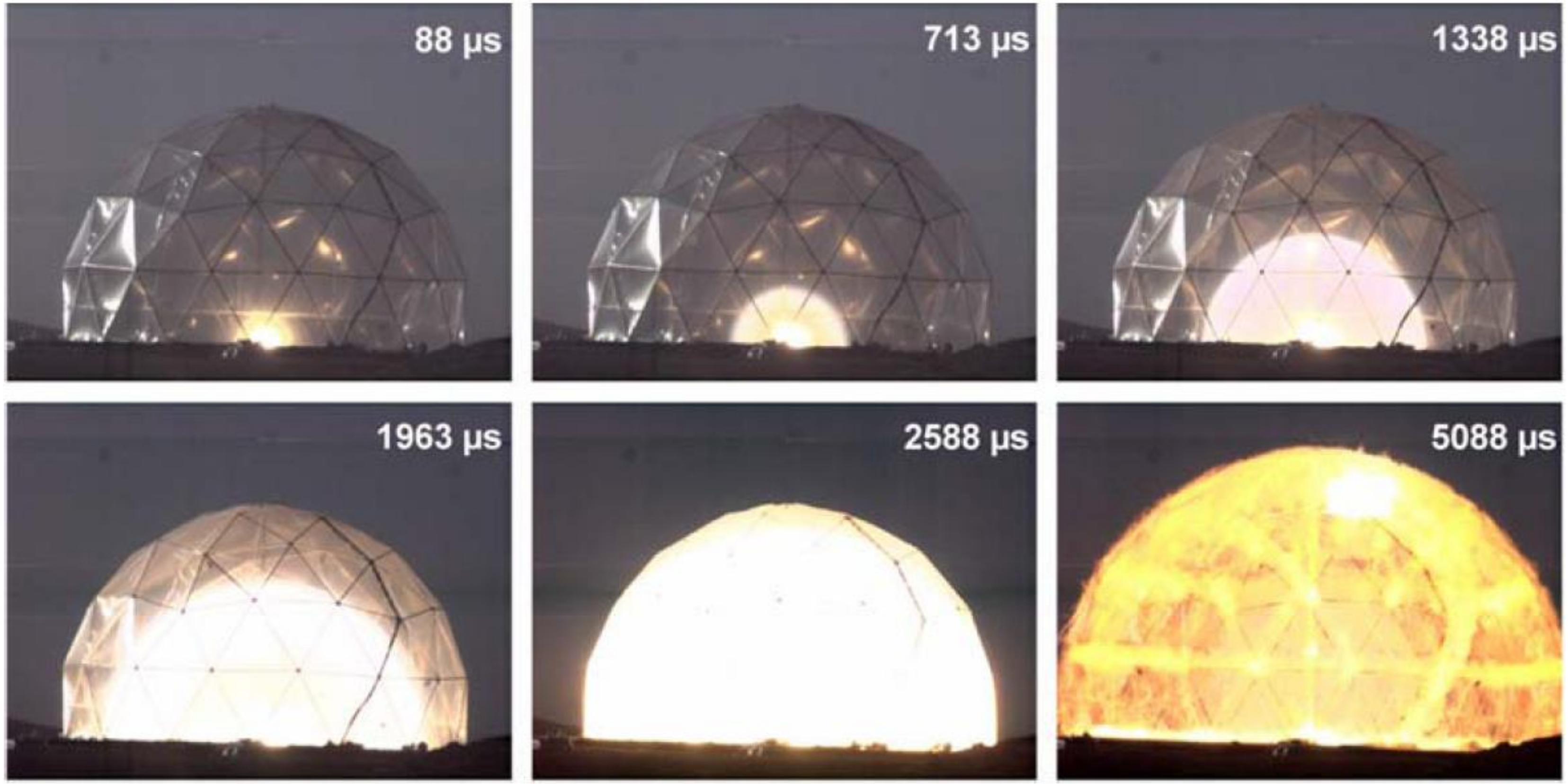
Minimum Ignition/Initiation Energy

The released/leaked hydrogen is very easily ignited. The MIE of GH_2 in air at NTP is 0.017 mJ. MIE for hydrogen is considerably less than that for methane (0.29 mJ) and petrol (0.24 mJ). Even a weak spark caused by a discharge of static electricity from a human body may be sufficient to ignite any of these fuels in air. The hydrogen-oxygen mixture could be ignited by the ignition energy as low as 0.0012 mJ.

Type of fuel	**Minimum Ignition/Initiation Energy**	
	Deflagration, mJ	Detonation, mJ
Hydrogen	0.017	10
Methane	0.25	230000
Propane	0.28	2500

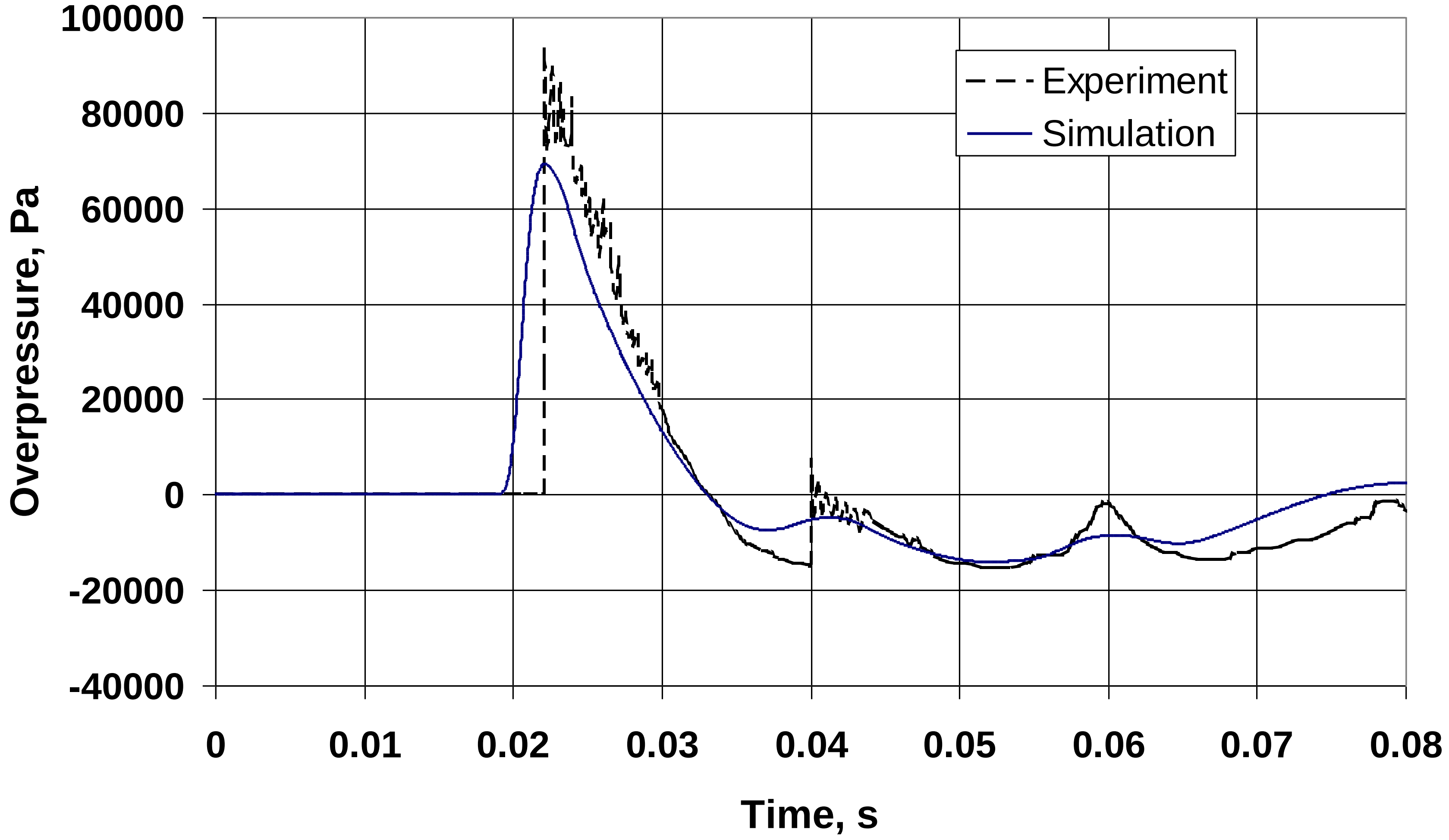
Dealing with hydrogen explosions

Experiment in the open atmosphere



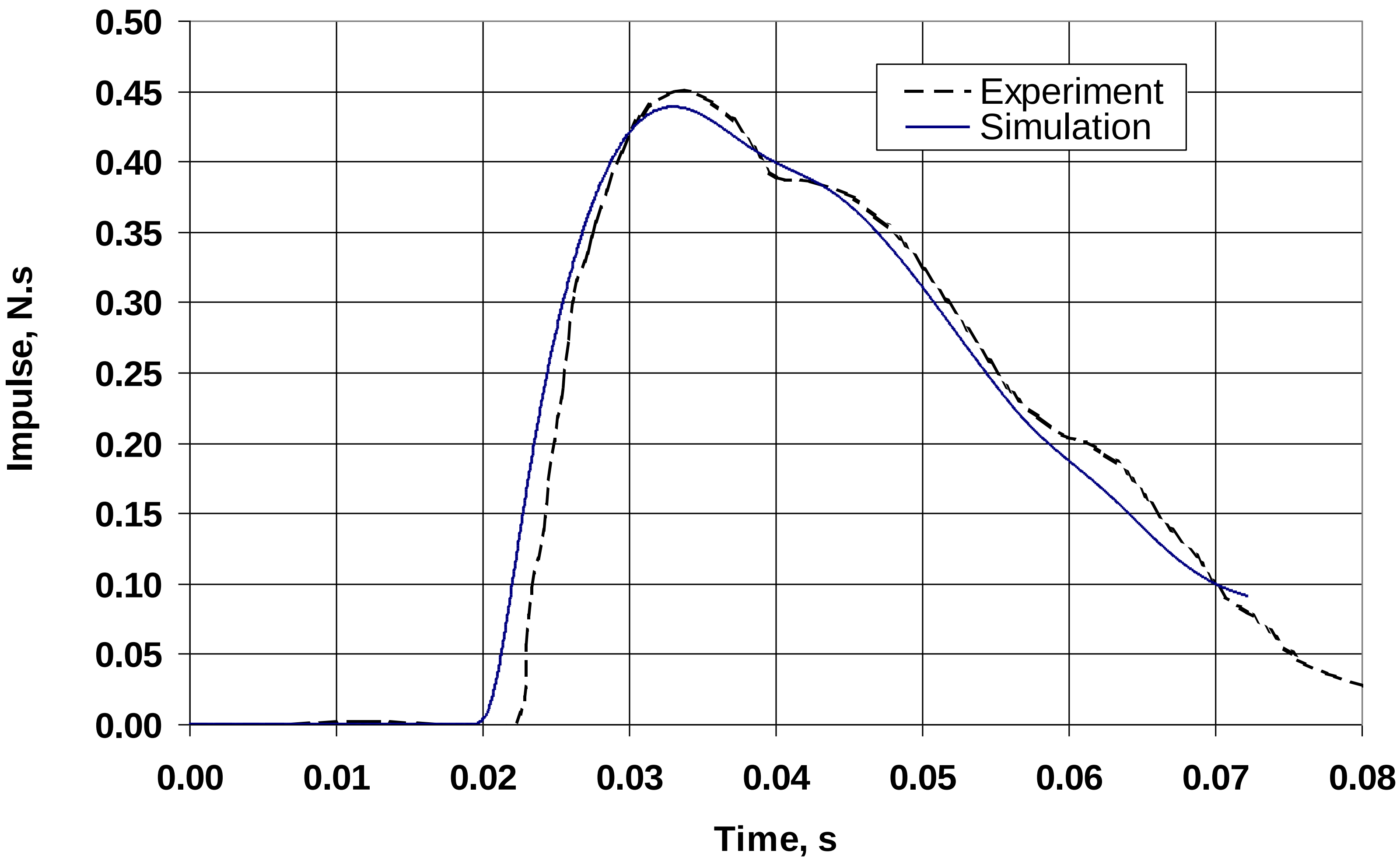
Groethe, M., et al. 1st ICHS: 30% hydrogen-air (D_{CJ}=1980 m/s, H_c=3.2 MJ/kg) in polyethylene balloon of radius R=5.23 m; Direct initiation; Blast wave overpressure was recorded at the radius R=15.6 m and the corresponding blast wave impulse was calculated.

Pressure dynamics at R = 15.61 m



Dealing with hydrogen explosions

Impulse at R = 15.61 m



Effects of blast waves

- Damage to hearing
- Damage to lungs and other internal organs
- Injuries due to flying debris (e.g. glass shards)
- Collapse of structures on to people resulting in severe injuries or death
- A whole-body displacement of an individual
- It is not only overpressure that causes harm (please see Lecture on Harm criteria) but also impulse imparted on a person or object, where person is located and what personal equipment he/she wears.
- Note: impulse is the integral of pressure and time.

Dealing with hydrogen explosions

Rupture of a hydrogen storage tank in a fire

Source: Zalosh, 2007

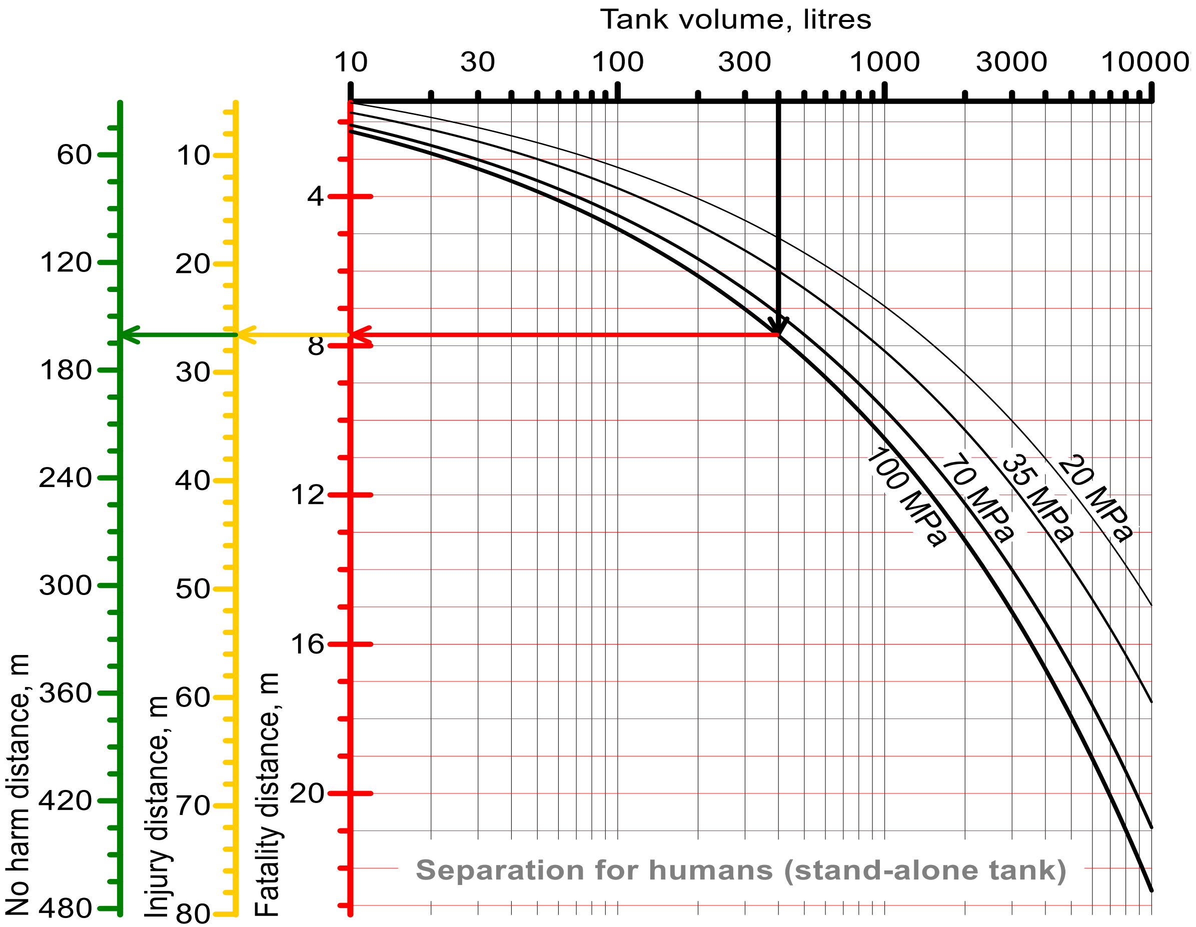
Threshold of overpressure: harm to humans

Harm criteria (selected thresholds)	Overpressure, kPa
1% fatality probability due to lung haemorrhage (Mannan, 2005): "fatality" hazard distance	100
1% eardrum rupture probability (Mannan, 2005): "injury" distance	16.5
Temporary threshold shift (Baker, 1983): "no harm" hazard distance (evacuation perimeter)	1.35

Dealing with hydrogen explosions

Blast wave: Evaluation of hazard distances (1/2)

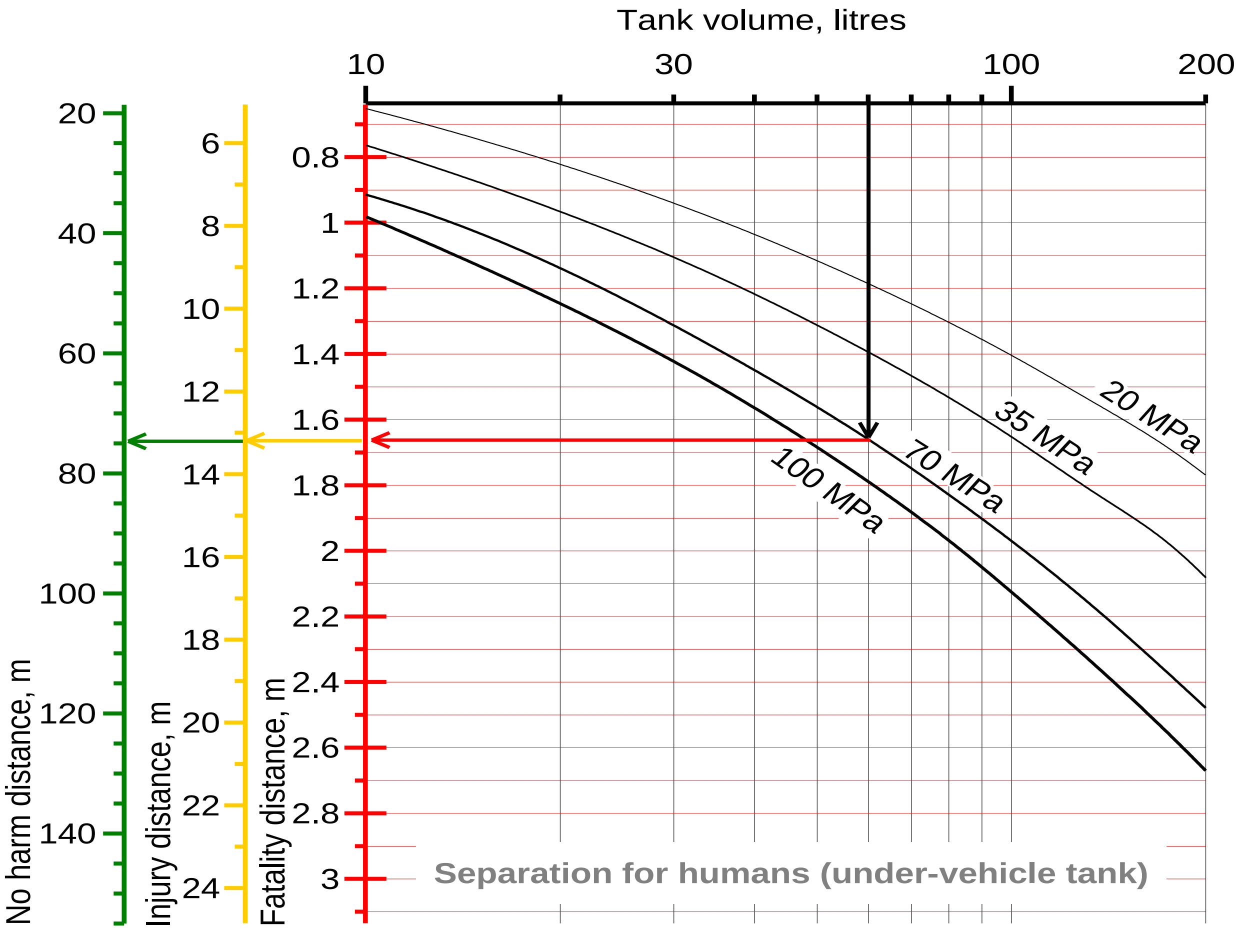
- For humans – from a rupture of a stand-alone tank in a fire



Dealing with hydrogen explosions

Blast wave: Evaluation of hazard distances (2/2)

- For humans – from a rupture of an under-vehicle storage tank in a fire



Threshold of overpressure: damage for buildings

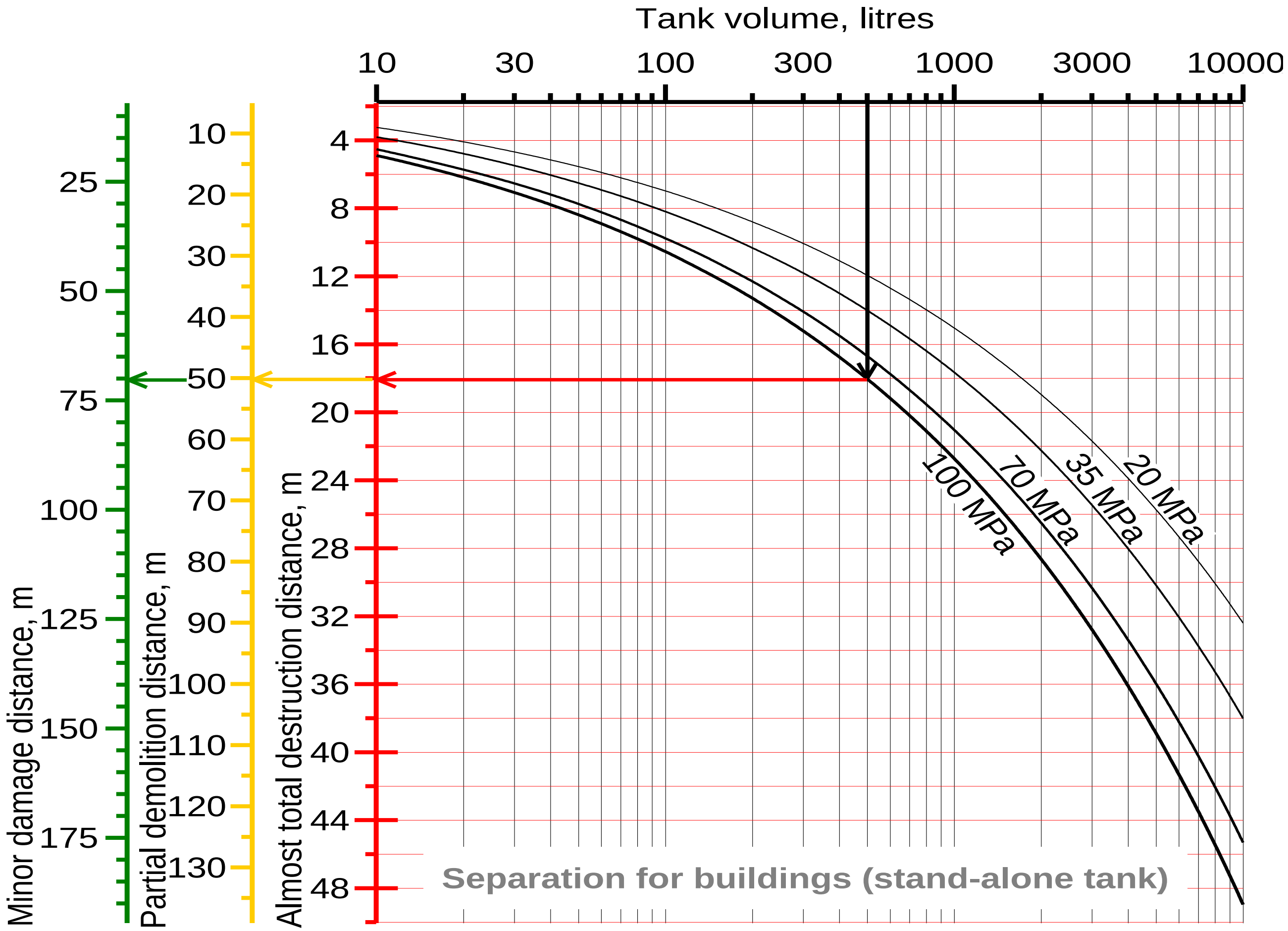
Damage	Overpressure, kPa
Minor damage of the house (chosen as “minor damage”)	4.8
Partial demolition of the house-remains inhabitable (chosen as “partial demolition”)	6.9
Almost total destruction of the house (chosen as “almost total destruction”)	34.5-48.3

Source: Mannan, 2005

Dealing with hydrogen explosions

Blast wave: Evaluation of hazard distances (1/2)

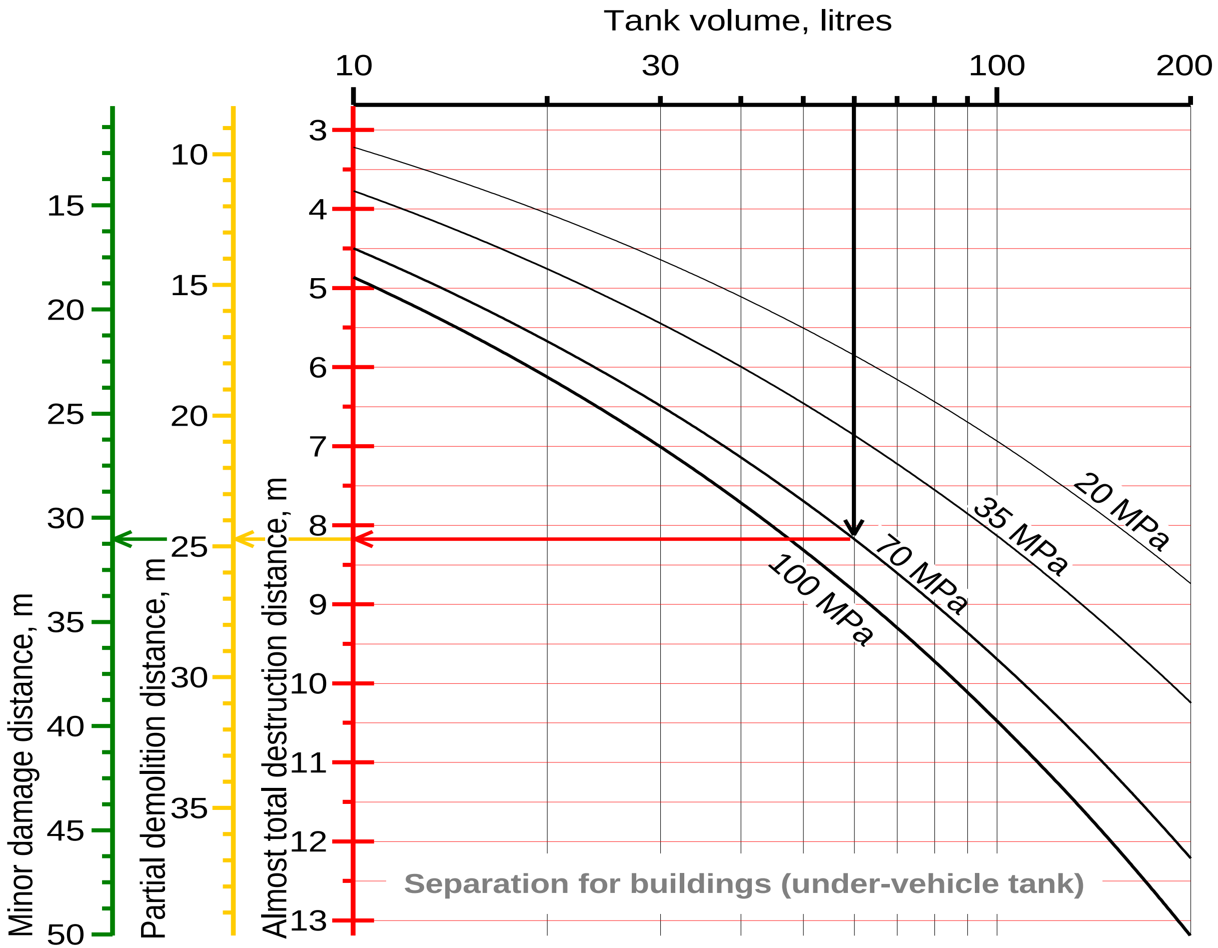
- For buildings – from a rupture of a stand-alone tank in a fire



Dealing with hydrogen explosions

Blast wave: Evaluation of hazard distances (2/2)

- For buildings – from a rupture of an under-vehicle storage tank in a fire



General prevention and mitigation measures

Prevention

Passive measures:

- Absence of ignition source(s)
- Avoid confined spaces if possible
- Natural ventilation

Active measures:

- Forced ventilation
- Detection and isolation

Mitigation

Passive measures:

- Deflagration venting
- Separation distances
- Barriers (see photo)

Active measures:

- Emergency response
- Detection
- Power shut-down

Mitigation of DDT

Strategies highlighted the standard ISO/TR 15916:2004 include:

- Avoid confinement and congestion where flammable hydrogen-air mixtures might form;
- Use flame arrestors, small orifices, or channels to prevent deflagration and detonation from propagating within a system;
- Use diluents, such as steam or carbon dioxide, or oxygen depletion techniques where possible and water spray or mist systems to retard flame acceleration. This recommendation of the standard should be taken with care as hydrogen-air flames are difficult to quench and they can burn or even accelerate around the droplets in heavy sprays of water (Shebeko et al., 1990);
- Reduce size of a system where possible to narrow detonability range.
- Knowing that hydrogen combustion is prone to DDT, especially at large scales, there are serious concerns on how technologies could be made safer. For such kind of applications, the safety strategy could be to organize and control the process of combustion of a hydrogen-contained mixture in a way that the mixture supplied to the burner is between the LFL and the LDL.

Prevention of DDT for FC

- Experiments of Pro-Science (Germany), mock-up of fuel cell (FC). A **significant flame acceleration** was recorded leading to a high overpressure, for the total injected mass of 15 g and 25 g, sufficient for complete demolition of the experimental rig. Both experimental and numerical studies of the FC mock-up suggest that **the total injected mass should be less than 6 g** for the configuration studied in order to keep overpressures below 10 to 20 kPa. Missile effects could be still possible for this 6 g inventory. Thus, **an inventory of 1 g** seems a good safety target for accidental release within this FC mock-up (Friedrich et al., 2009).
- The feed line pressure and diameter of a pipe and restrictor orifice should, by design, limit the mass flow rate of hydrogen to a technological level that is required for the FC to function. The release duration, due to the time required to detect the leak and operate the valve should be reduced as much as possible to exclude release of more than 1 g of hydrogen. An estimate shows that for a **50 kW FC,** that needs **consumption rate of hydrogen** just **below 1 g/s**, **a leak detection time and time of shutting down supply line should be together less than 1 s**. Any reduction of this time would have a positive impact on safety.
- This requirement is difficult to achieve for currently available sensors. Innovative systems of leak detection, e.g. based on supply pressure fluctuation analysis, have to be developed and implemented to provide acceptable level of safety. The grid obstacle, used in the Pro-Science experiments to mimic the congestion within real fuel cell, led to strong flame acceleration (Friedrich et al., 2009). The congestion of internal space of the FC enclosure should be avoided as much as possible by a careful design.

Dealing with hydrogen explosions

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