International Short Course Series "Progress in Hydrogen Safety"
Short course: "Hydrogen and fuel cell technologies - Safety issues"
29th September to 3rd October 2008, Belfast

Hydrogen Safety
- State of the Art -

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Representing the HySafe coordinator

Content

Hydrogen Safety - State of the Art -

1. Definitions
2. Risk Assessment
3. State-of-the-Art Consequence Modelling
4. Some simplified methods
5. Further Documentation and Training

Definitions

- Safety is the freedom from unaccepted risk
- Hazard: “potential source of harm”
- Risk = Probability * Severity
- Harm: “physical injury or damage to health or property”

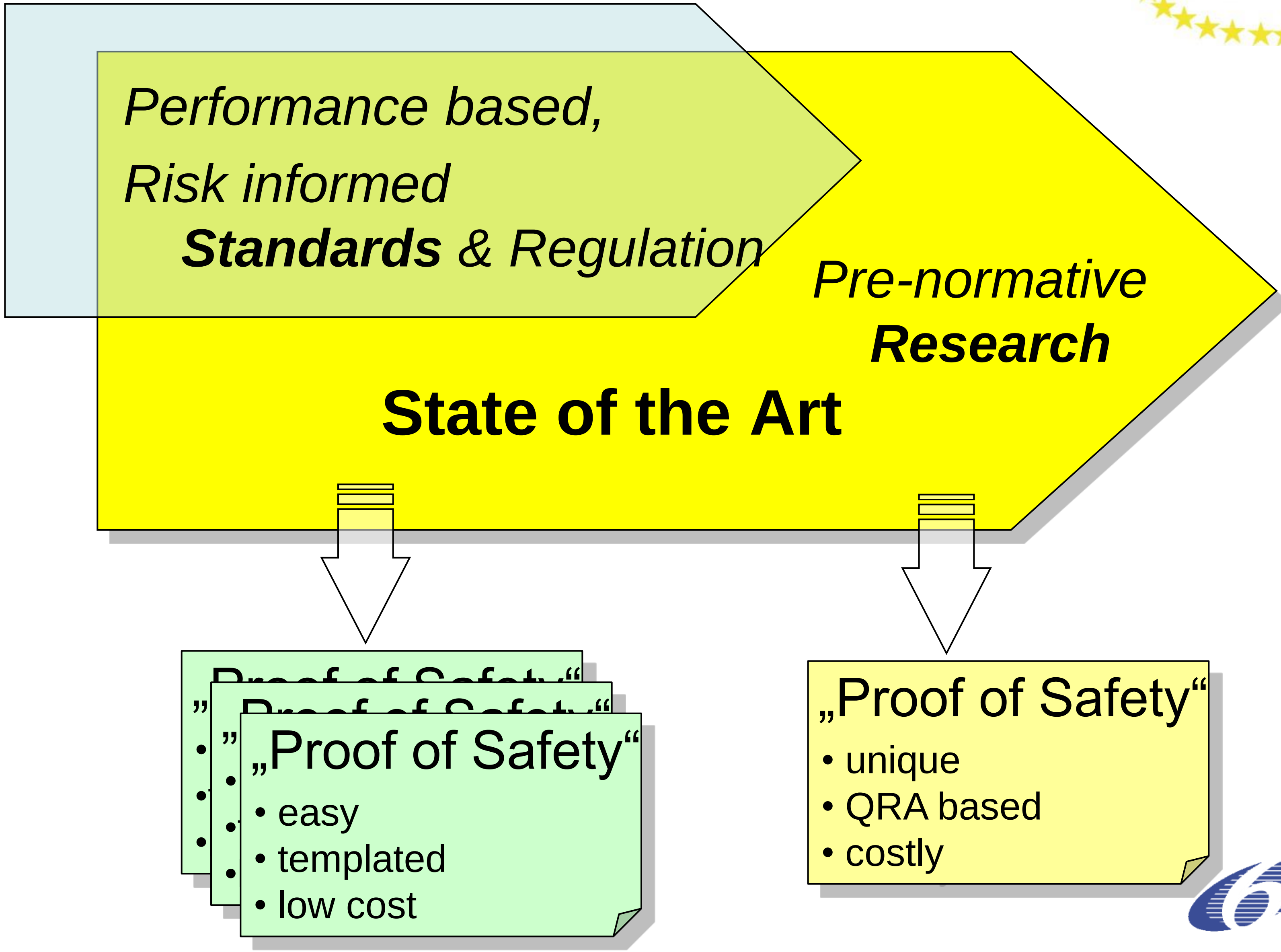
ISO/IEC Guide 73:2002

Definitions

State of the Art is

the level of development (as of a device, procedure, process, technique, or science) reached at any particular time usually as a result of modern methods

Marriam-Webster (1910)


Performance based,
Risk informed
Standards & Regulation
Pre-normative
Research
State of the Art
„Proof of Safety“
• easy
• templated
• low cost
„Proof of Safety“
• unique
• QRA based
• costly

State-of-the-Art

Coordinated Research (NoE HySafe)

Consortium

- 24 partners from 12 European countries incl. Russia (Kurchatov Institute) and one Canadian partner (University of Calgary)
- 13 public research organisations, 7 industrial partners, 5 universities
- ~150 scientists involved

Budget

Total > 13 M€ with a EC grant of max. 7 M€

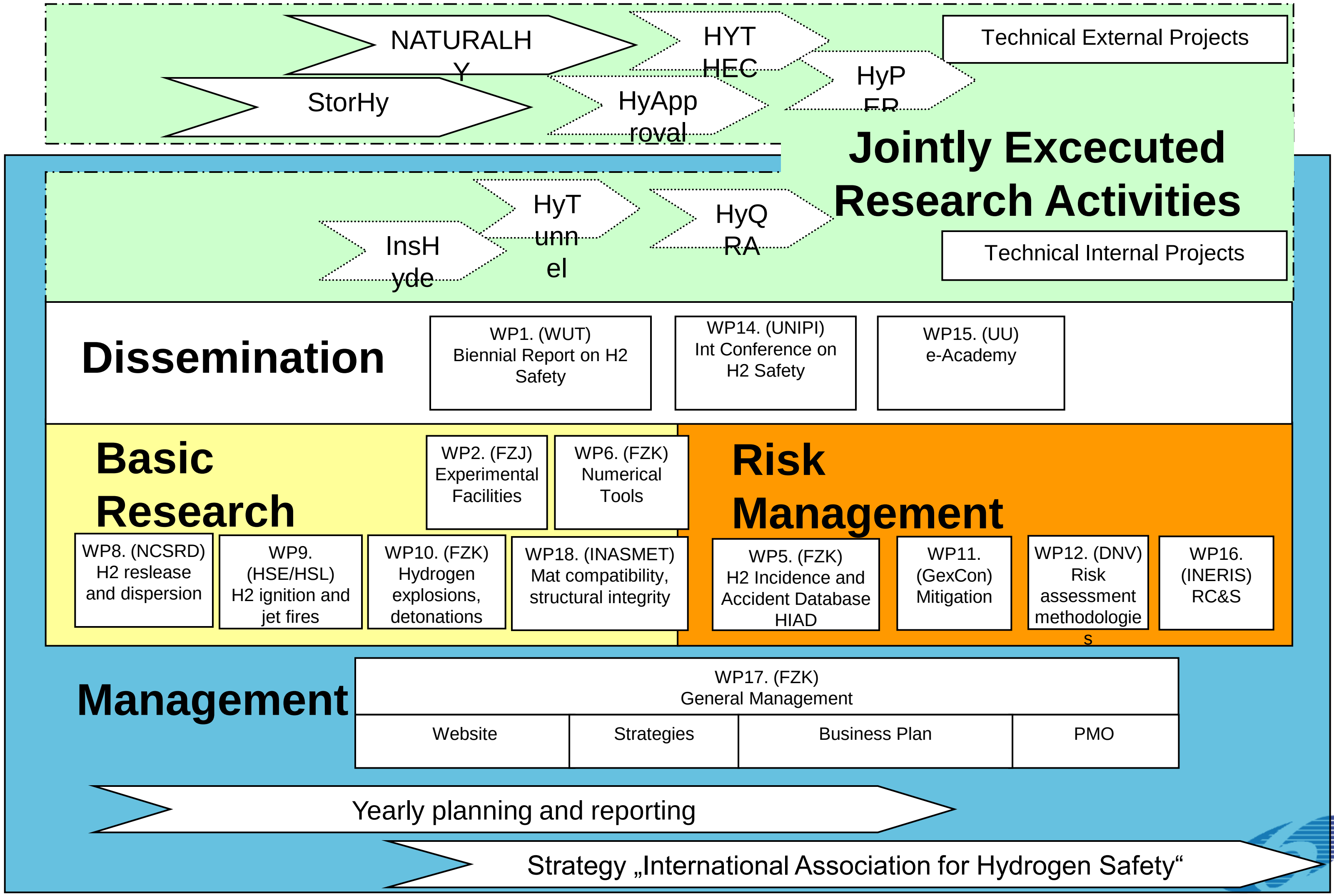
Time schedule

network/project start: 03/2004

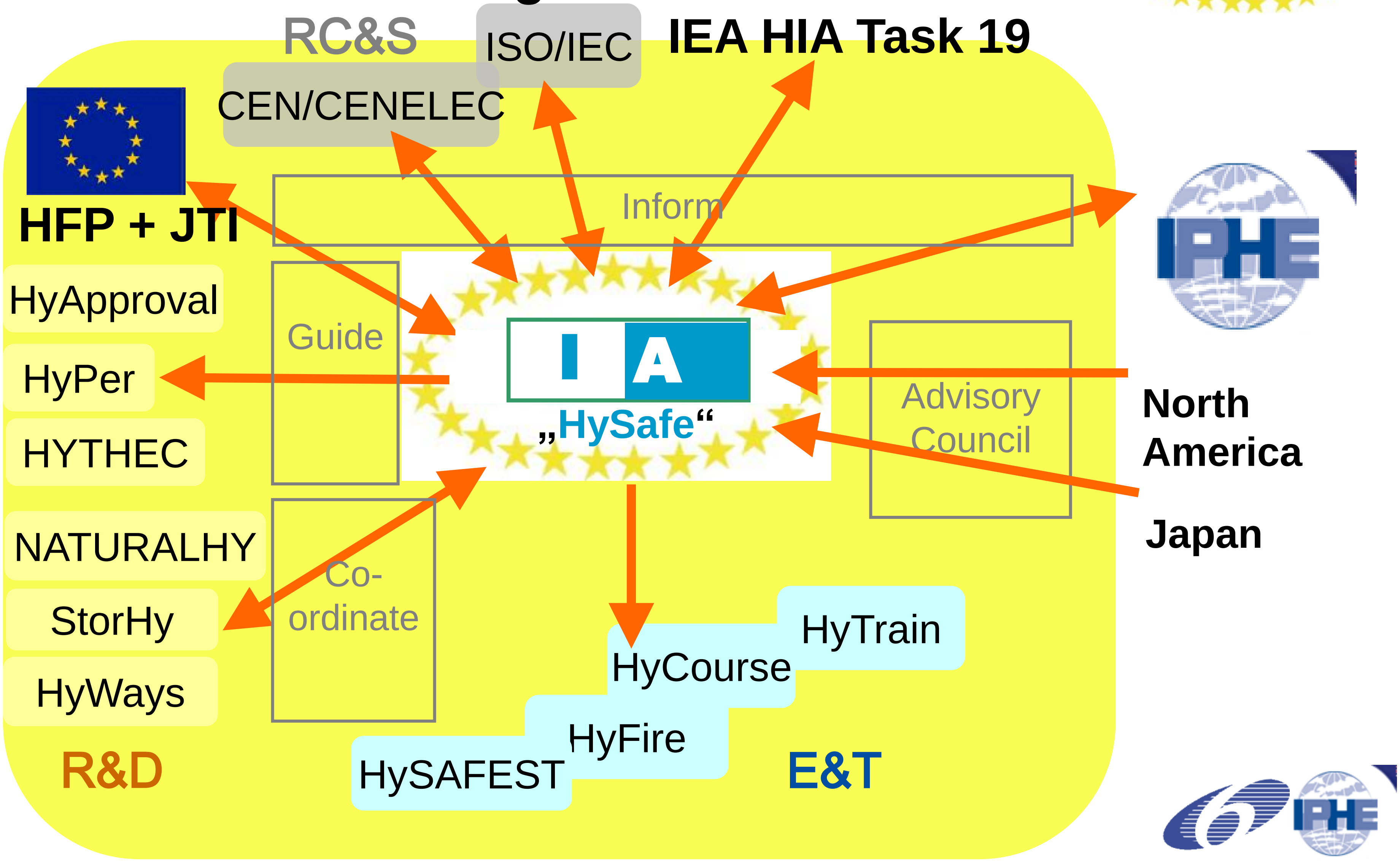
subsidised max. duration: 5 years

→ 02/2009 activities transferred to the International Association "HySafe"

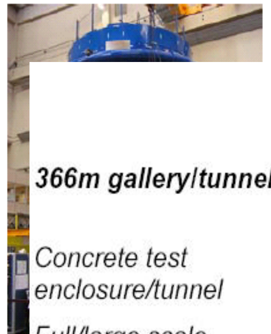
HySafe
Current Activities



HySafe
External Networking



State-of-the-Art
Experimental Facilities (HySafe-IEF)



MISTRA

cylindrical steel vessel

originally designed as 1/10th in linear scale of Pressurized Water Reactor containment

studies of H2 (simulated by He) release and distribution in a confined geometry

366m gallery/tunnel

Concrete test enclosure/tunnel

Full/large scale

Combustion and ventilation controlled overpressures Fragmentation.

V1, V2 and H4, H5

REKO-2

only 6 out of > 100

GexCon 168 m^3 open geometry with internal obstructions

explosion vessel

large scale (168 m^3)

studies on explosions in open, congested geometries

A1 Vessel

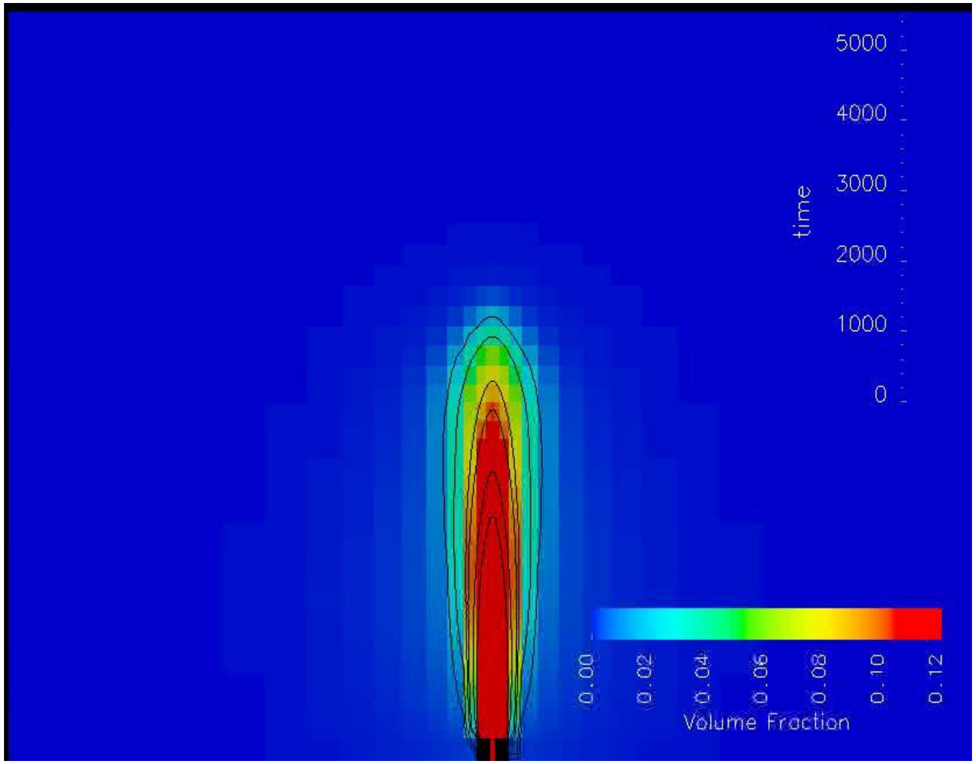
cylindrical vessel

full or large scale

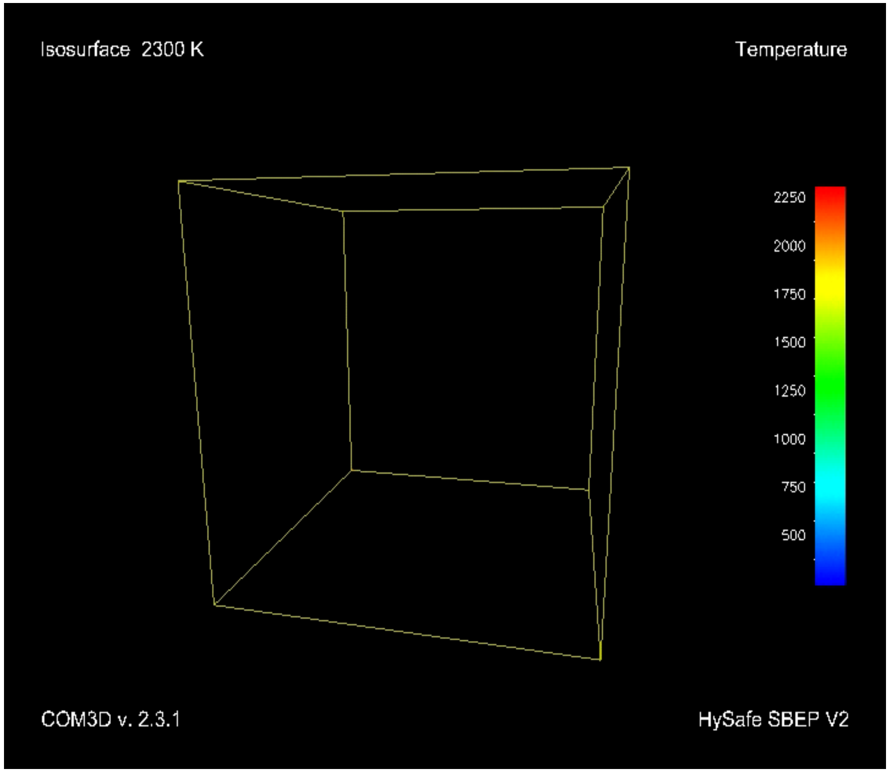
studies on turbulent combustion and detonations, vented explosions, hydrogen distribution, integrity of mechanical structures under high pressure load

State-of-the-Art
Numerical Tools (HySafe-NT)

SBEP V3 (Dispersion)
240g H2 into „garage"



SBEP V2 (Deflagration)
20m hemisphere (Fh-ICT test)

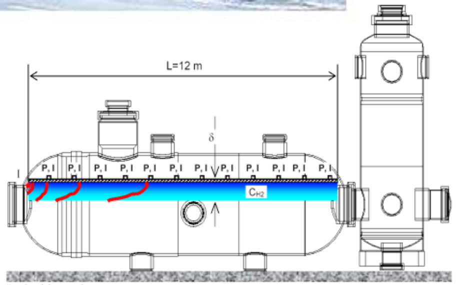


State-of-the-Art

Pre-normative research directions (HySafe WP7)

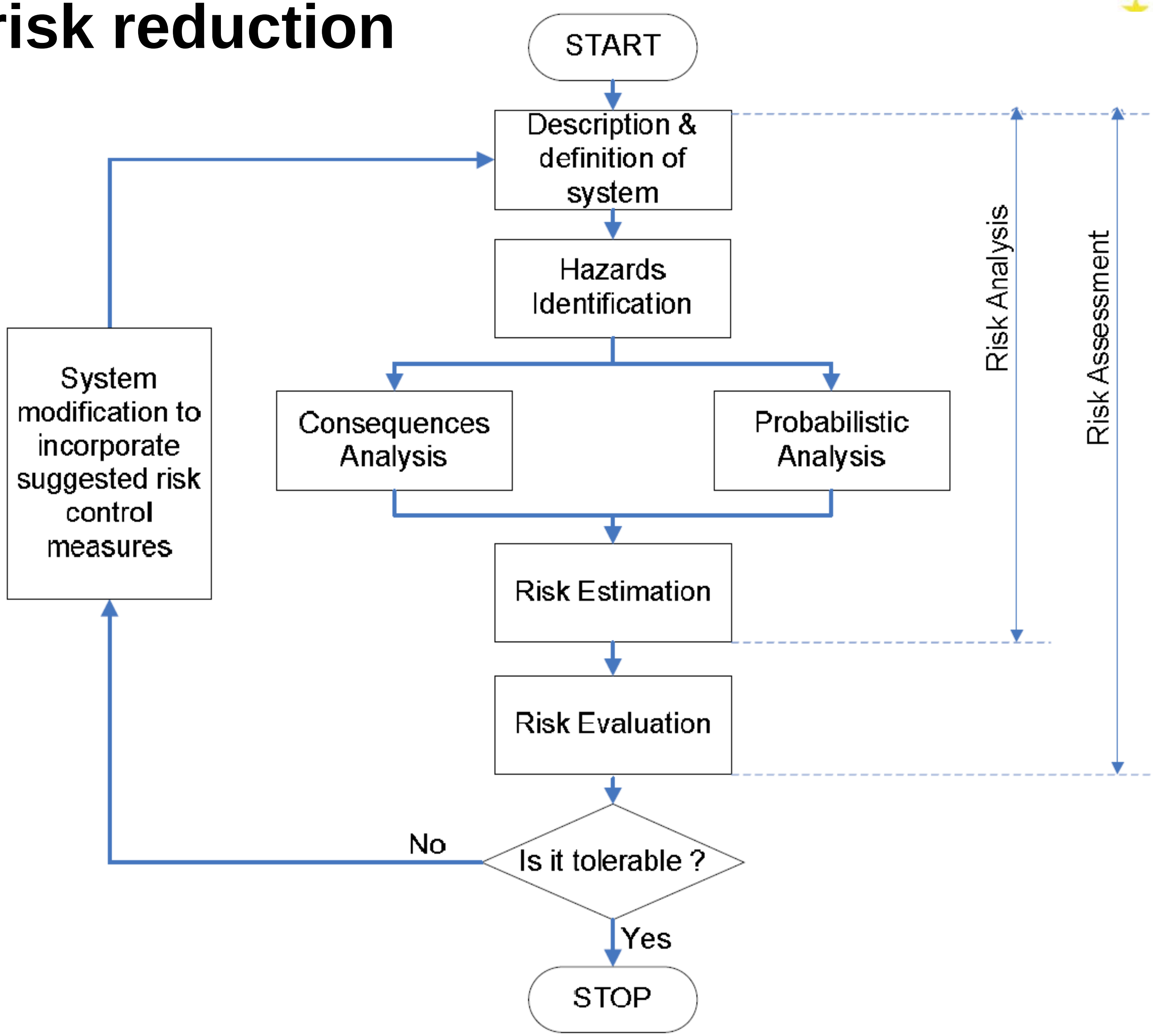
- **(Partially) Confined Releases**
- **Mitigation**

have been determined by
- initial PIRT study
- expert questionnaire
- state-of-the-art survey



communicate the network's working topics, **orientate** the work on intermediate time scale (proposals for experiments, benchmarking, Internal Projects …)

Iterative process of risk assessment and risk reduction



Risk Assessment
Some Elements

Some established methods for safety analyses

More qualitative methods

- Check list method
- Preliminary hazard identification
- What if method
- Hazard identification amd Operability HAZOP

More quantitative methods

- Fault tree analysis
- Fault sequence analysis
- Failure Mode and Effect Analysis FMEA

Source: TÜV Rheinland

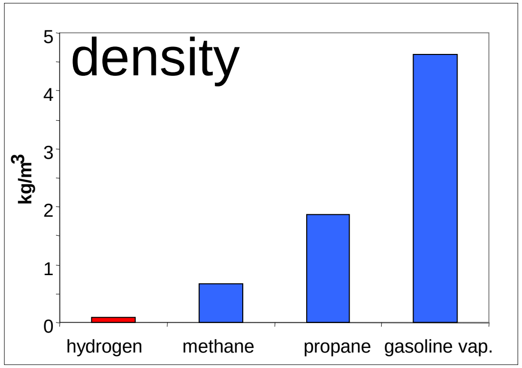
Hazard Identification
HAZOP

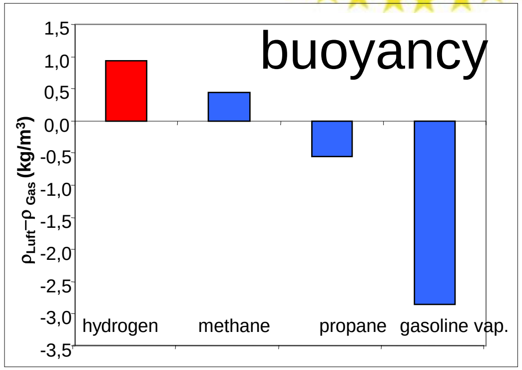
Guide words	Meaning	Parameter	Deviation
No	Negation intention	Flow Level	No flow Zero level
Less	Quantitative decrease	Flow Level Temperature	Low flow rate Low level Low temperature
More	Quantitative increase	Flow Level Temperature	High flow rate High level High temperature
Reverse	Logical opposite	Flow Pressure	Reverse flow Reverse pressure
Part of	Qualitative decrease	Concentration Flow Level	Concentration decrease Flow decrease Level decrease
As well as	Qualitative increase	Concentration of impurity Temperature of substance Level of impurity Pressure of substance	Concentration increase Temperature increase Level increase Pressure increase
Other than	Complete substitution	Concentration of desired substance Level of desired substance Flow of desired substance	Concentration zero Level zero Flow rate zero

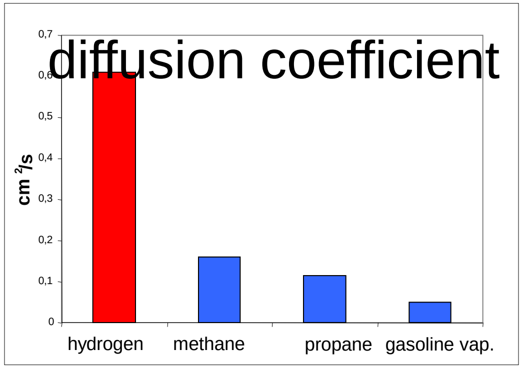
Hazard Identification

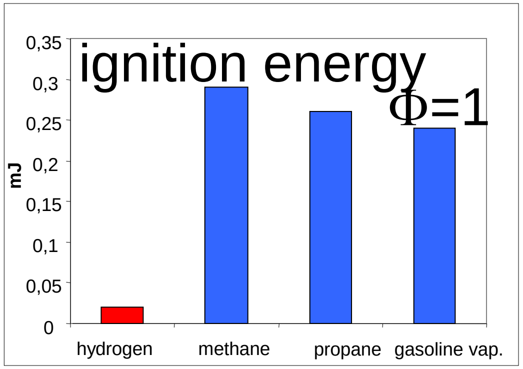
Safety relevant properties of GH2

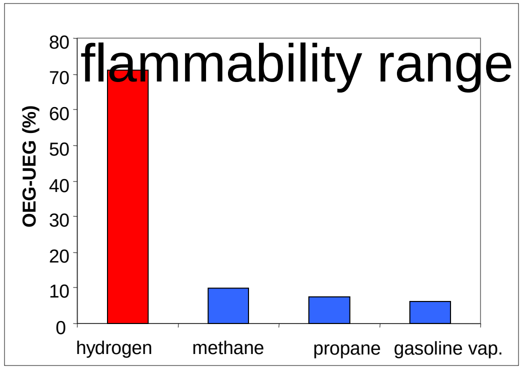
- hydrogen
- methane
- propane
- gasoline vapour

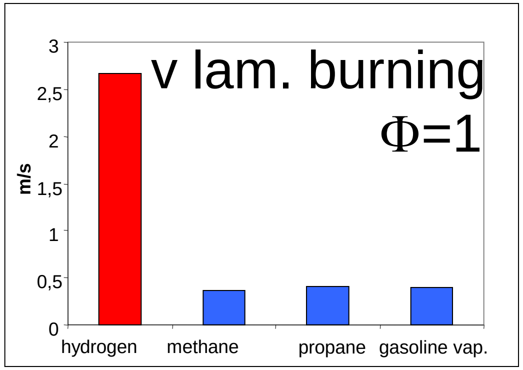


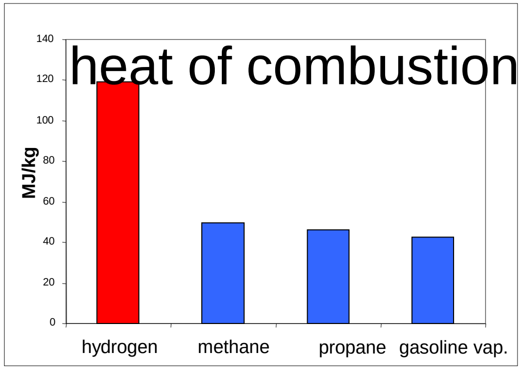


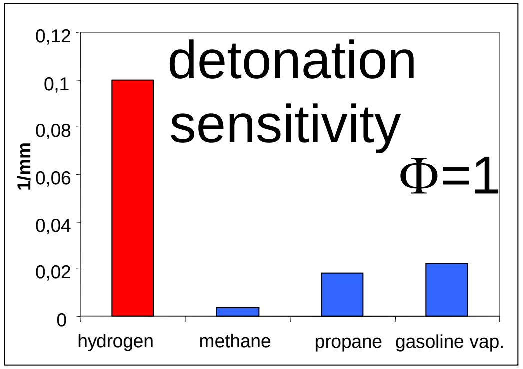












Hazard Identification
Specific issues of LH2

- **-253°C** → cold burns, material degradation, NDTT
- **780 x volume expansion** during evaporation → asphyxiation
- **cryo pump effect in open LH2 pools** → condensing air, spontaneous ignitions

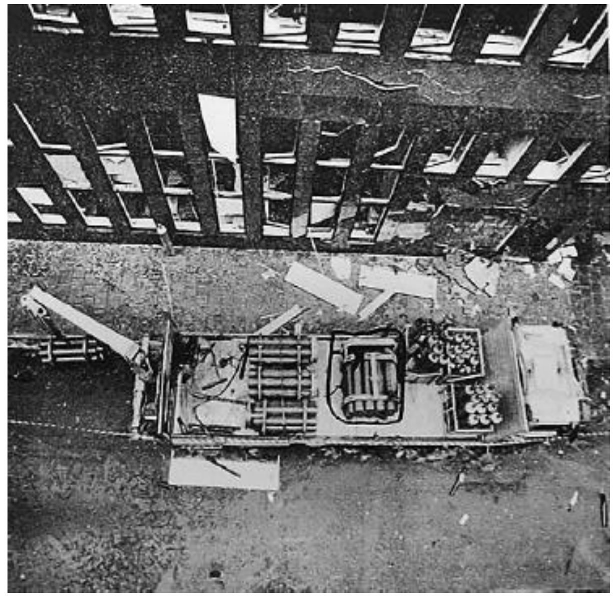
Hazard Identification

Based on experience

Norwegen 1984

Detonation of ~5 kg, 2 fatalities, Destruction of the whole industry building

Stockholm 1984



H_2-Source 180 Nm^3
16 injuries, damage on vehicles and buildings in a radius of 90 m

Köln 2005

What if …?

Hazard Identification

Collection of event versions in HIAD

> 250 H2 specific events

Hazard Identification

Incidence and Accidents Database (HIAD) Structure

Administration & Risk "environment"
Where (application, environment,…)

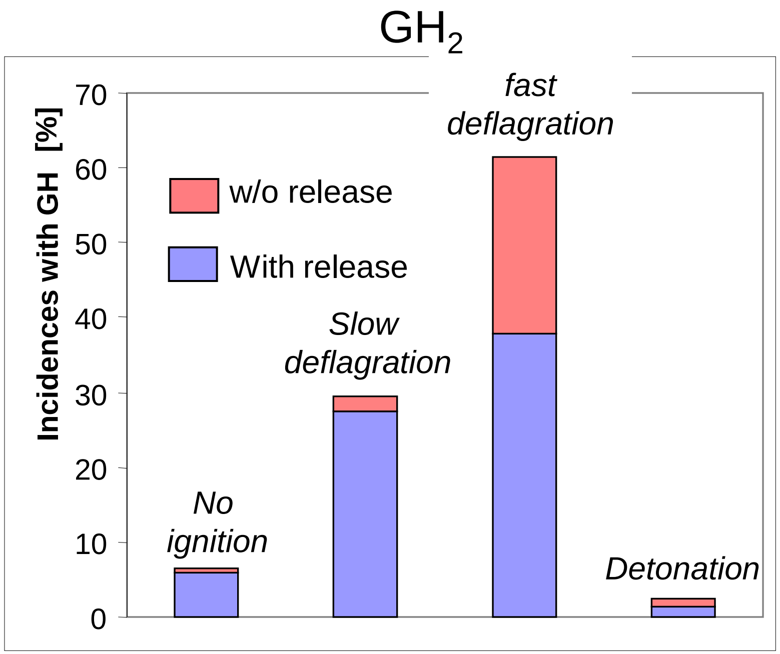
Technical specification of the event
Equipment spec, location,….

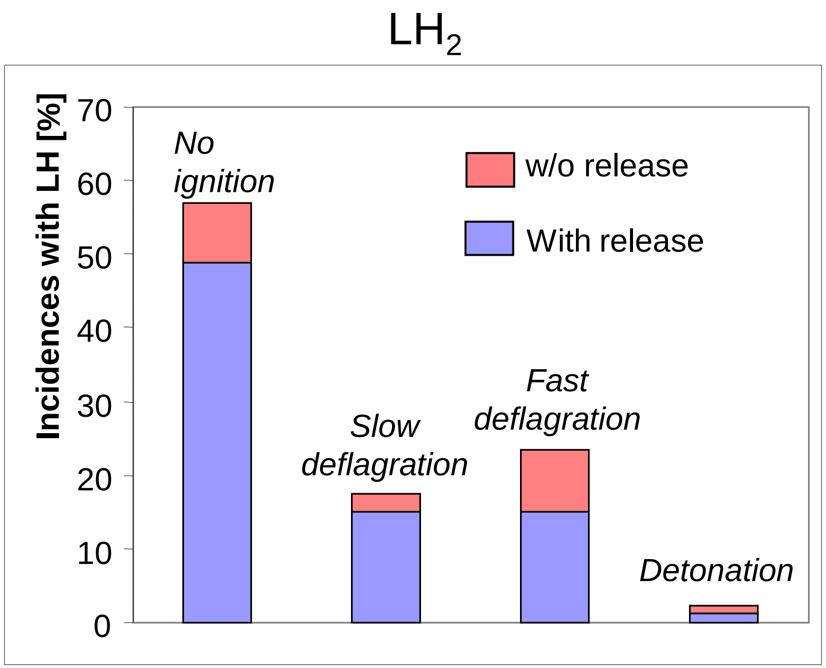
Hazardous Event Specification
What happened and why

Hazardous Event Consequences Specification
Fatalities, injuries, property damage, …

Hazard Identification

Some conclusions from statistics

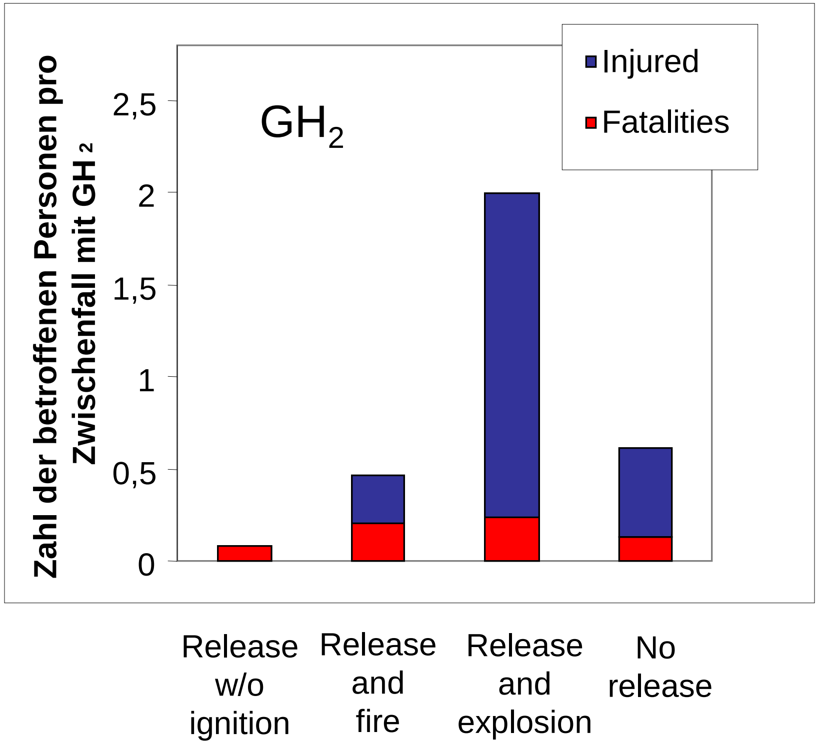


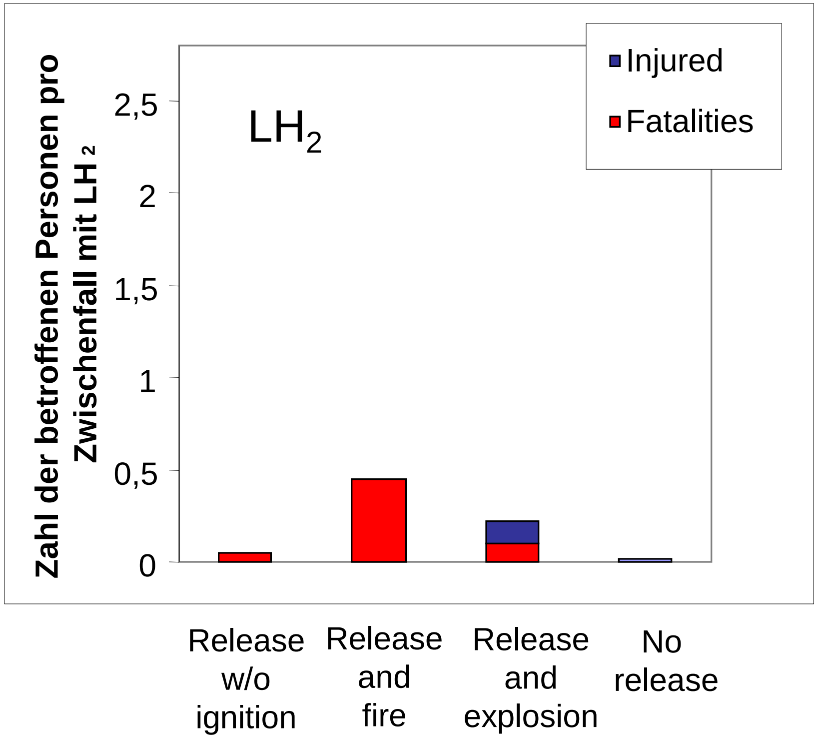


- Incidences with GH2 lead often to fast deflagrations
- Ignition in LH2 incidences is less probable

Hazard Identification

Some conclusions from statistics

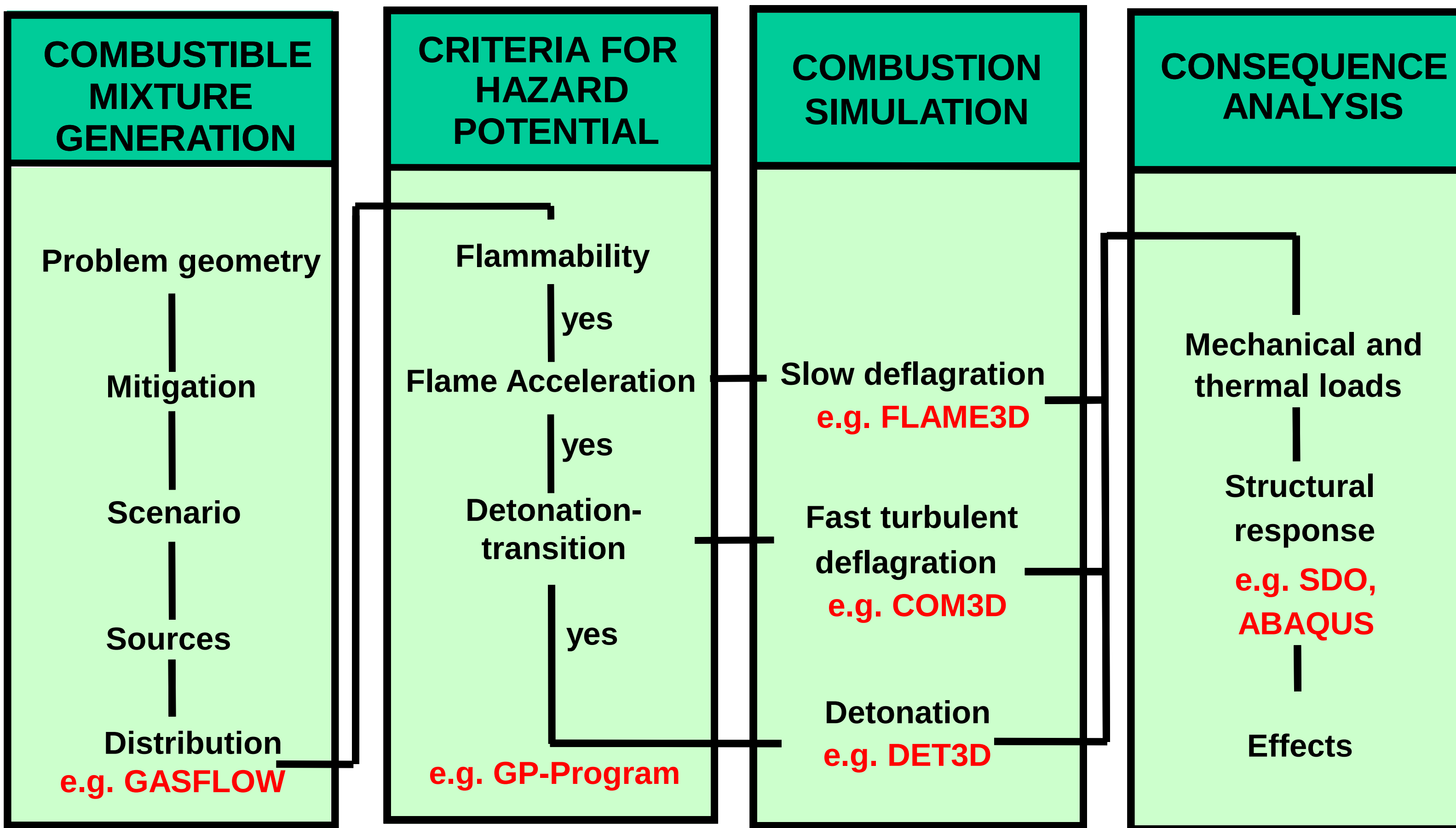




- Considerably less injured with LH_2 / GH_2, but same fatalities
- All combustion phenomena occur, depending on many parameters

State of the Art Consequence Modelling

Analysis Methodology



State of the Art Consequence Modelling

Mixture Generation

COMBUSTIBLE MIXTURE GENERATION

Problem geometry

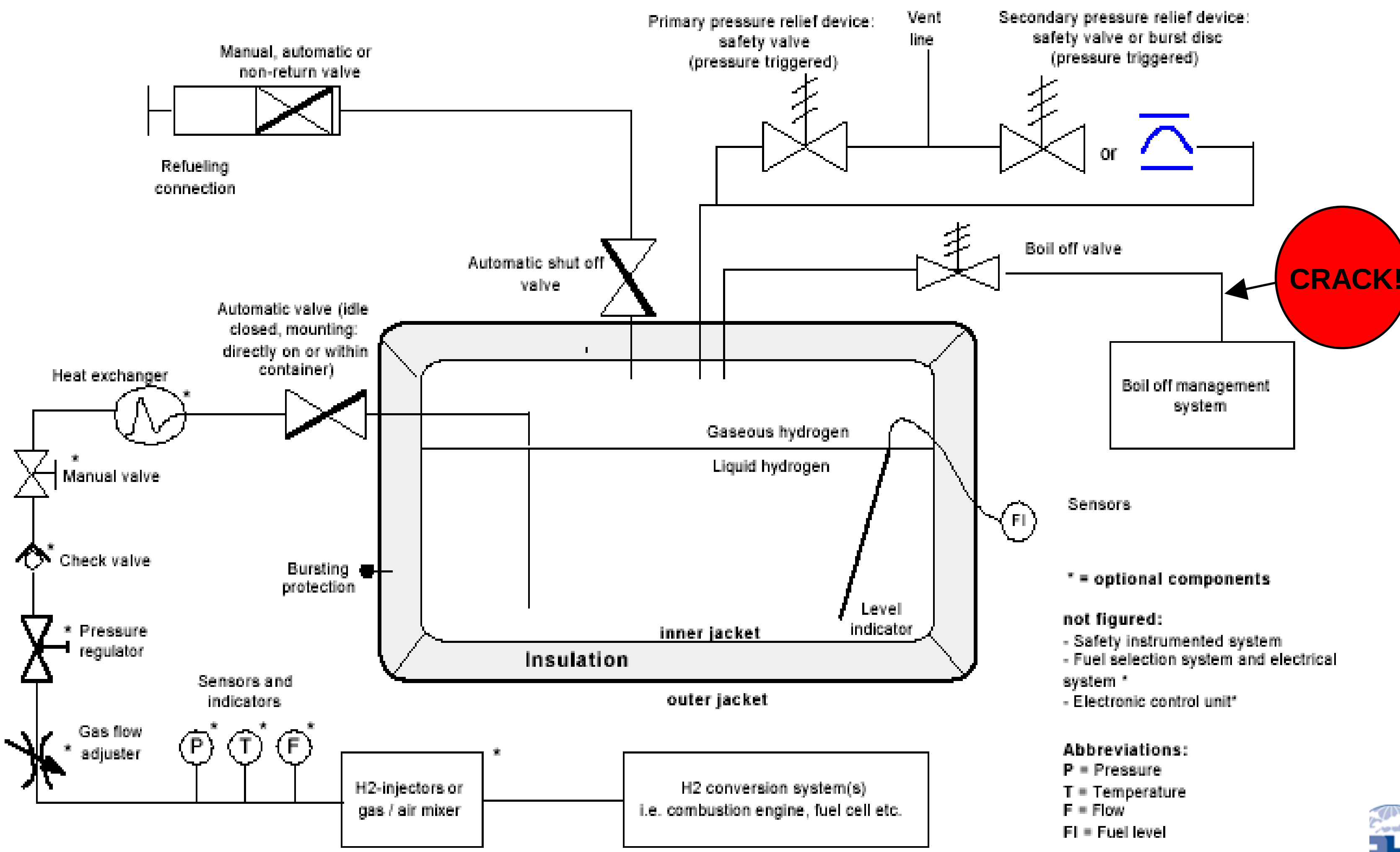
Mitigation

Scenario

Sources

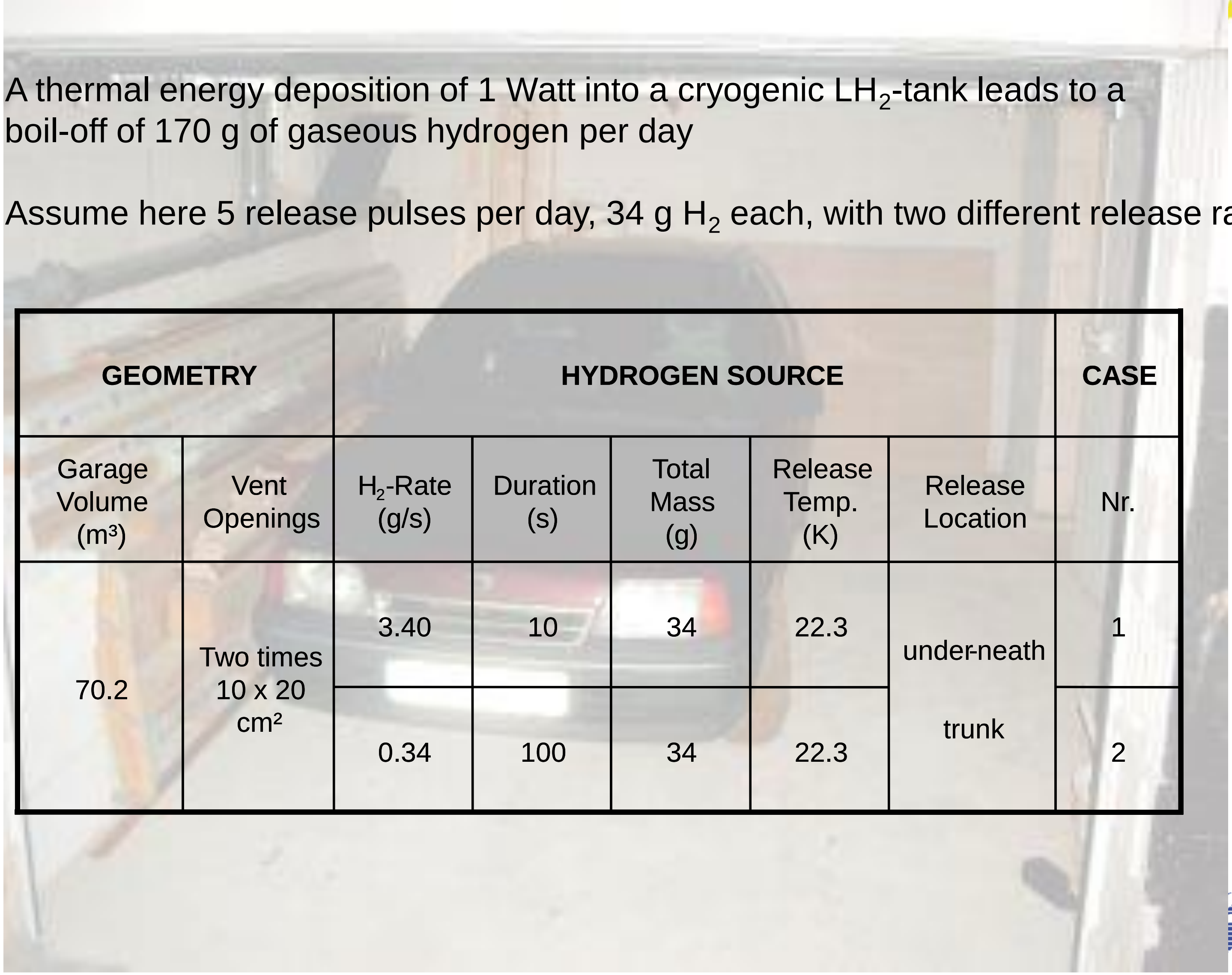
Distribution

GENERIC ARCHITECTURE OF AN LH_2-TANK SYSTEM



Source: EU-Project EIHP-2, Final Report 2004

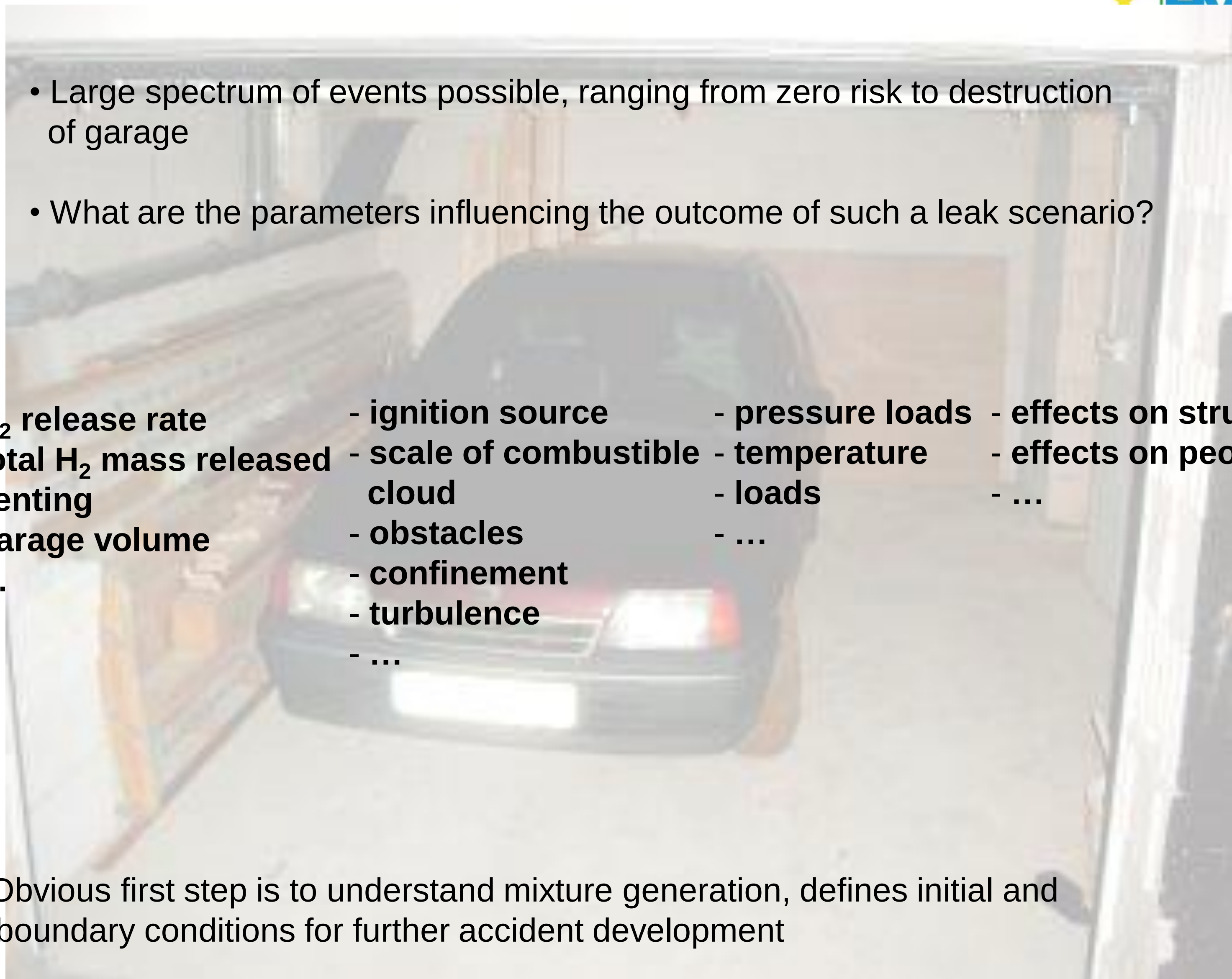
INVESTIGATED GARAGE SCENARIOS



- A thermal energy deposition of 1 Watt into a cryogenic LH_2-tank leads to a boil-off of 170 g of gaseous hydrogen per day
- Assume here 5 release pulses per day, 34 g H_2 each, with two different release rates

GEOMETRY		HYDROGEN SOURCE					CASE
Garage Volume (m³)	Vent Openings	H_2-Rate (g/s)	Duration (s)	Total Mass (g)	Release Temp. (K)	Release Location	Nr.
70.2	Two times 10 x 20 cm²	3.40	10	34	22.3	under-neath trunk	1
		0.34	100	34	22.3		2

WHAT ARE THE IMPORTANT RISK DETERMINING PARAMETERS?



- Large spectrum of events possible, ranging from zero risk to destruction of garage
- What are the parameters influencing the outcome of such a leak scenario?

- H_2 release rate
- total H_2 mass released
- venting
- garage volume
- …

- ignition source
- scale of combustible cloud
- obstacles
- confinement
- turbulence
- …

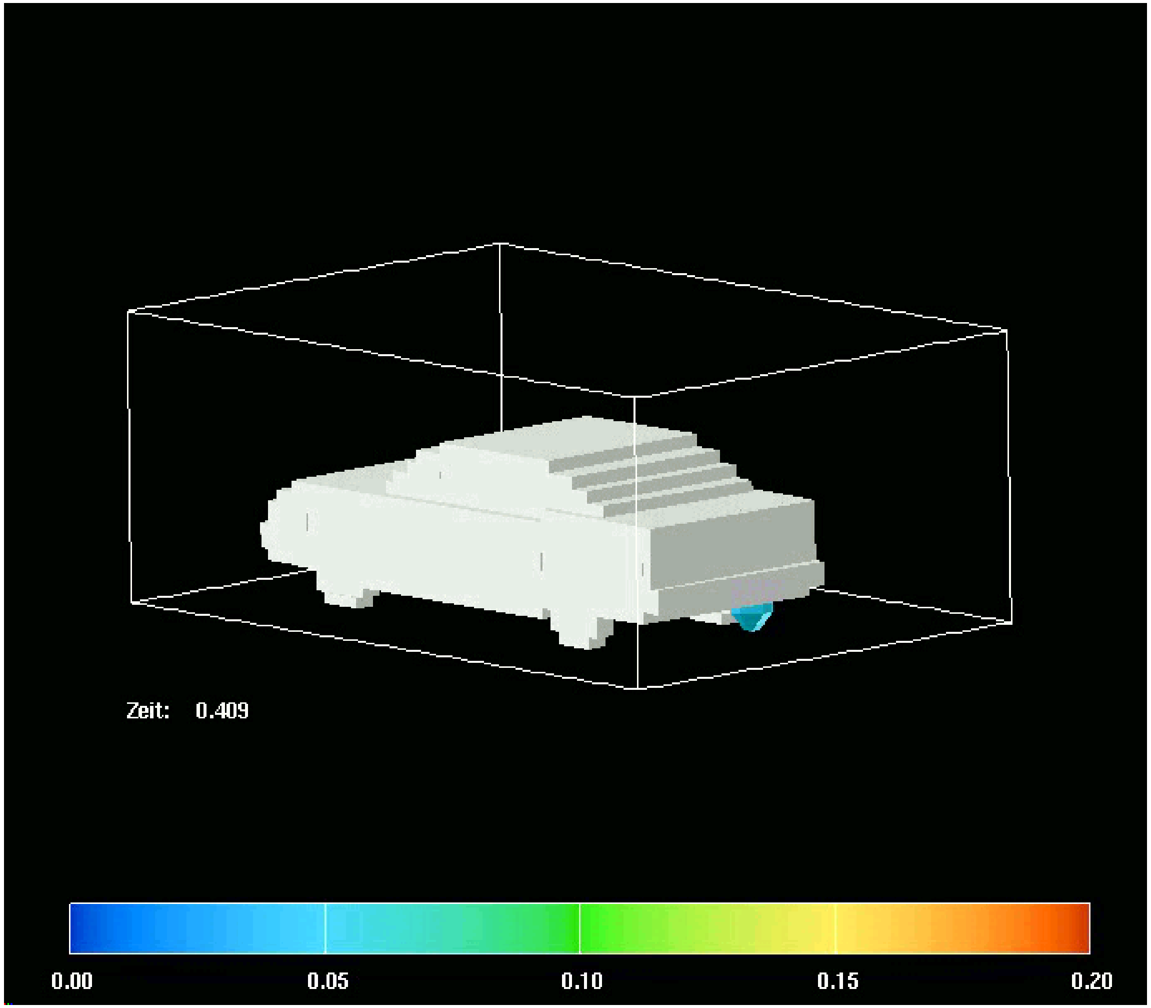
- pressure loads
- temperature
- loads
- …

- effects on structures
- effects on people
- …

- Obvious first step is to understand mixture generation, defines initial and boundary conditions for further accident development

GASFLOW SIMULATION OF GARAGE SCENARIO

- Case 1: release rate 3.4 g H_2 / s for 10 seconds

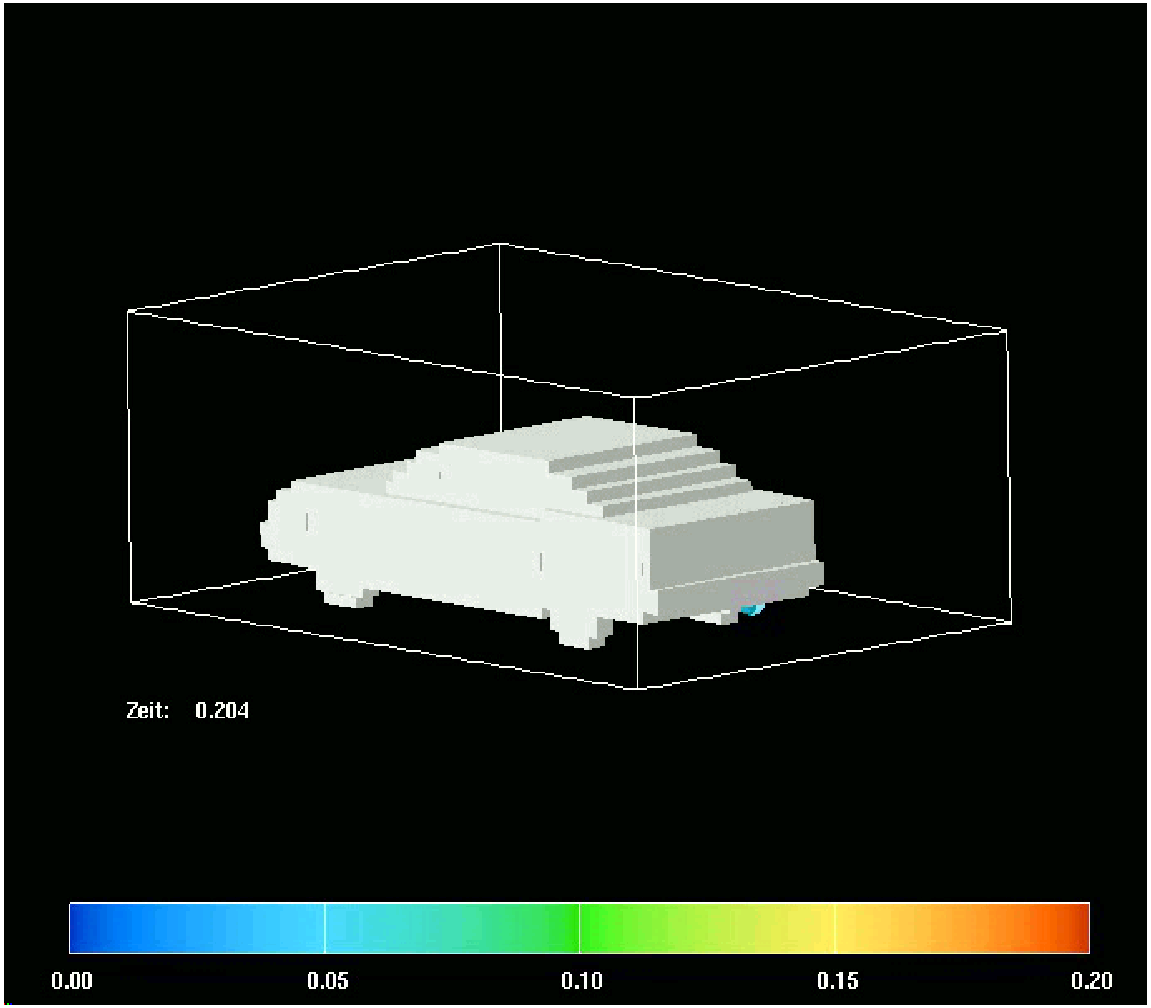


volume fraction H_2

Isosurface with ≥ 4 vol% H_2, depicts flammable mixture in garage

GASFLOW SIMULATION OF GARAGE SCENARIO

• Case 2: release rate 0.34 g H_2 / s for 100 seconds



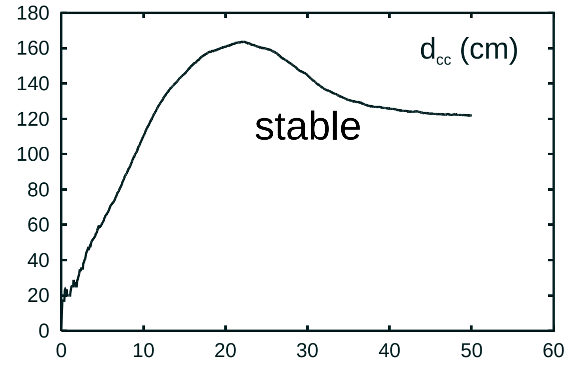
volume fraction H_2

Isosurface with ≥ 4 vol% H_2 , depicts flammable mixture in garage

Resulting Hydrogen Cloud
in the garage

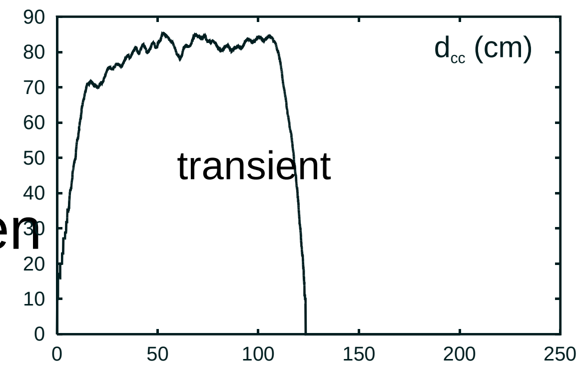
- Computed dimension of combustible H_2-air cloud in garage (4…75% H_2)

Case 1
3.4 g H_2/s for 10 s



- Characteristic size of combustible cloud expressed as $d_{CC} = (V_{cc})^{1/3}$

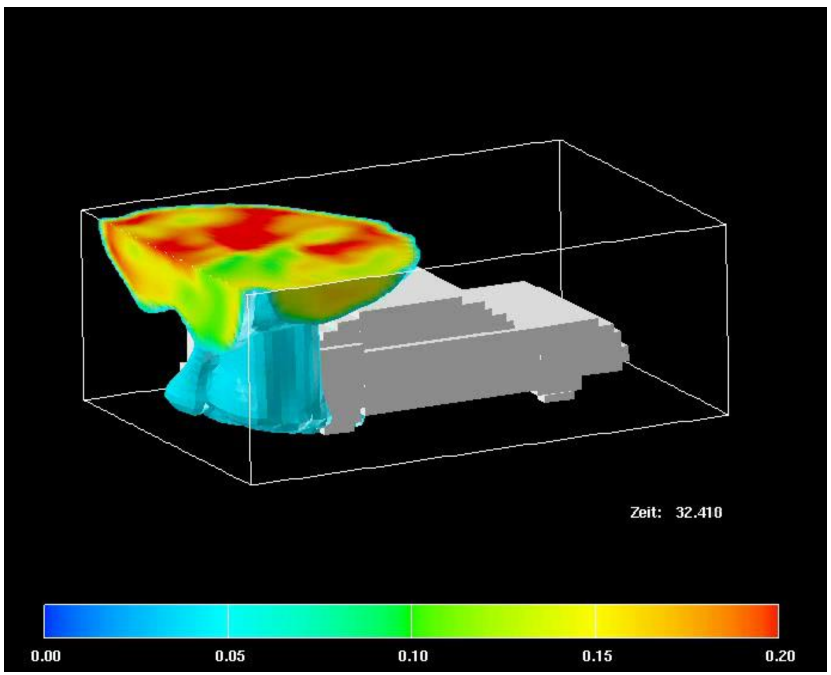
Case 2
0.34 g H_2/s for 100s



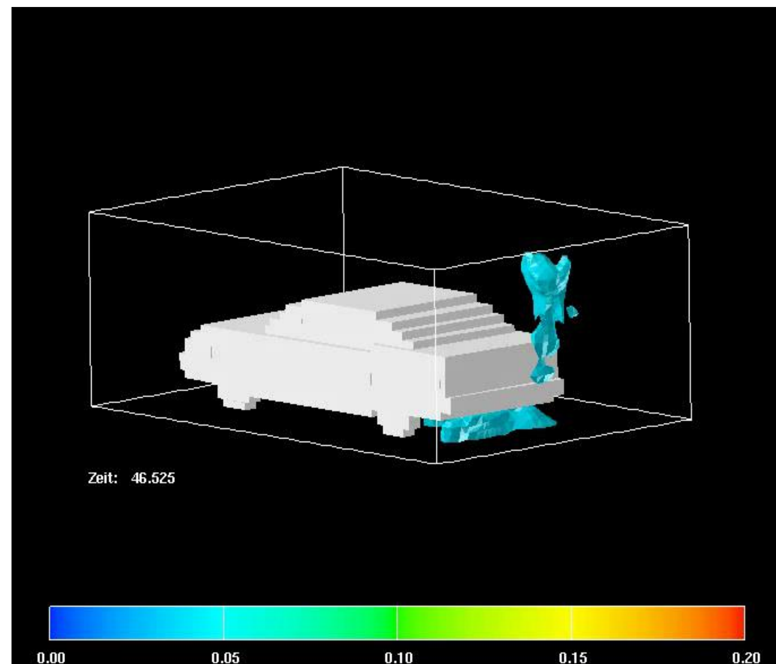
- Combustible cloud size strongly dependent on release rate, is result of balance between source strength and sinks, or release rate and mixing mechanisms

What is the risk from a combustible cloud ?

- How would you judge the hazard in both cases?
- Who would switch on lights in the garage?
- What physical quantities determine the hazard potential of a combustible H_2-air cloud?



Case 1



Case 2

State-of-the-Art CFD code Verification
Based on HySafe SBEPs

PHYSICAL PROCESS	
• Distribution, GASFLOW	
- geometry	- 3d, cylin - graphica
- flow and transport	- Navier-S vollkomp
thermophys. properties	JANAF T
molekular transport	CHEMKI
- turbulence	- k/ε
- turbulent heat transfer gas/wall	- wall func
- heat conduction in struct..	- Fourier e
- radiation	- Moment
- vaporation/condensation	- homoge
- critcal flowl	- analyt. C
• Mitigation:	
- rekombiners a) Siemens b) NIS	 - 1-cell mo - 1-cell mo
- igniter	- 1-cell mo
- sump vaporization	- homoge

SBEP #	Short description	Year	Dispersion	Combustion
V01	'Russian' test	2005	+	
V02	FhICT baloon deflagration test	2005		+
V03	INERIS jet experiments	2005	+	
V04	FZK jet experiments	2006	+	
V05	GexCon muti-compartment experiments	2006	+	
V06 ext.	BAM experiments with LH2	2006	+	
V07	Shell RS premixed experiments	2006		+
V08	KI combustion tube with end venting	2006		+
V09 ext.	FHICT experiments with DDT	2006		+
V10	HSL jet tests	2007	+	
V11	QRA-connected exercise (Tunnel)	2007	+	
V12	Tunnel (Groethe, et al.)	2007		+
V13	KI tests in RUT (Detonation)	2007		+
V14	Explosion with vent (Pasman et al)	2007		+
V15	QRA-connected exercise (comvustionof V11)	2007		+
V16	HSL / Shell dynamic tests H2-air for RS model	2008		+
V17	SNL free space & impinging jets	2008		+
V18	Vessel 10.3 m3 Whitehouse H2-air	2008		+
V19	Combustion tube with transverse venting	2008		+
V20	Swain test in garage with car	2008	+	
V21	CEA dispersion tests in garage - to be finally decided	2008	+	

Mixing classification

Main phenomena and processes which has to be considered in mixing simulations including their coupling

- **Extreme thermodynamic states (20K, 80 MPa)**
- **Compressibility**
- **Buoyancy**
- **Diffusion**
- **Phase changes**
  - **Condensing gases (H2, H20, air, etc)**
  - **Evaporating liquids (H2, H20…)**
- **Multiple components**
- **Gradient mixtures**
- **Turbulence**
- **Frictional and electrostatic effects**
- **Heat transfer**

State of the Art in Gas Mixing
Open issues vs established techniques

- **Jet Releases**
  - ☑ **Free, slow, vertical upwards**
  - **Cold**
  - **Fast**
  - **Horizontal**
  - **Wall attached**
  - **Multiphase**
  - **Cross-wind**
  - **Discharge coefficients**

- **LH2 pools**
  - ☑ **Heat transfer (soil, gases)**
  - **Condensing air**

- **Diffusion**
  - **Gravitational effects**

Models:

- ✓ Conservation equation of fluid flow (fully compressible, 3-dim, Navier-Stokes)
- ✓ Thermophysical properties of components (JANAF, internal energy, specific heats, for all relevant components including two-phase water)
- ✓ Molecular transport coefficients (CHEMKIN, thermal conductivity, dynamic viscosity, binary diffusion coefficients)
- ✓ Convective and radiative heat transfer between gas and structure
- ✓ Heat conduction within structures
- ✓ Condensation and vaporization of water (film, droplets, sump)

State of the Art in Gas Mixing

Open issues vs established techniques

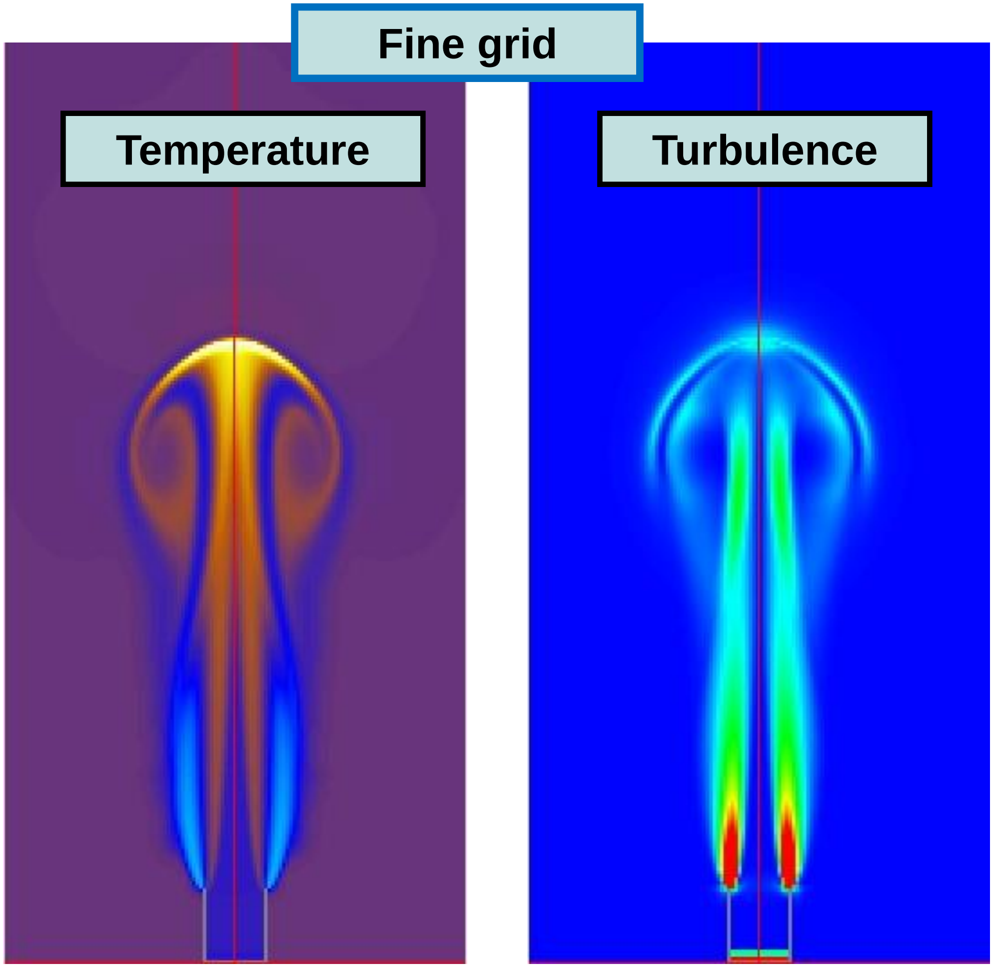
- **Permeation releases**
  Particle vs Continuum

- **Turbulent transport**
  ☑ **Turbulence models for middle sized scenarios**
  Parameters for high pressure, cryogenic gases
  Gravitational effects on turbulent transport
  Wall effects
  Complex geometries
  ☑ **Turbulent dissipation**

- **Multi-phase transport**
  Droplet, dust, gas interaction

Models:
- ✓ Boundary layer model for wall shear stress
- ✓ Turbulence modeling (algebraic, k-e, LES, effects on molecular transport coefficients)
- ✓ At least lumped parameter models for accident mitigation measures (recombiner and igniter models, liquid sumps,…)
- ✓ Ventilation systems (ducts, pipes, junctions, blowers, dampers, valves, filters, etc.)

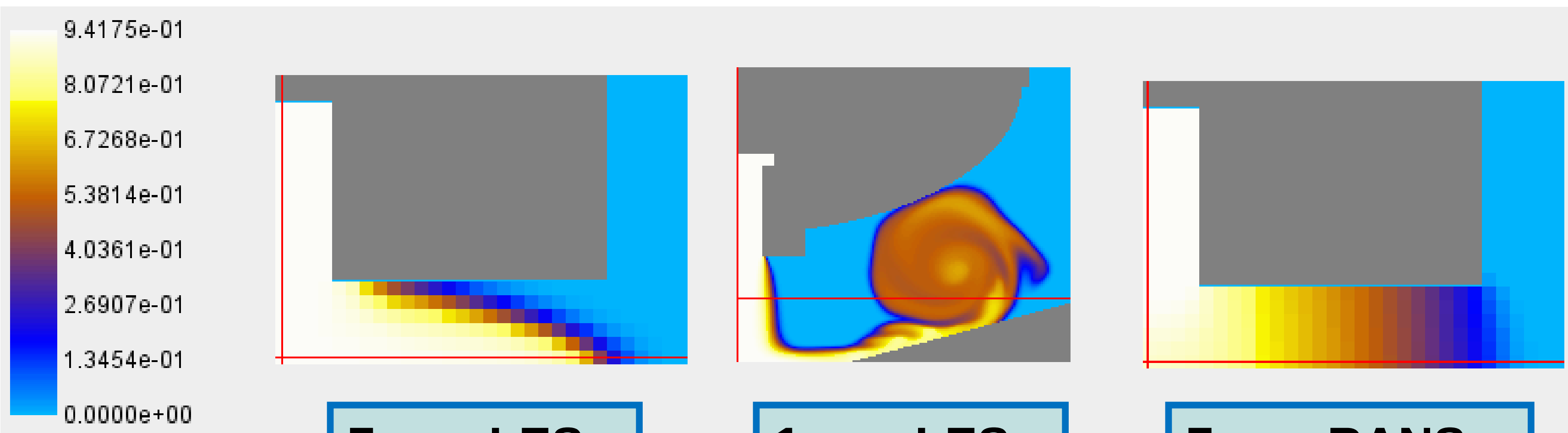
State of the Art in Jet Modelling
Free vertical upward jet



3D simulation of the head of H_2 jet in air
Turbulence: LES Smagorinsky

Eternal problem: spatial resolution

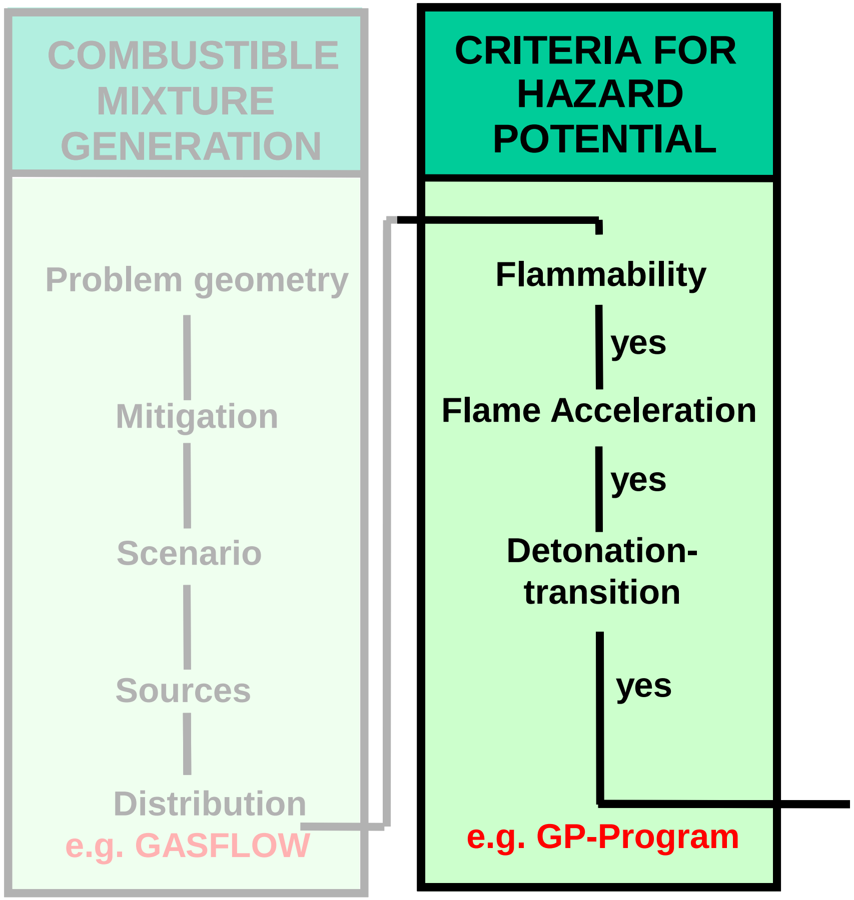
e.g. downward release into a cavity



7 mm LES | **1 mm LES** | **7 mm RANS**

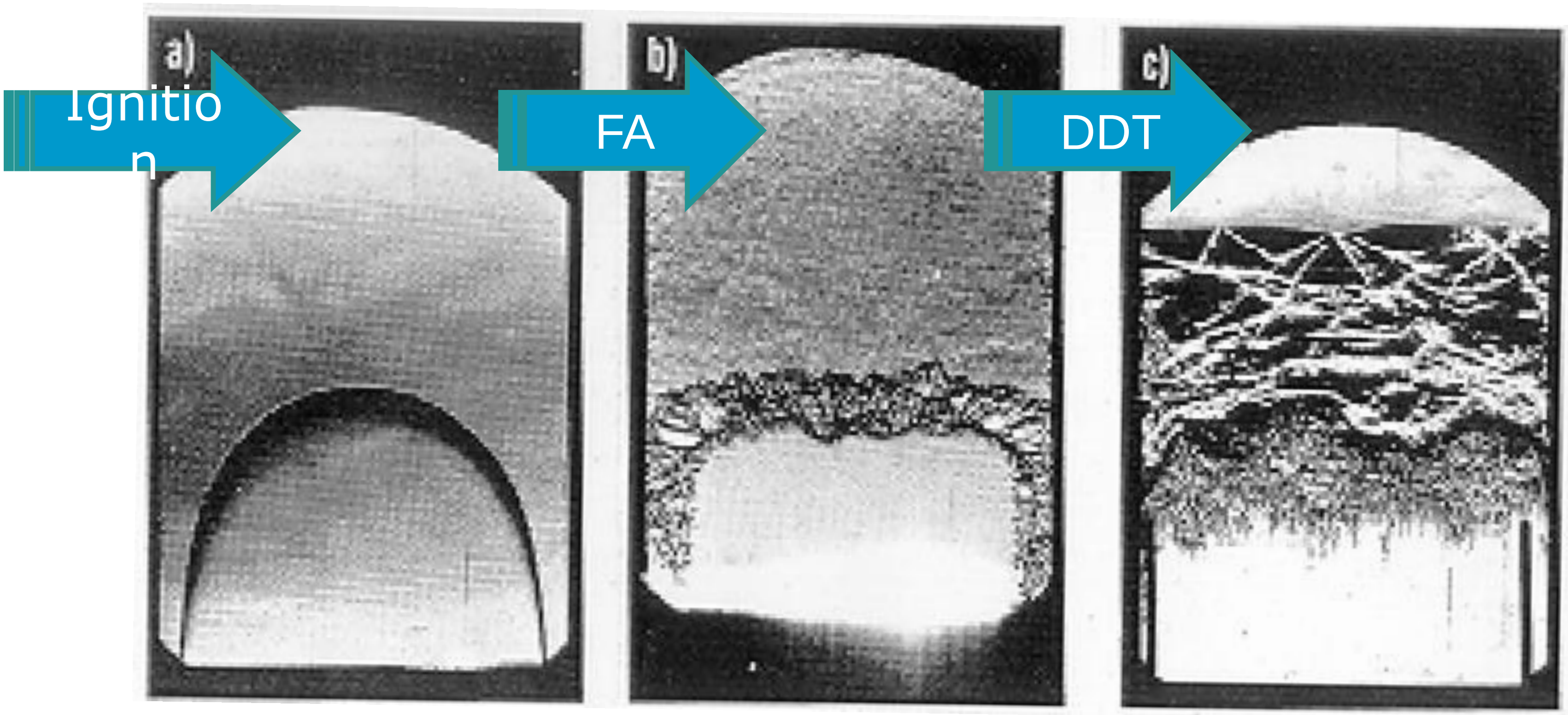
State of the Art Consequence Modelling

Criteria for Hazard Potential



Transient phenomena
Cross-over of combustion regimes

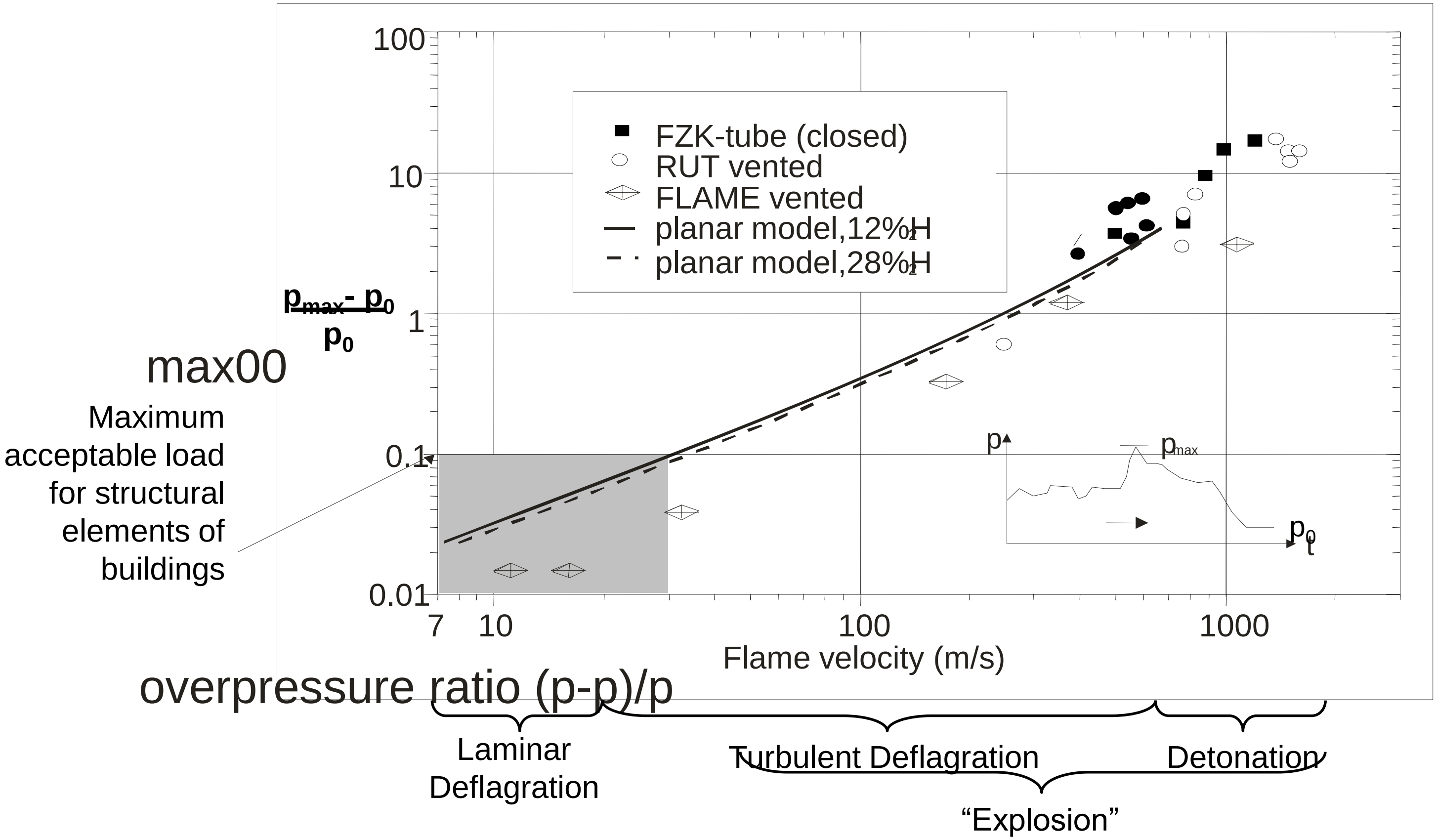
Schlieren images of different combustion regimes



Laminar deflagration	Fast turbulent deflagration	Detonation
v = 8 m/s, Ma << 1	v = 850 m/s, Ma ≈ 1	D = 1970 m/s, Ma >1

M. Kuznetsov et al

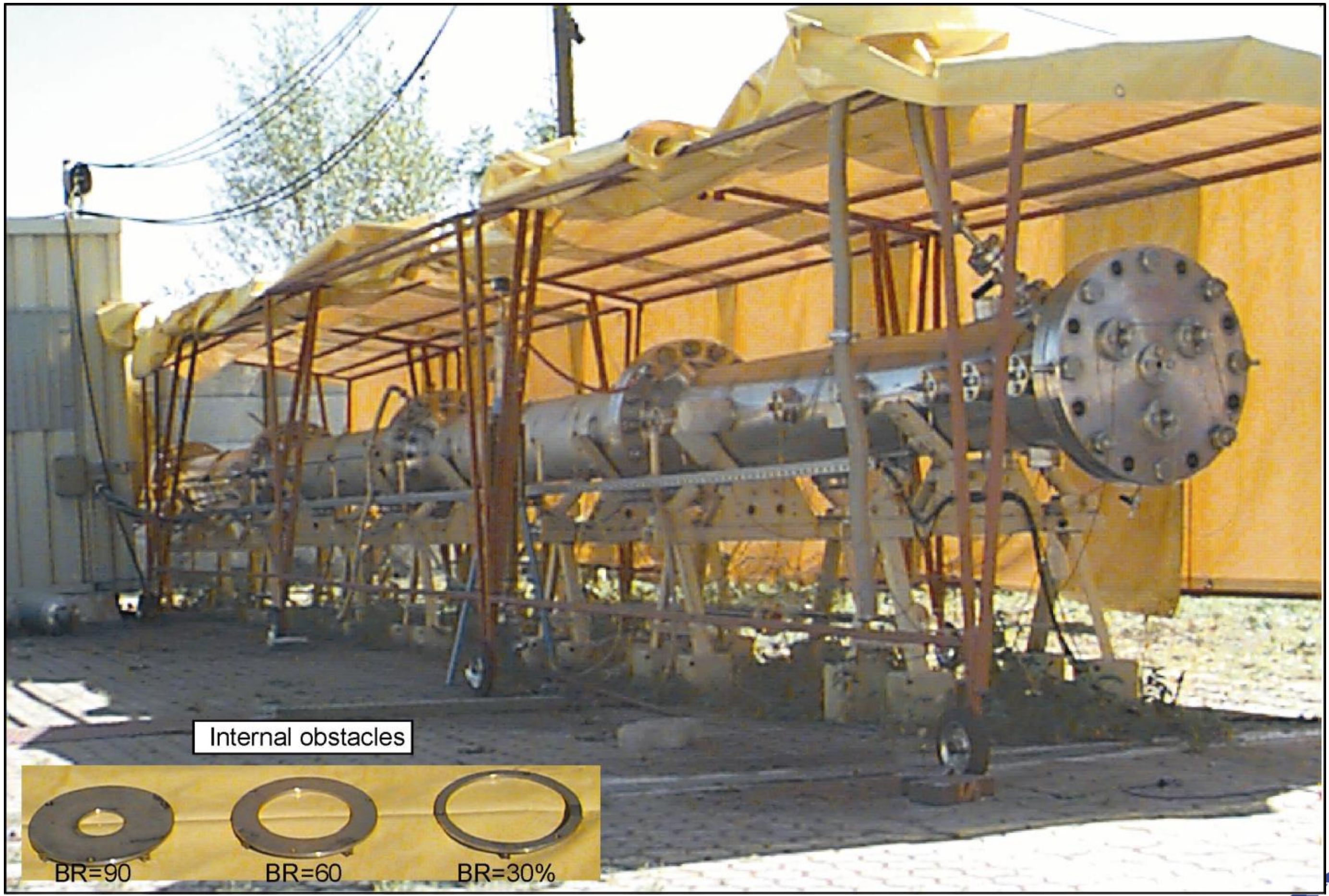
Combustion Consequence
Overpressure



- The maximum flame speed generally governs the damage potential
- Which combustion regime for given mixture and geometry?
- How fast can it burn?

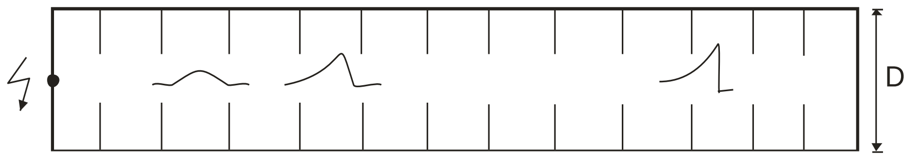
Flame Acceleration FA

Conservative conditions for flame acceleration in hydrogen mixtures were investigated in closed obstructed tubes, e.g. FZK 12m-tube



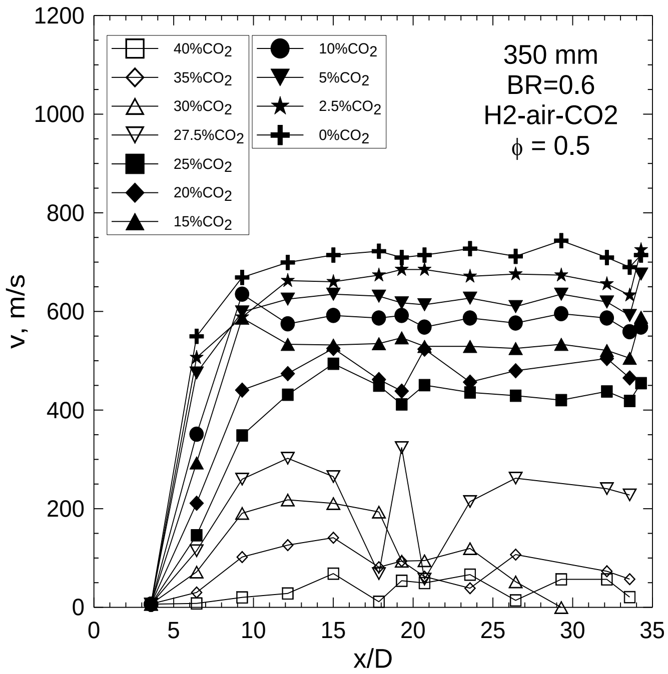
FA criterion

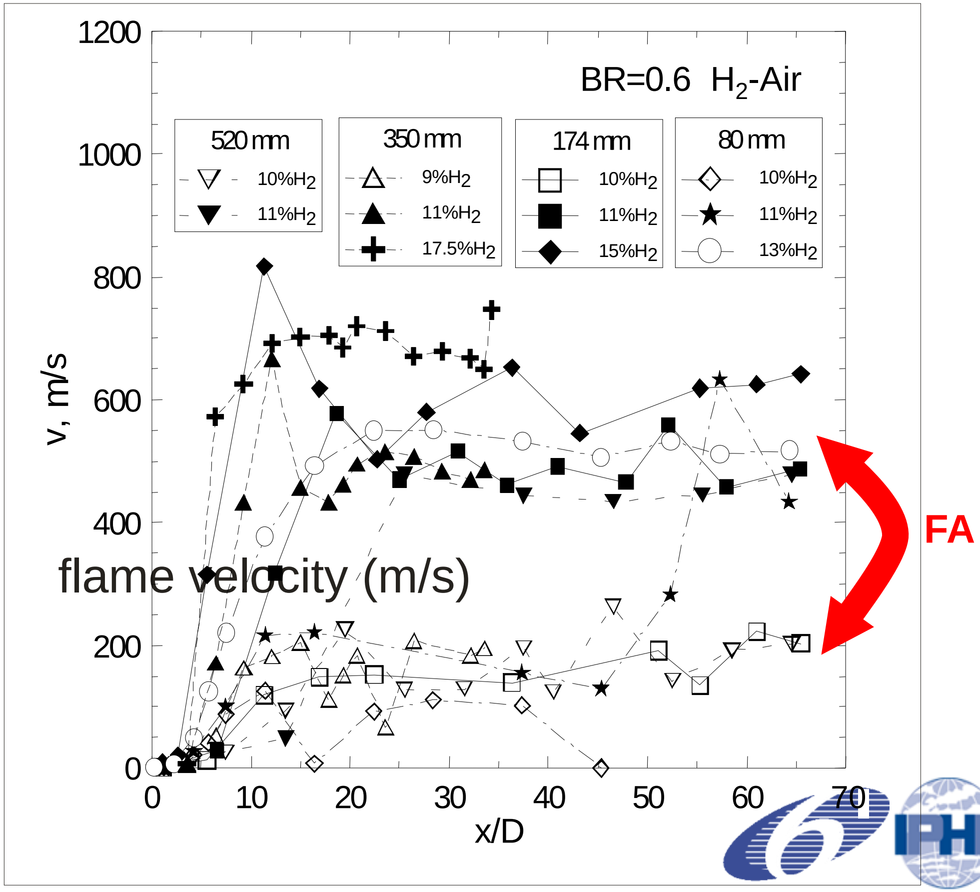
Influence of obstruction



- Lean hydrogen mixtures in obstructed tubes with different tube diameters D and 60% blockage ratio (BR)

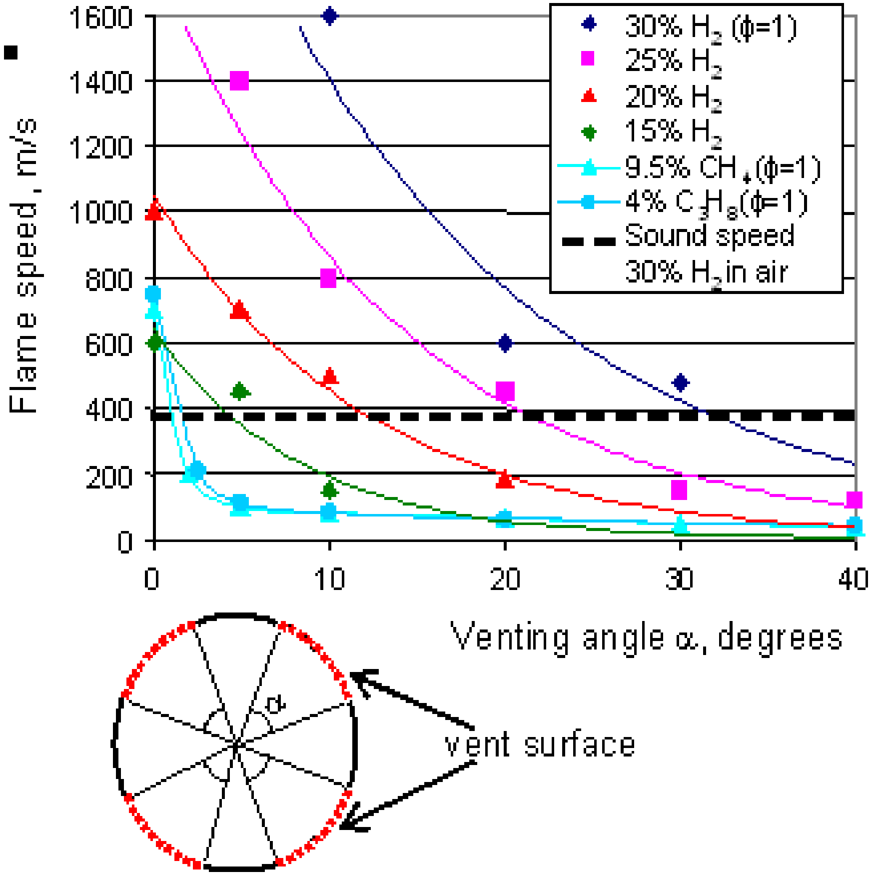
- Two distinct regimes with slow and fast flame propagation are observed





FA criterion

Influence of confinement



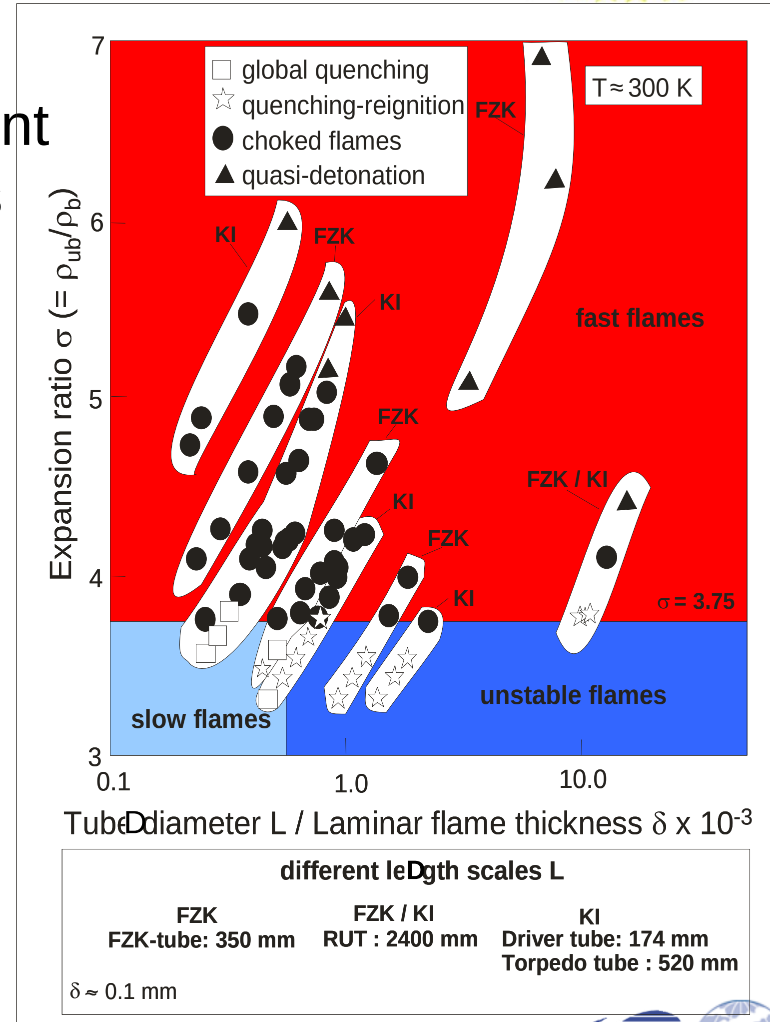
S.B. Dorofeev et al, KI/FZK

FA criterion

Summary

- Summary of experiments with different H_2-O_2- dilutend (N_2, Ar, He) mixtures in obstructed tubes of different scales
- Each point represents one experiment

- Results of data evaluation: expansion ratio σ of mixture is is mixture property which governs flame acceleration limit
- No flame acceleration for $\sigma < 3.75 \pm 0.1$ (10.5% H_2 in dry air)

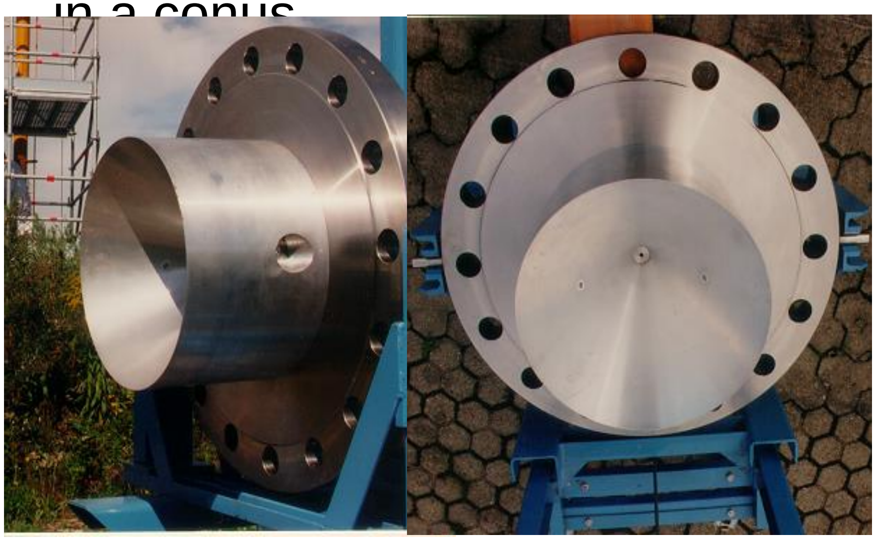


S.B. Dorofeev et al, KI/FZK

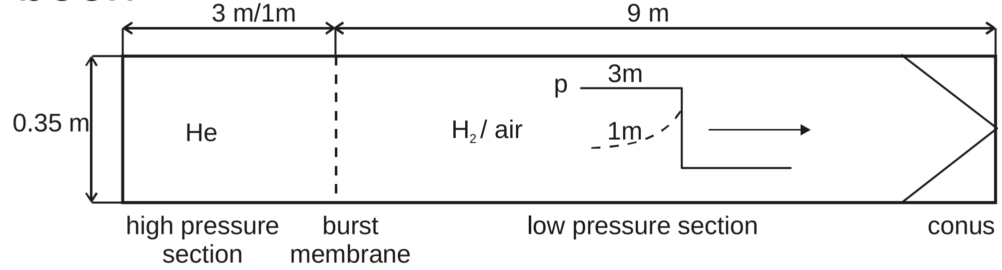
Deflagration-to-Detonation-Transition DDT

- Two different modes of DDT have been observed
  - shock focussing
  - detonation on-set in turbulent flame brush

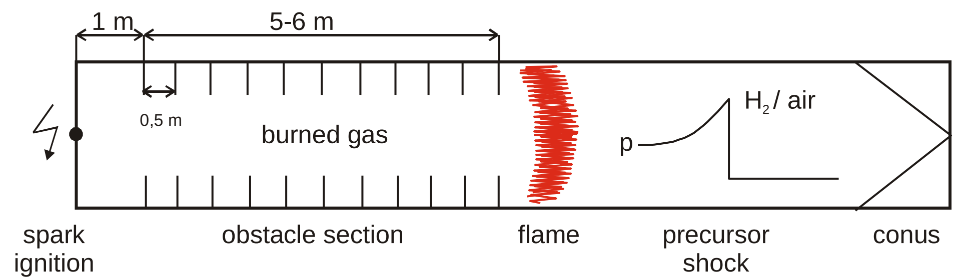
- Present here are one example for DDT with pressure wave emitted from an obstructed region and focussed in a conus



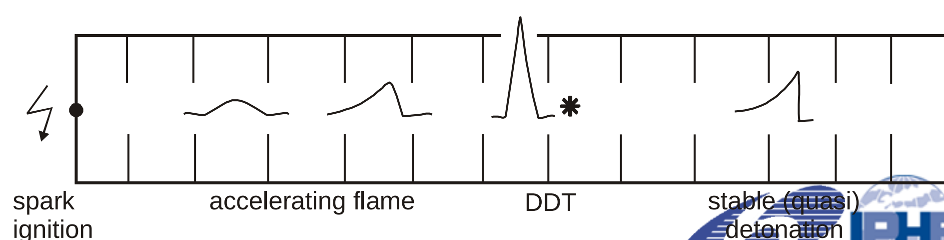
- **Shock tube with conus (idealized mode A)**



- **Partially obstructed tube with conus (prototypic mode A)**



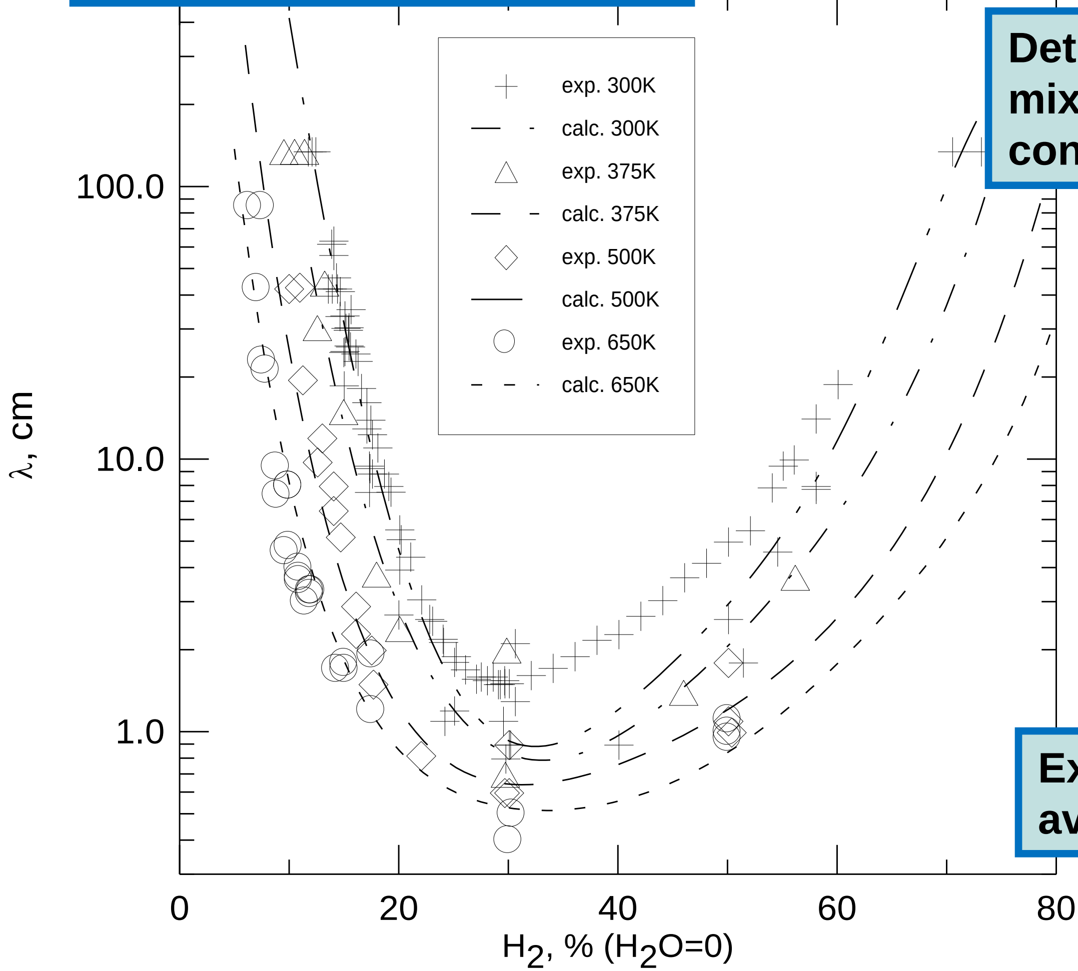
- **Fully obstructed tube (prototypic mode B)**



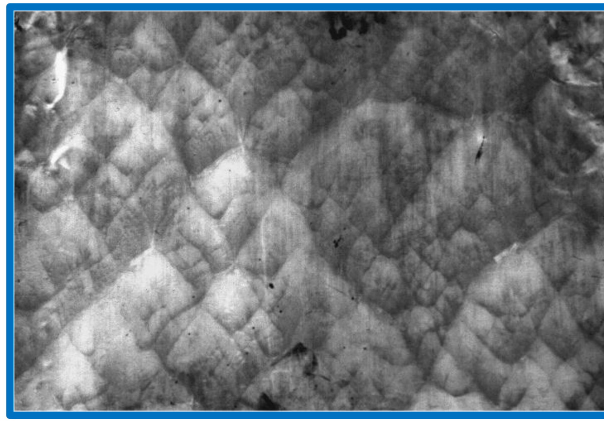
DDT criterion

Detonation cell size

Cell sizes for H_2-air mixtures at various initial temperatures



Detonation cell sizes λ depend on mixture composition and initial conditions

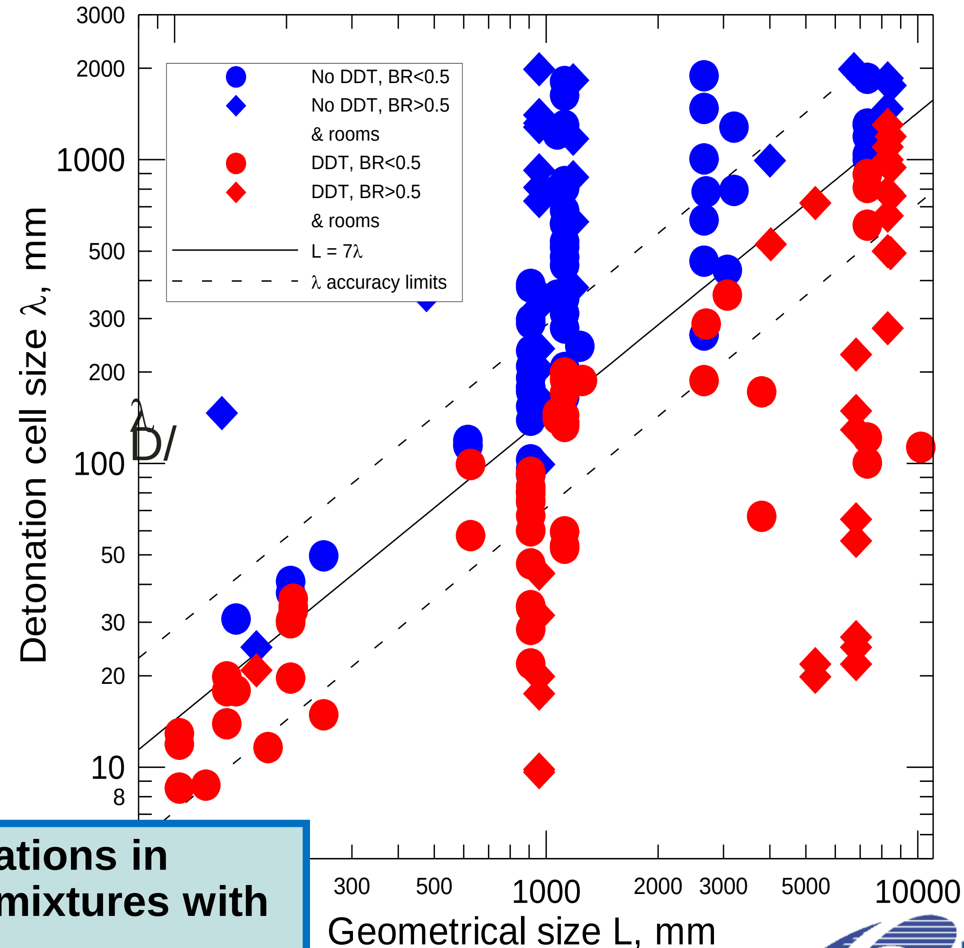


Experimental data and models are available for λ evaluation

DDT criterion

7λ-criterion

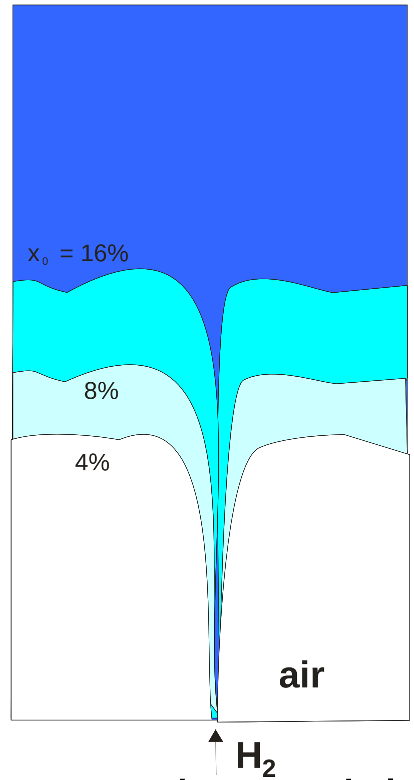
- Experiments on DDT in differently sized and shaped facilities have shown that a certain minimum scale is required for DDT
- Correlation of all experimental data with given definitions of D and detonation cell size data shows that detonations are only possible for $D/\lambda > 7$
- Current uncertainty in detonation cell size $\lambda \approx$ factor 2
- In accident scenarios D/λ can vary by orders of magnitude, criterion has predictive capability



Critical conditions for onset of detonations in rooms and channels with obstacles (mixtures with irregular cellular structure)

Summary of Criteria

Criteria for possible occurrence of fast combustion regimes were evaluated from many experiments on different scales

Flame acceleration		Detonation transition
$\sigma_{index} = \dfrac{\sigma_{(average\ mixture)}}{\sigma_{critical}\ (T)} = \begin{cases} < 1 \text{ excluded} \\ > 1 \text{ possible} \end{cases}$		$\dfrac{D}{7\lambda} = \dfrac{(\text{Cloud volume})^{1/3}_{\sigma_{index} > 1}}{7\lambda\ (\text{average mixture})} = \begin{cases} < 1 \text{ exluded} \\ > 1 \text{ possible} \end{cases}$

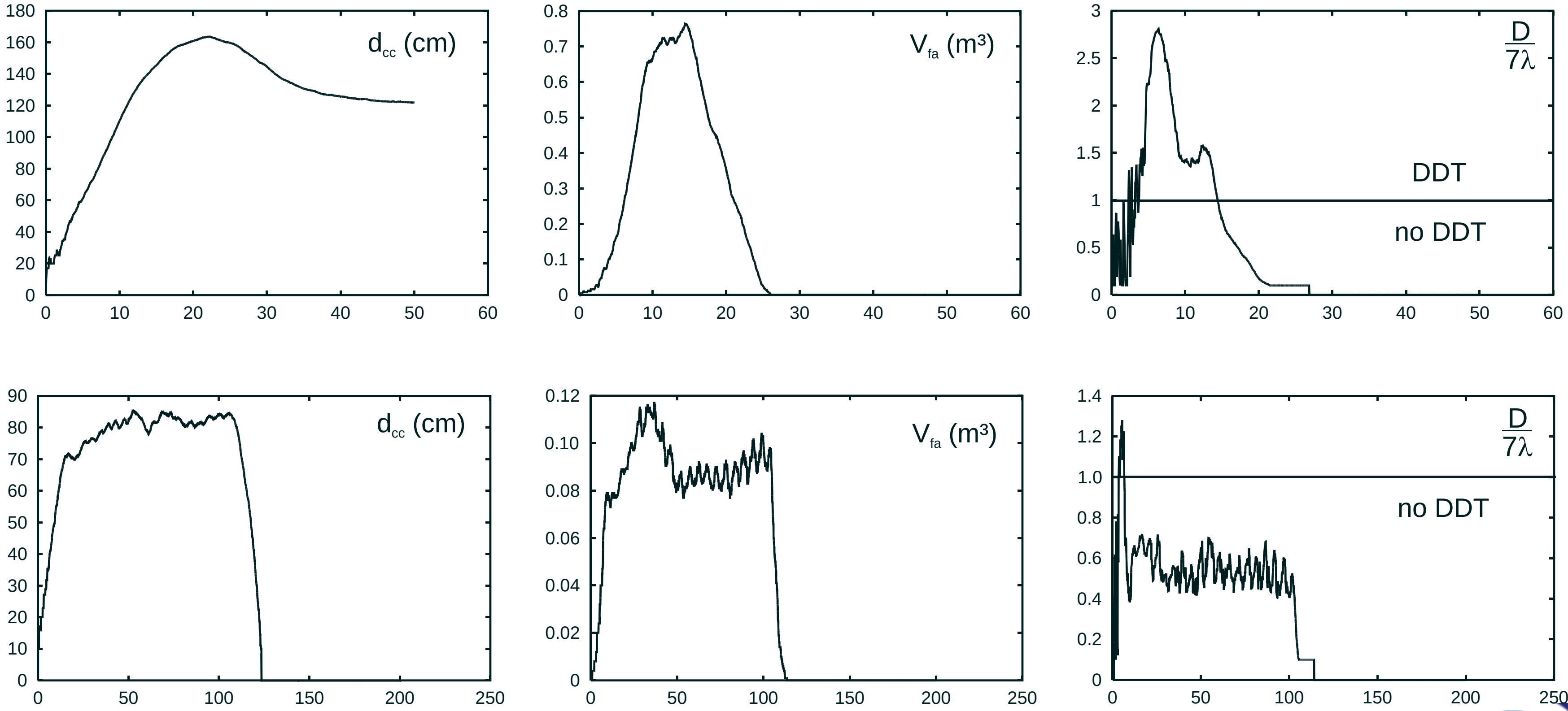
- Transition phenomena cannot be modeled numerically on large building scale
- Criteria allow selection of fastest possible combustion mode from computed H_2-air cloud composition and scale

Computed Hazard Parameters
for selected garage scenario

- Dimension of combustible cloud, 4 to 75 % H_2, $d_{cc} = (V_{cc})^{1/3}$
- Volume of cloud with potential for spontaneous flame acceleration (10.5 to 75 % H_2)
- DDT index of cloud (10.5 to 75 % H_2)

CASE 1 3.4 g H_2/s for 10 s

CASE 2 0.34 g H_2/s for 100s



Computed Hazard Parameters
for selected garage scenario

- Risk parameters show strong dependence on H_2 release rate

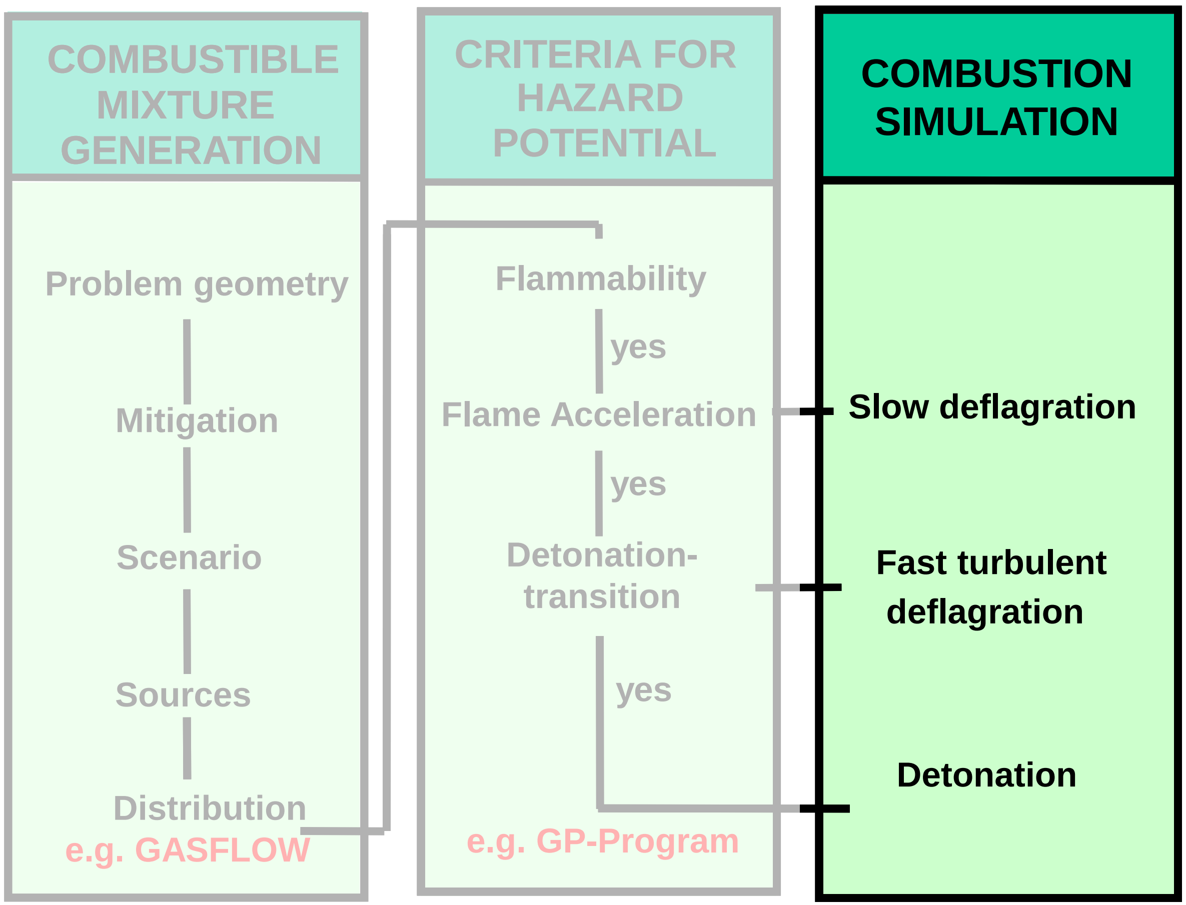
- Case 1:
  (3.4 g H_2/s)
  - Contineous potential for slow deflagration (≈ 20 g of 34 g)
  - potential for supersonic combustion regimes during the release period
  - high release rate not tolerable without mitigation measures

- Case 2:
  (0.34 g H_2/s)
  - only small potential for slow deflagrations, natura mixing processes sufficient
  - release rate (and mass) seems tolerable for present garage design

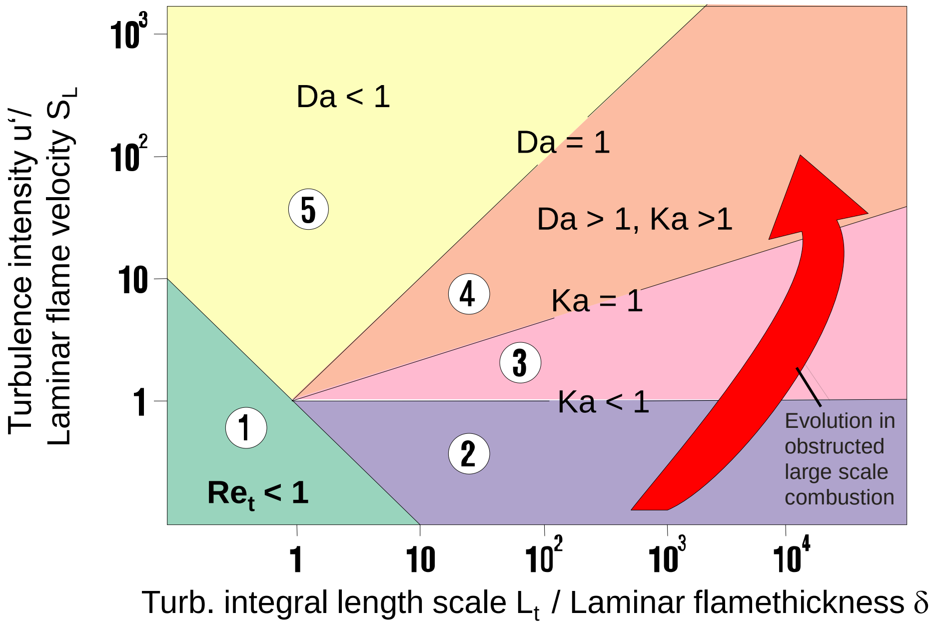
→ Only Case 1 followed in further safety analysis

State of the Art Consequence Modelling

Analysis Methodology



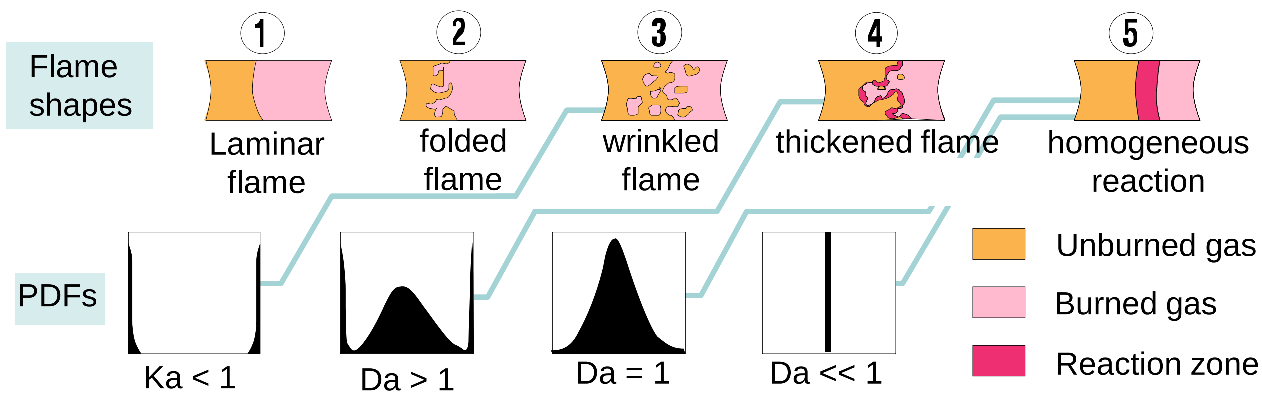
Turbulent combustion regimes



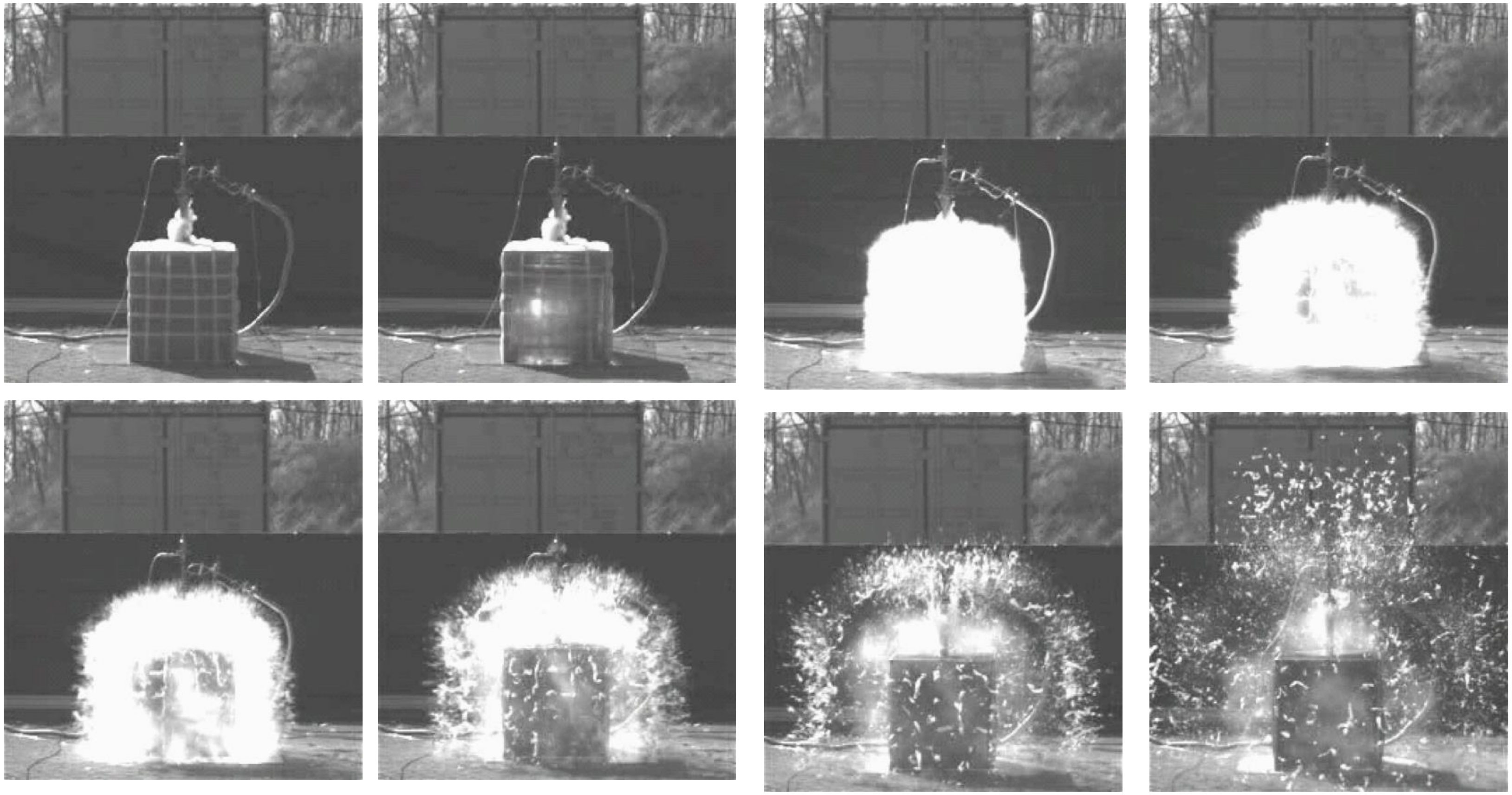
$$Re_t = \frac{u' L_t}{\nu}$$

$$Da = \frac{\text{Turb. Transport time (makro)}}{\text{Laminar reaction time}} = \frac{L_t / u'}{\delta_L / S_L}$$

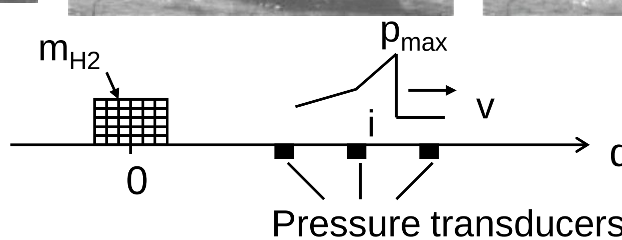
$$Ka = \frac{\text{Laminar Reaction time}}{\text{Turbulent transport time (Kolmogorov scale)}} = \frac{\delta_L / S_L}{l_K / u'_K}$$



Unconfined Tests
with the Combustion Unit

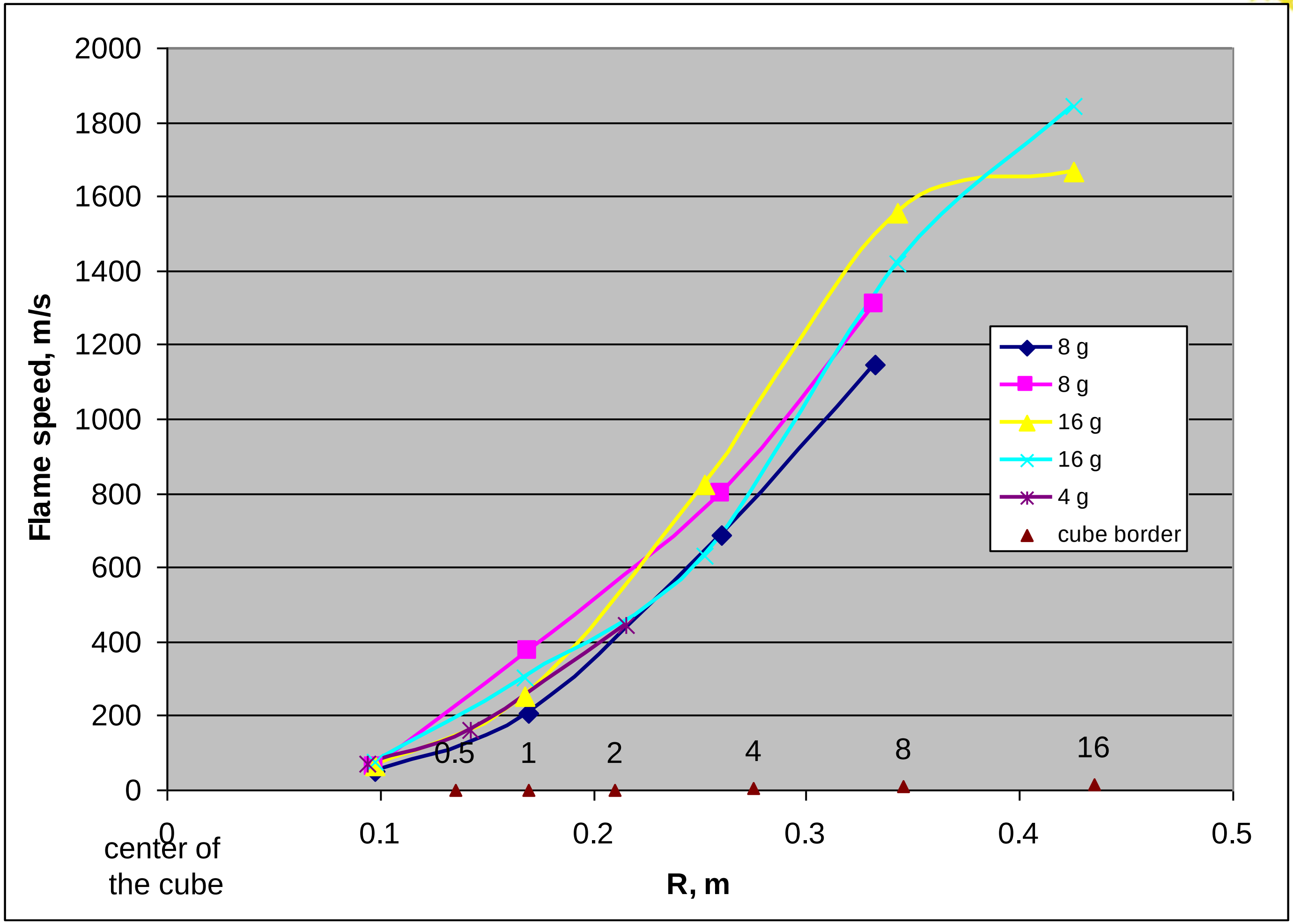


- Peak overpressure and impulse measured as function of distance to characterize blast effects from combustion unit



$$I_+ = \int_{\Delta p>0} \Delta p(t)dt$$

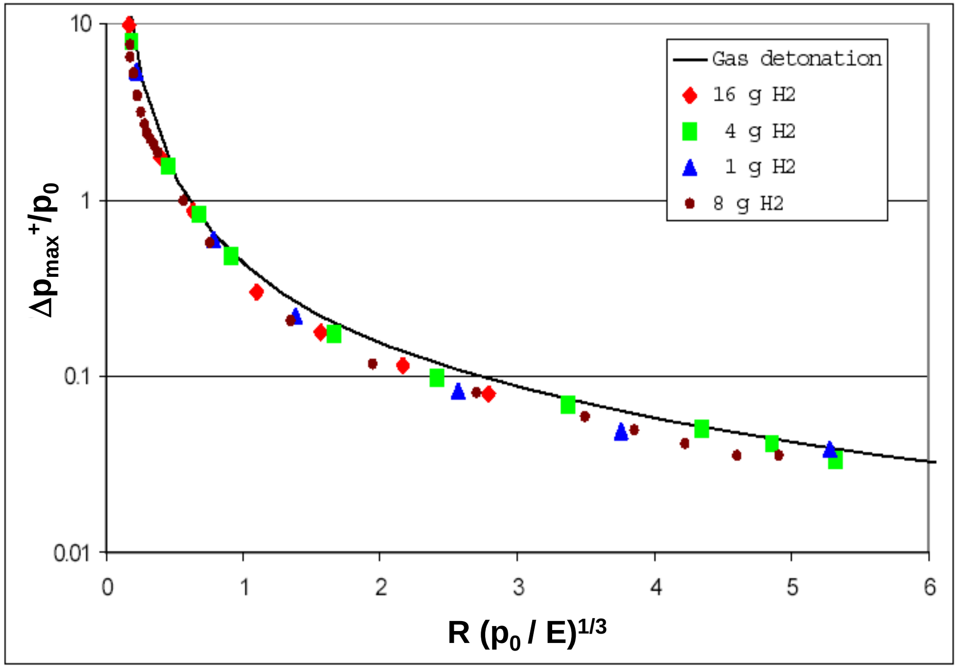
Flame speeds in the Combustion Unit



- The flame acceleration inside the combustion units measured with photodiodes
- For 8 and 16 g H_2 detonation speeds are obtained at the outer edge of the cube

Simulation of Unconfined Tests

- The unconfined tests with different combustion units were simulated (with COM3D in this case)
- The combustion model was fit to the measured flame speed in the combustion units



- The calculated peak overpressures agree with the experimental values and follow Sachs scaling

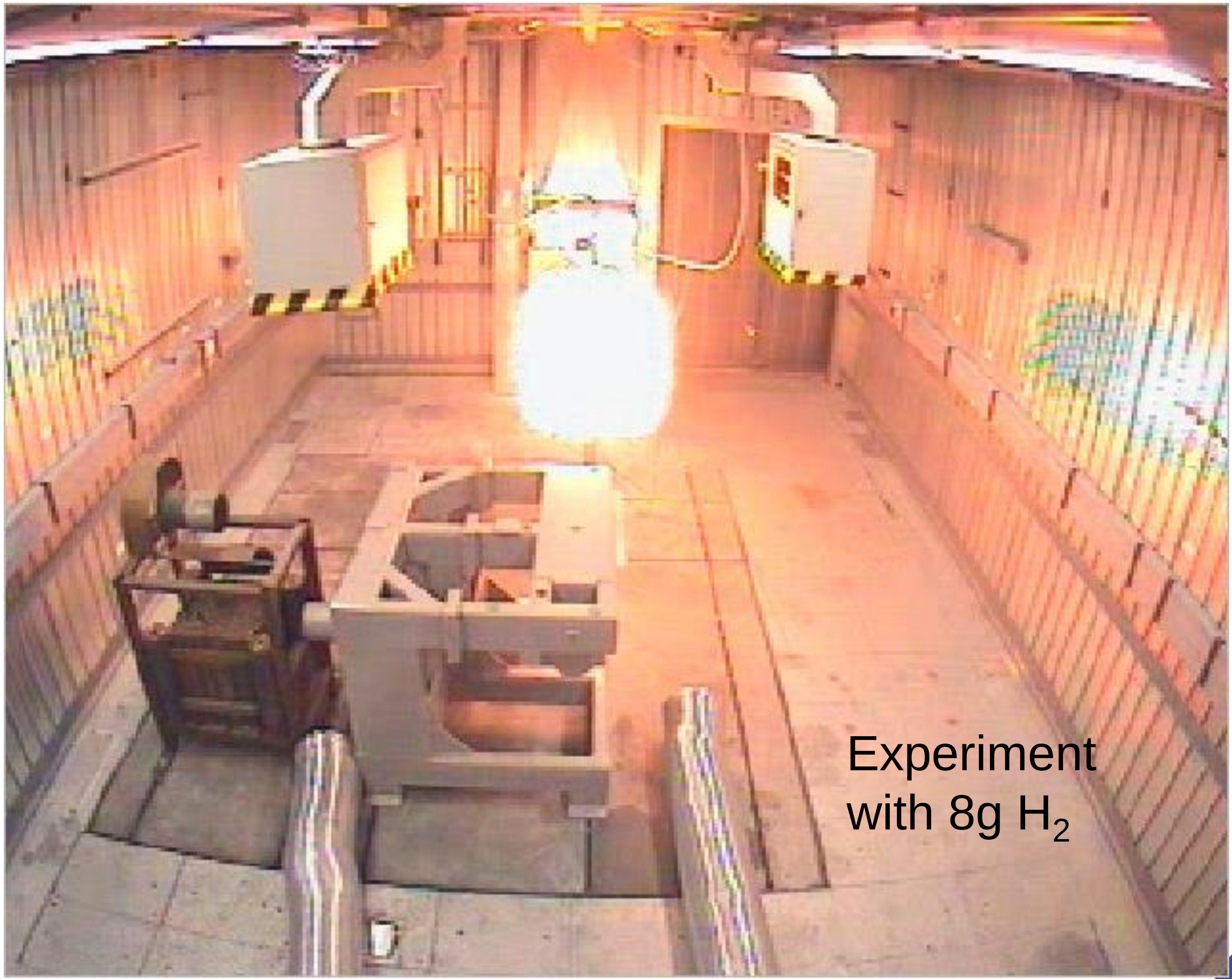
Combustion experiments for Case 1

- Up to 20 g of hydrogen would be in burnable concentrations
- A significant part of this could potentially burn with high flame speeds
- What would be pressure loads and consequences from a local explosion in the garage?
- Outcome uncertain, experiments performed in test chamber simulating the garage

Local H2 Explosions in a "Garage"

H_2 - mass:

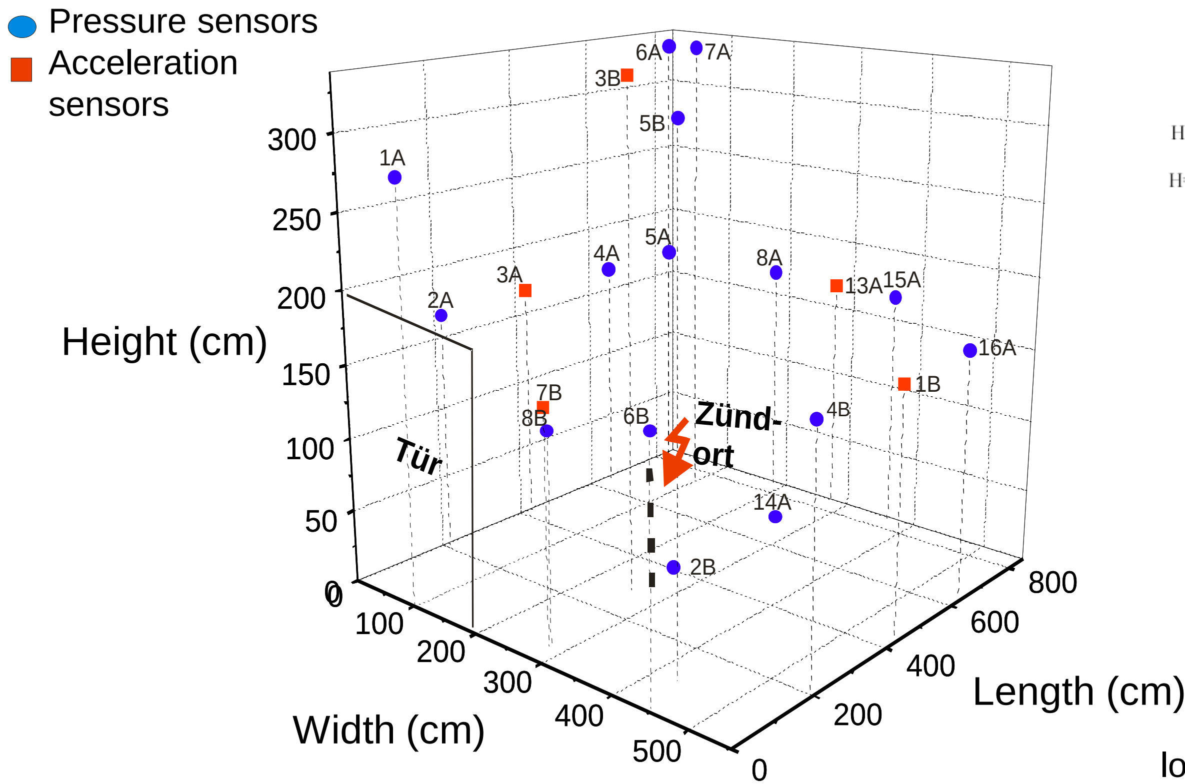
- 1g
- 2g
- 4g
- 8g
- 16g

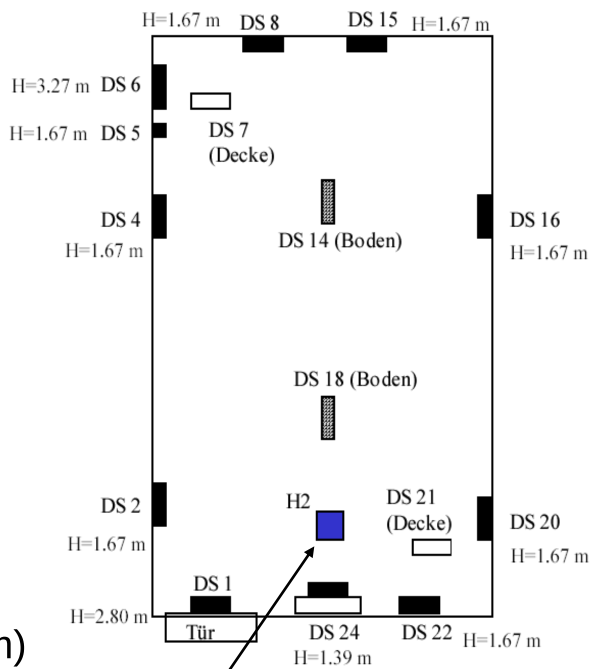


Experiment with 8g H_2

Instrumentation of the „Garage“

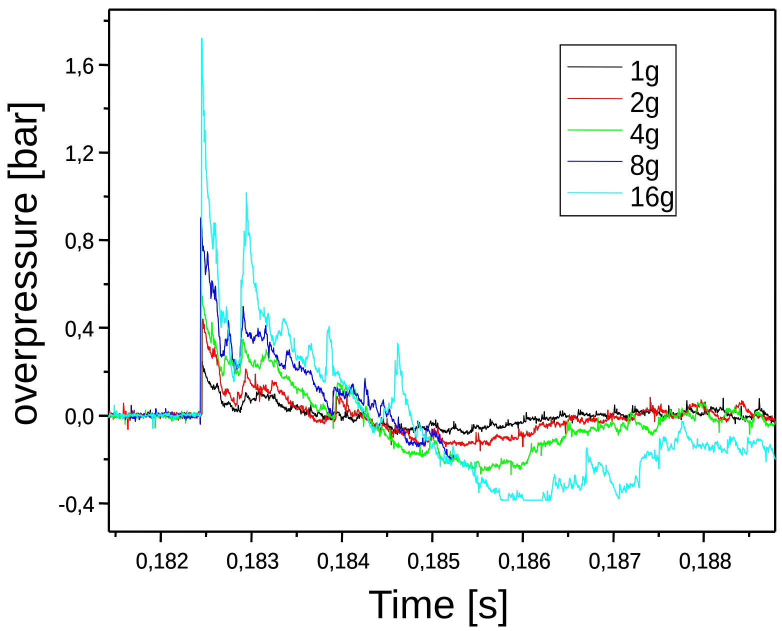
The instrumentation included pressure and acceleration sensors at different locations, covering flat surfaces, (2d) edges and (3d) corners



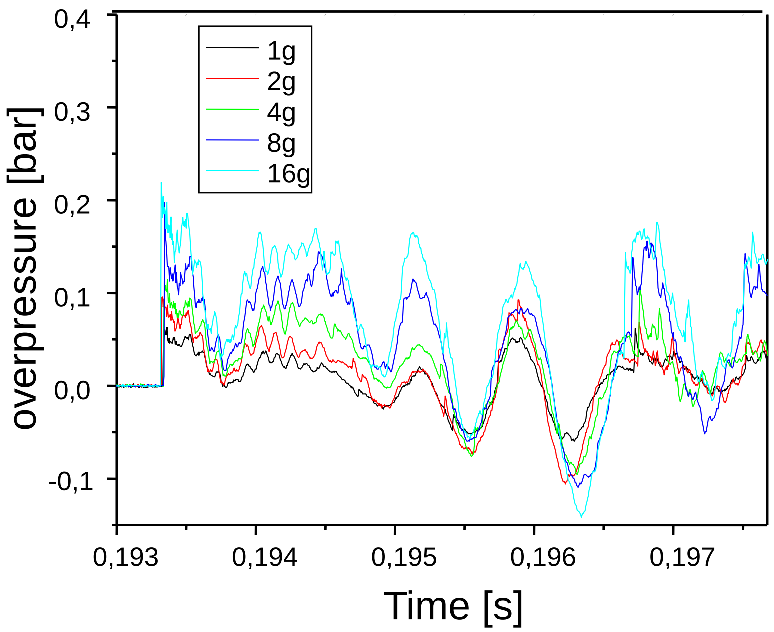


Comparison of Overpressures

- Pressure sensor 2 B,
  floor near combustion unit



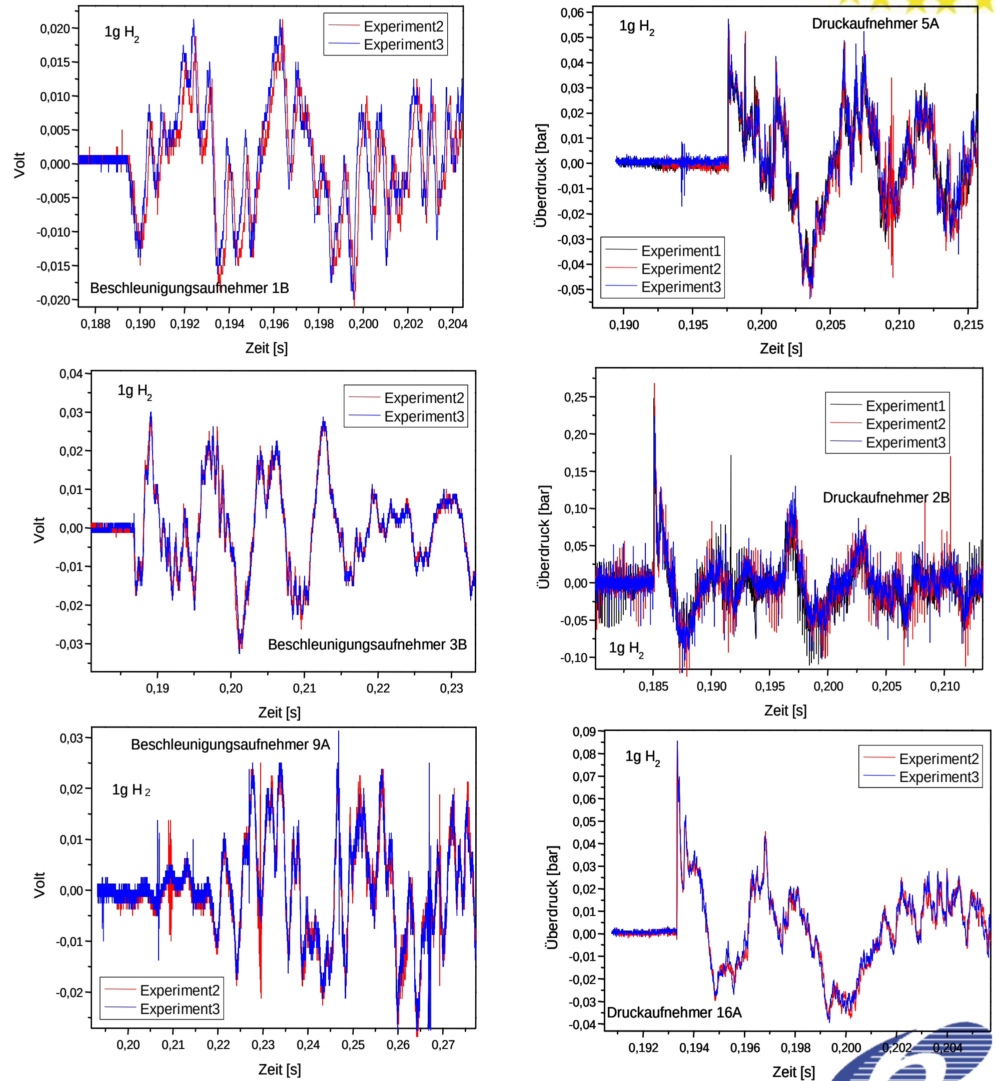
- Pressure sensor 8 A,
  back wall, half wall height



- Pressure signals very consistent in timing, amplitudes increase systemarically with H_2 mass, reproducible pattern of reflected pressure waves in confined volume.

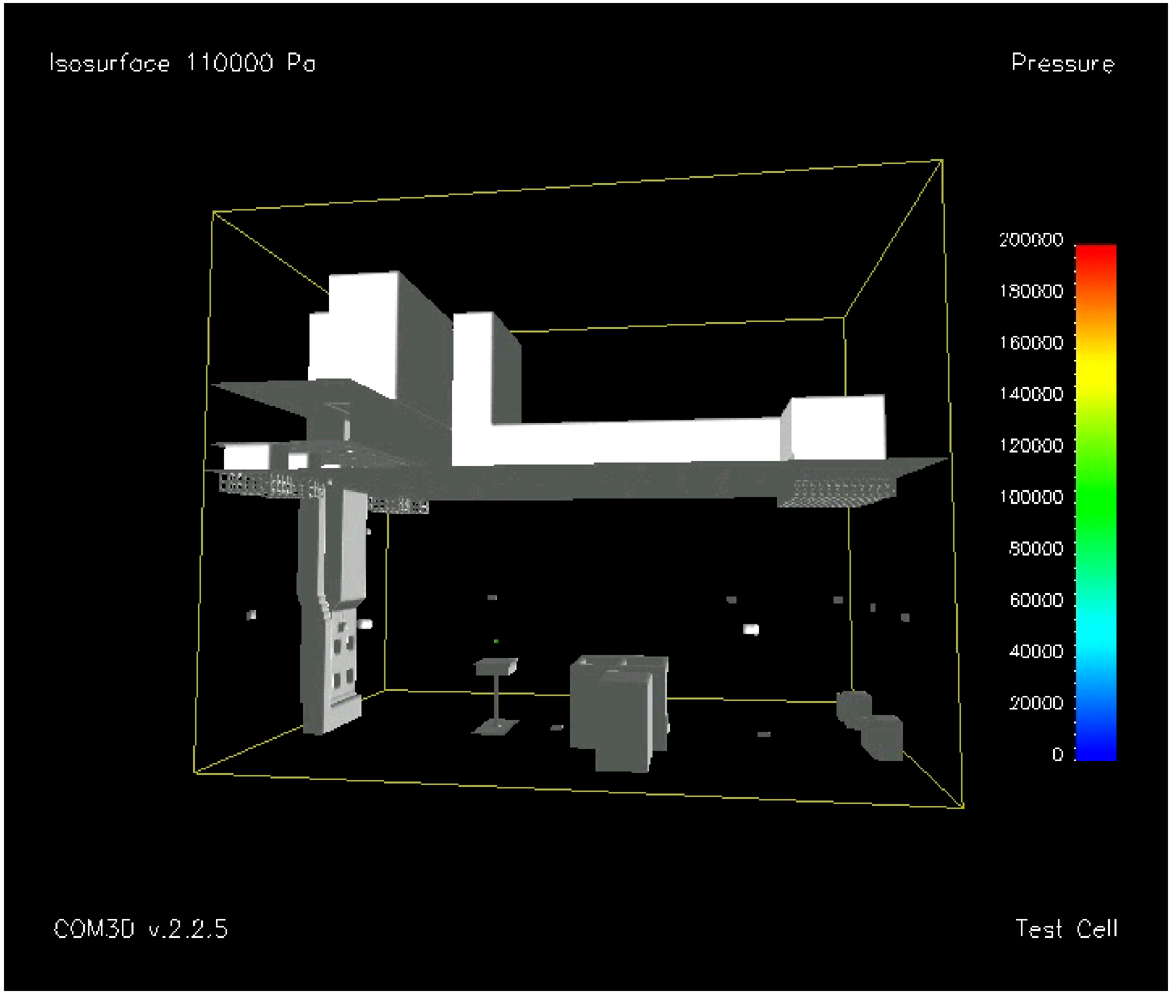
Reproducibility of Measured Data

- The experiment with 1 g H_2 was performed three times
- Acceleration and pressure sensors show very good reproducibility of measured signals
- Complex, but reproducible pressure waves are created in confined local explosions of H_2-air mixtures



COM3D State-of-the-Art Combustion Simulation

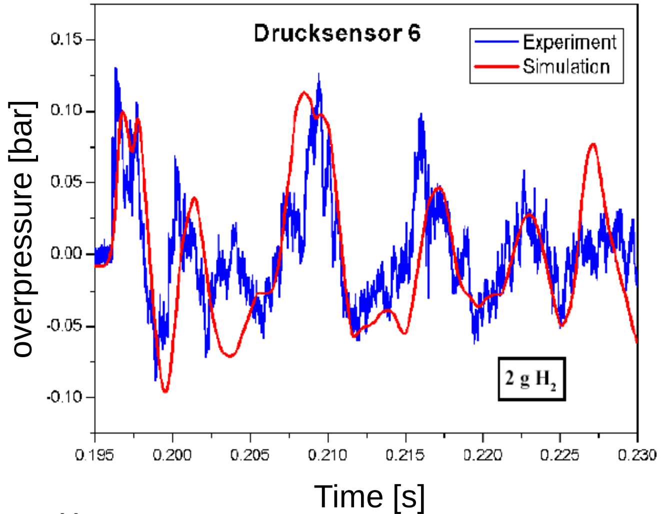
Test
with 8g H_2

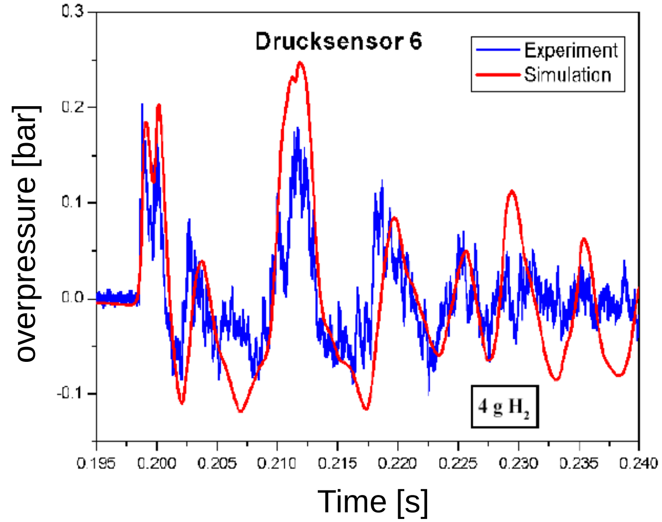


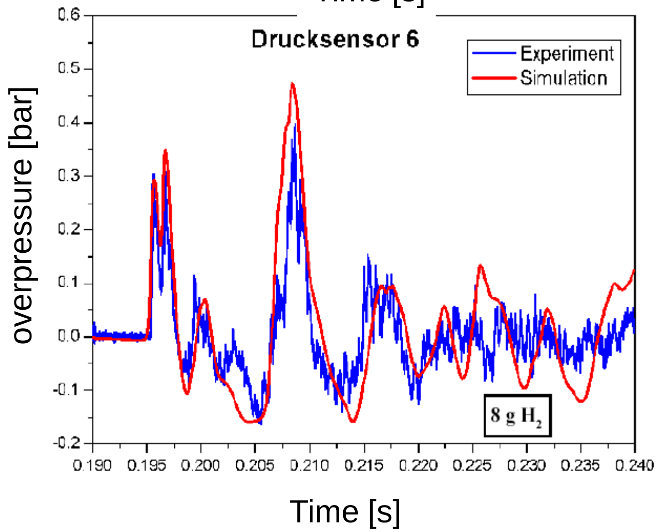
3d pressure field, calculated isosurface for 1.1 bar

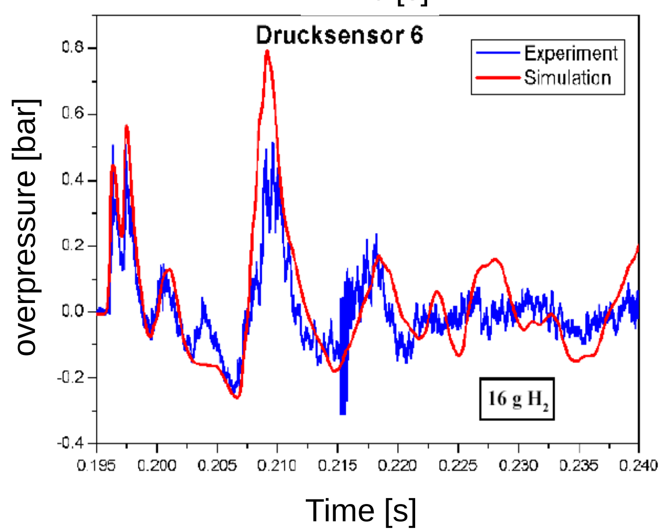
Comparison of Overpressures

Good agreement, remaining differences are due to geometry simplification and rigid wall model in simulation







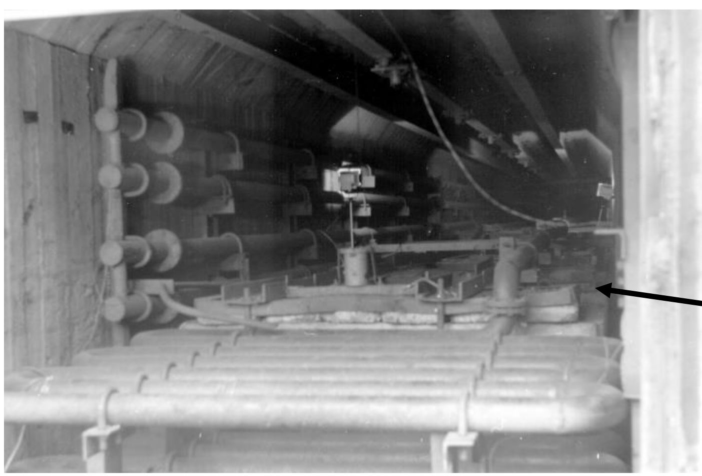


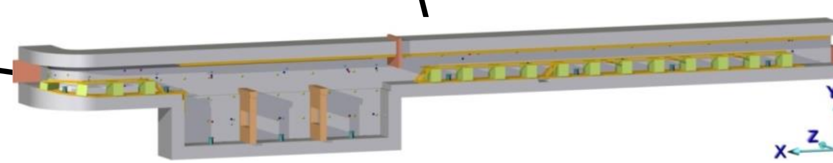
State-of-the-Art Reactive CFD Validation

Large scale experiments (HySafe SBEPs)

performed in RUT facility near Moscow (FZK, CEA, partly NRC), H_2-air, H_2-air-steam

- Total length 62 m
- Total volume 480 m^3
- First channel with obstacles
- Second part without obstacles

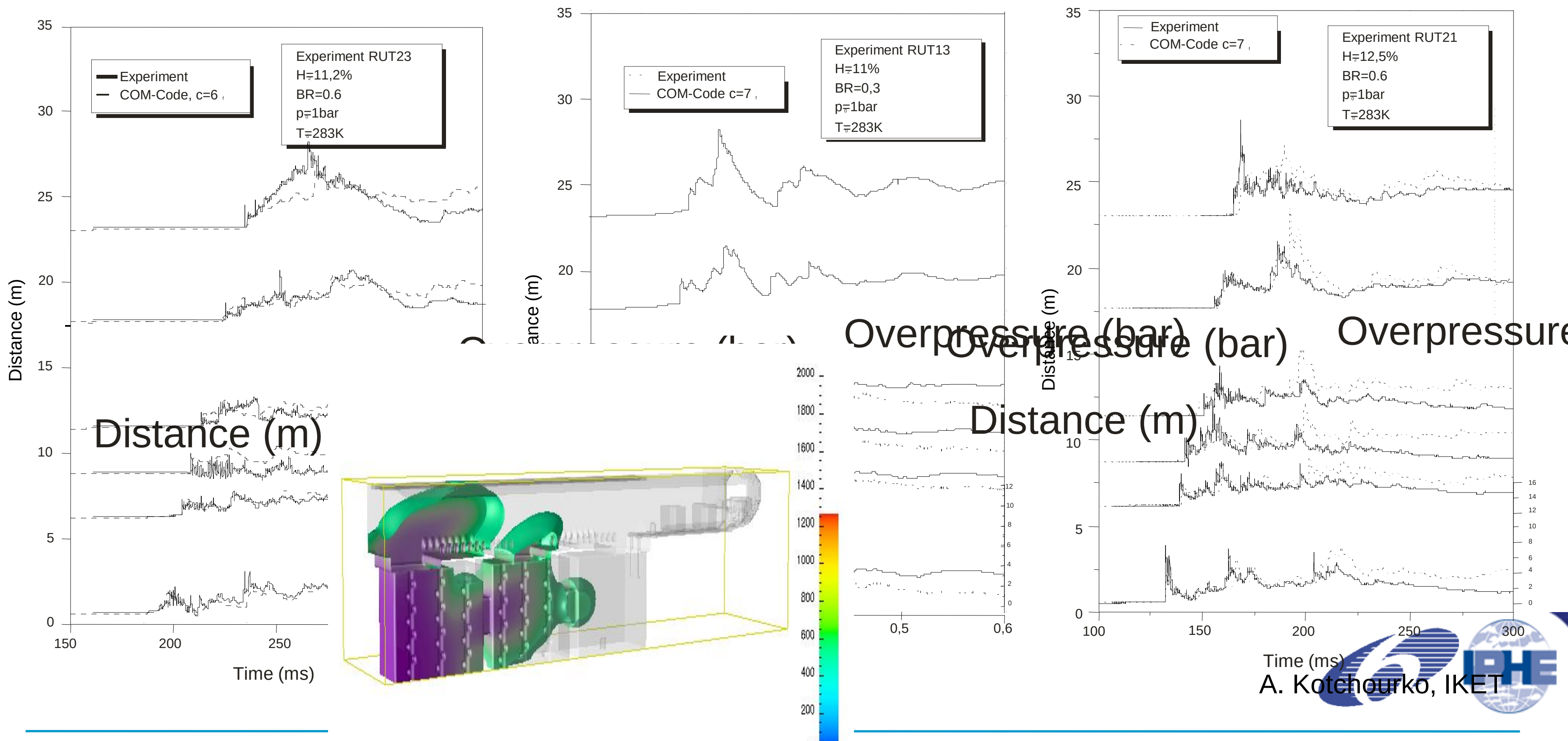




RRC KI 1995 – 2002: RUT-2200

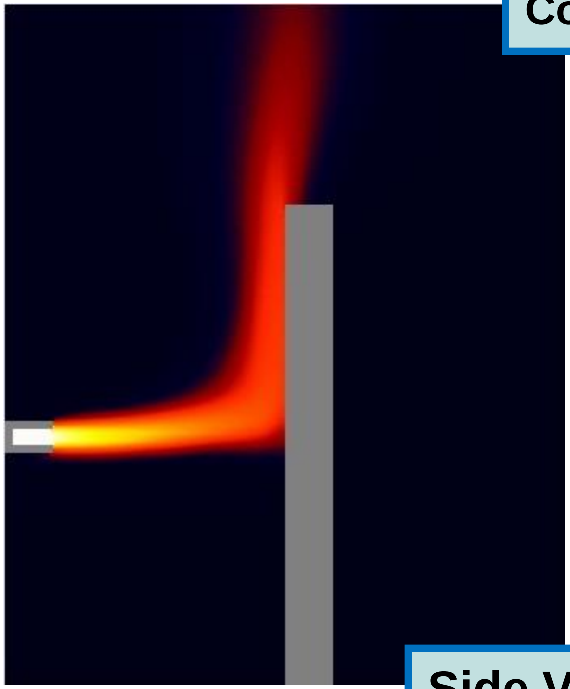
State-of-the-Art Reactive CFD Validation
Large scale experiments

Numerical simulation of RUT experiments with hydrogen-air and hydrogen-air steam mixtures.
Standard k-ε and Eddy-Break-up model.

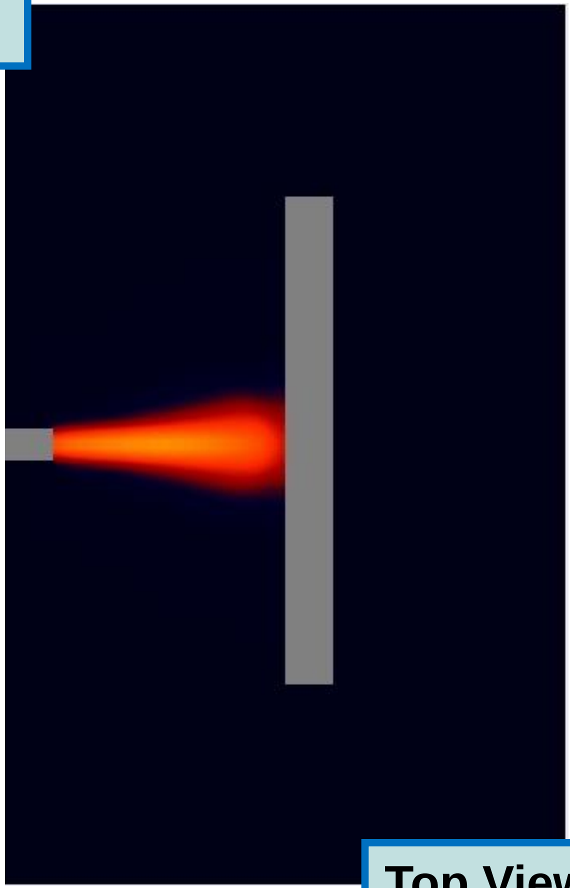


Impinging jet flame

Coarse grid



Side View



Top View

Modeling of the H2 impinging jet
Injection time 200 ms

Combustion classification

Main phenomena and processes which has to be considered in combustion simulations due to their strong influence on combustion/explosion consequences

- **Ignition**
- **Combustion in different regimes**
- **Initial conditions**
  - **Mixture composition**
  - **Turbulence**
  - **Gradients (e.g., concentration)**
- **Boundary conditions**
  - **Obstructions**
  - **Confinement**
  - **Heat Transfer**
  - **Turbulence**

State of the Art in Combustion

Open issues vs established techniques

- **Ignition**
  - **Weak / Mild ignition (e.g., spark, glowing plug, igniter, recombiner)**
  - **Strong ignition (e.g., spark, high explosives, ignition in reflections)**
  - **Jet ignition**

- **Combustion mode**
  - **Laminar combustion**
  - **Flame acceleration / deceleration**
  - **Turbulent deflagration**
  - **DDT**
  - **Detonation**
  - **Quenching**
    - **Local quenching**
    - **Global quenching**
  - **Standing flames and fires**

Models:

✓ Turbulence models
- Standard k-ε model
- RNG k-ε model
- LES with SGS models:
- Smagorinski [Deardorff, 1970]
- mixed [Biringen, 1981]
- dynamic [Germano, 1991]
- approximate deconvolution method (ADM)

✓ Eddy-Break-Up model

✓ EDM

✓ Set of phenomenological combustion models (CREBCOM, HEAVDET, etc)

✓ Presumed β-PDF

✓ 1D PDF (f)

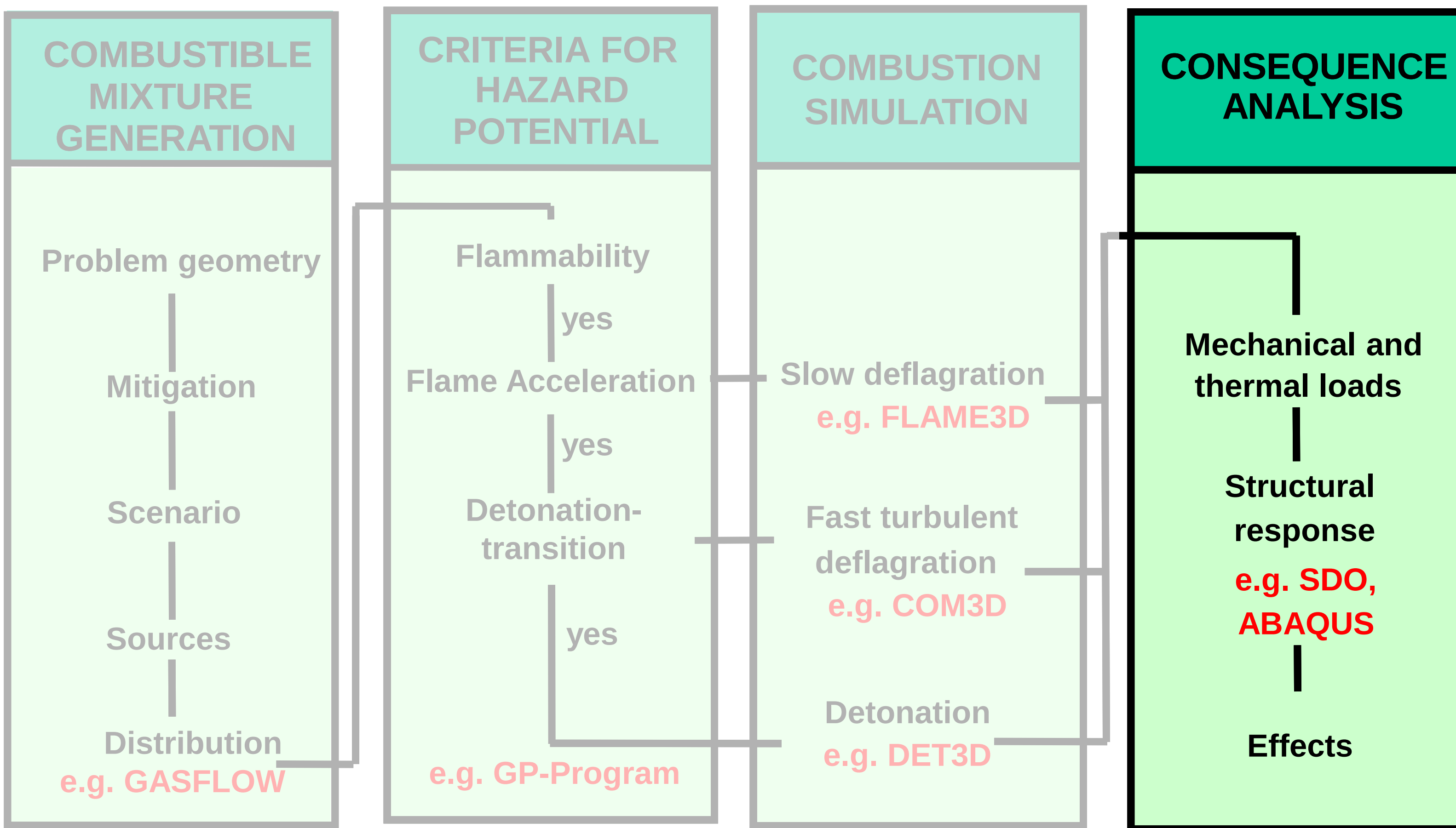
✓ joint PDF (at least 2D: f, T)

State of the Art in Combustion

Open vs established issues and established

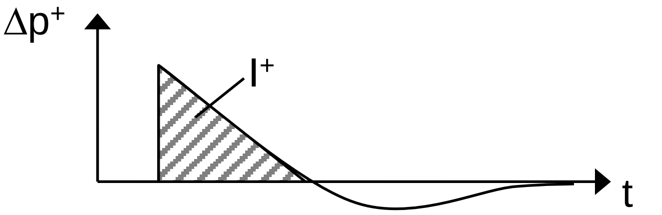
- **Spatial and time resolution**
- **Initial conditions**
  - **Mixture composition**
    - ☑ **Initial concentrations, release rates**
    - **Fuel additives: Carbon monoxide / Hydrocarbons**
    - ☑ **Combustion inhibitors: Steam / Carbon dioxide**
  - **Initial turbulence**
  - **Gradients (concentration, temperature, etc)**
- **Boundary conditions**
  - **Obstructions**
    - ☑ **Large scale obstructions (resolved: same size as the characteristic size of the problem)**
    - **Small scale obstructions (unresolved: much less than the characteristic size of the problem)**
  - **Confinement**
    - **Closed**
    - ☑ **Vented / Semi-confined and open**
  - **Additional sources of turbulence (fans, jets, etc)**

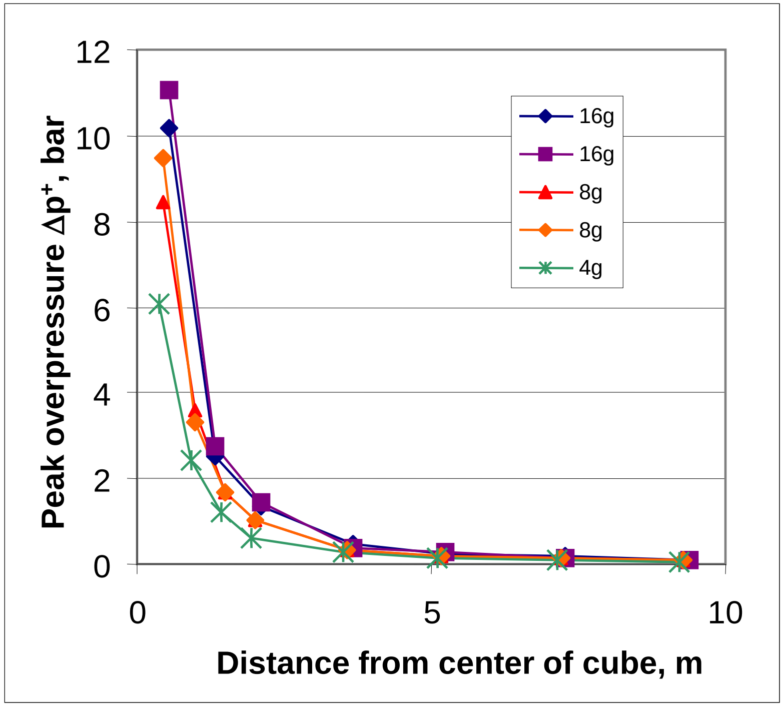
State of the Art Consequence Modelling
Structural response

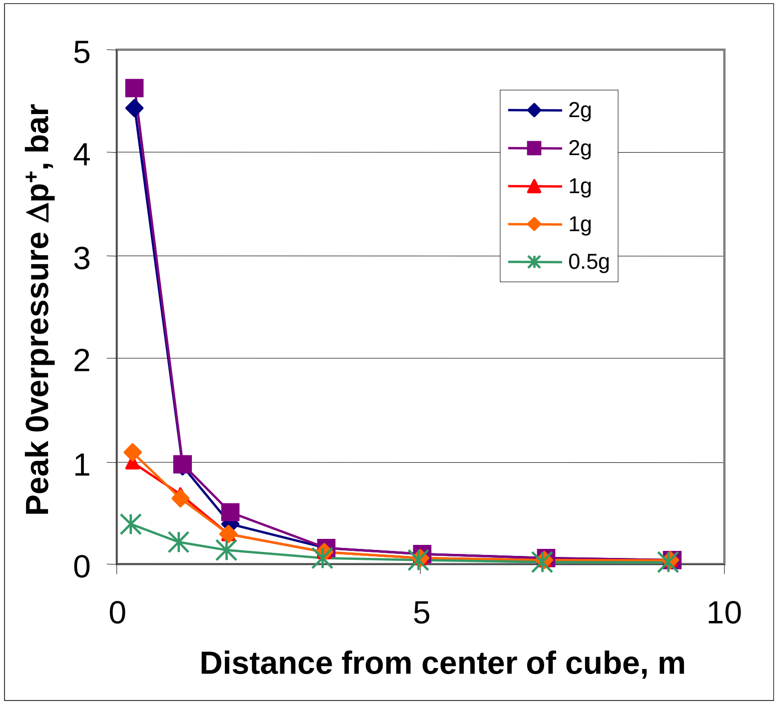


Maximum Overpressures vs Distance

- Measured peak overpressures Δp^+ in unconfined tests with combustion unit of 0.5 to 16 g H_2
- Data are well reproducible

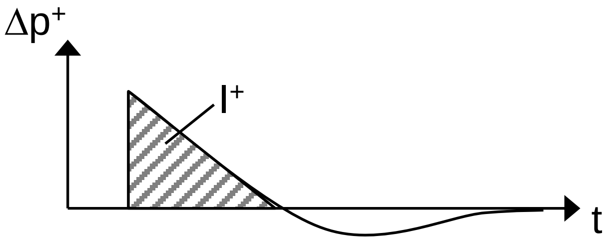


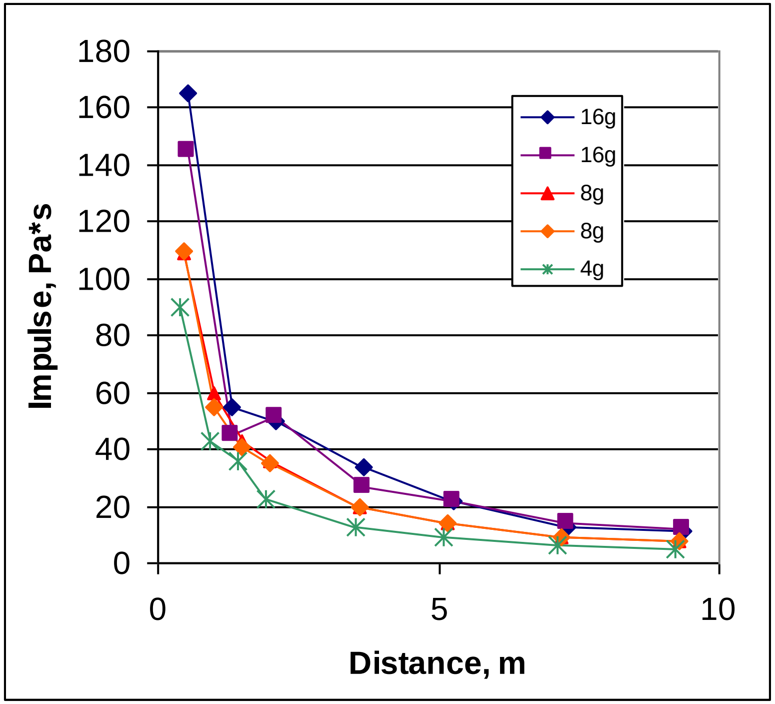


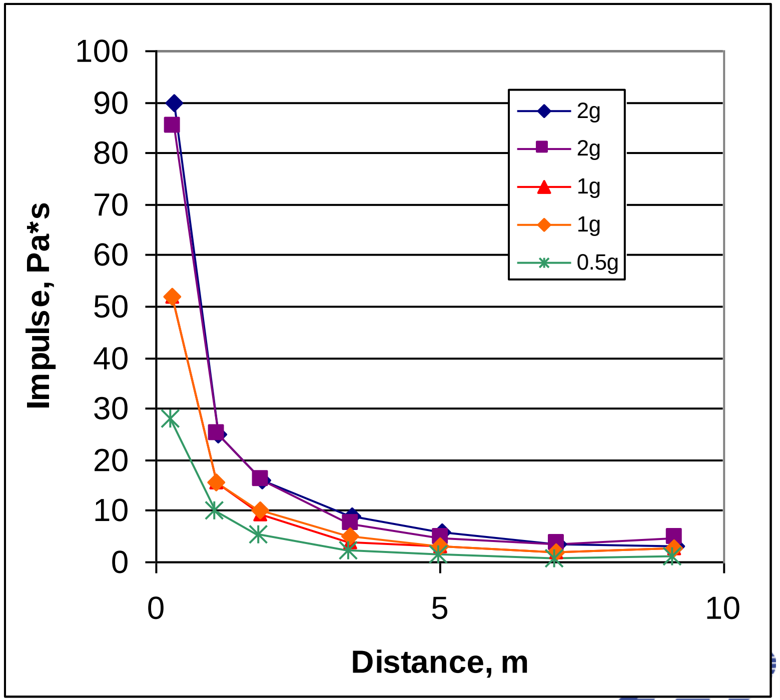


Impulse vs Distance

Measured positive impulse I+ values from unconfined combustion units



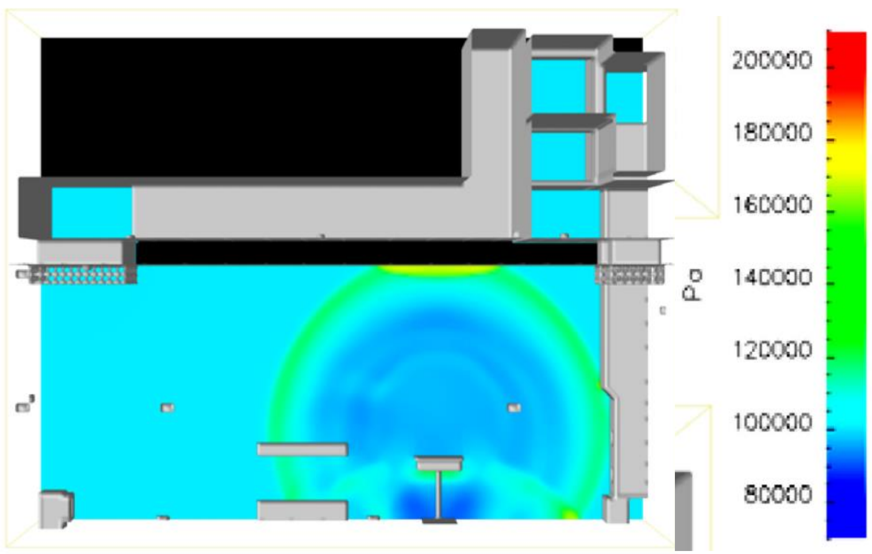


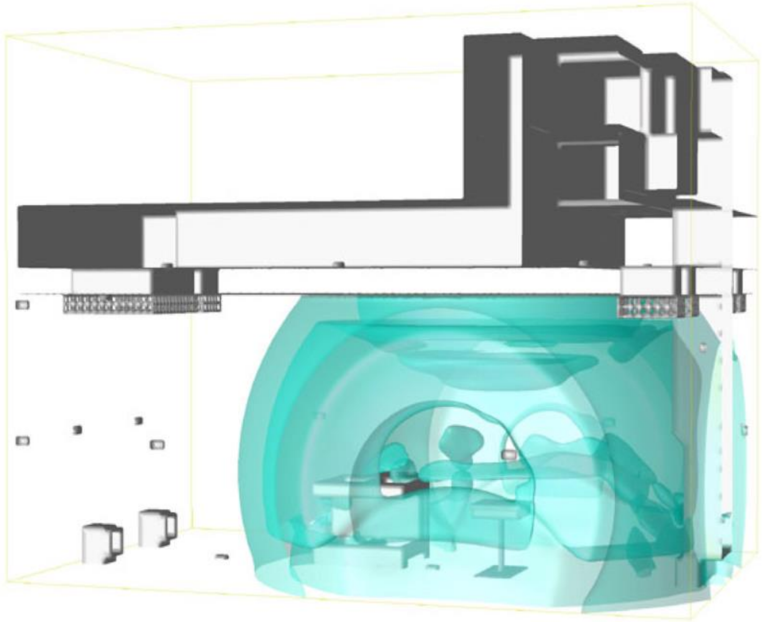


State of the Art Consequence Modelling

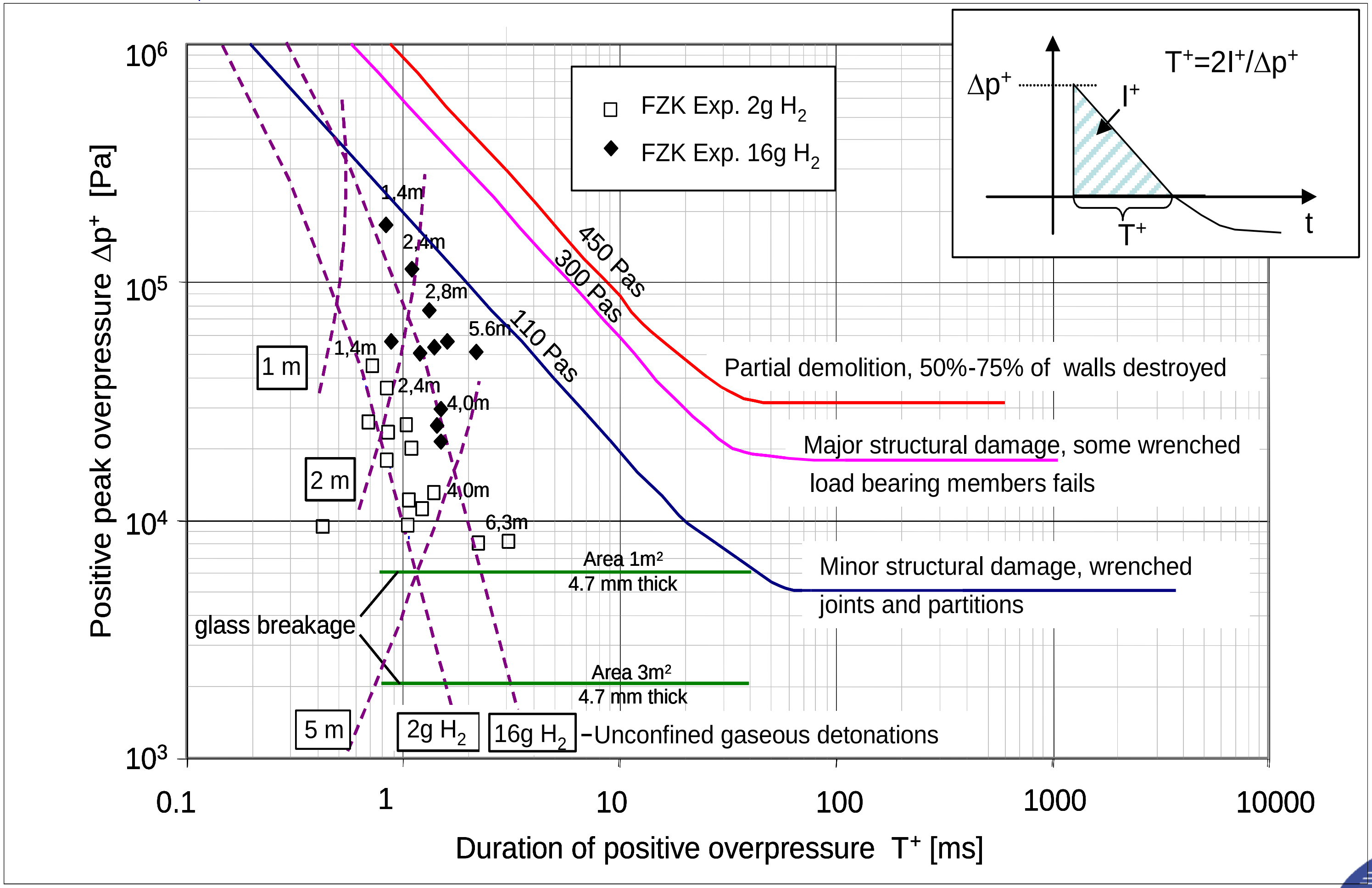
Structural response

What are effects of blast loads on the structure?
Commercial systems like LS-DYNA, PAMCRASH, etc…

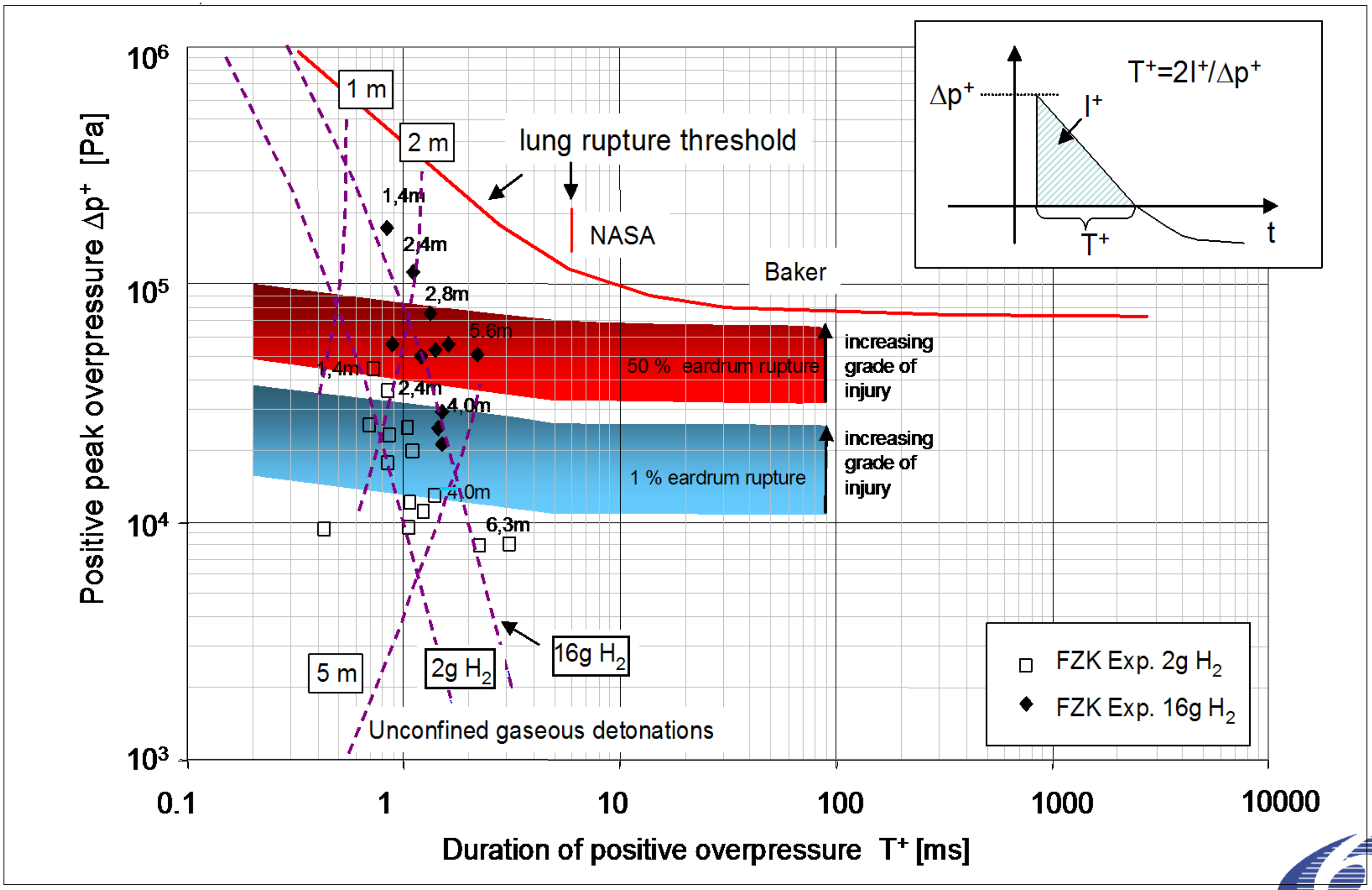




Limiting Pressure Loads
on Structural Elements



Limiting Pressure Loads
on Humans



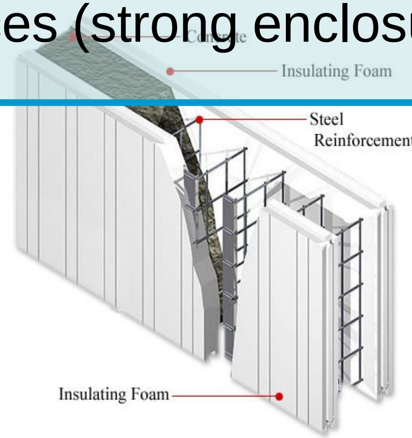
Mitigation Measures

The proposed analysis procedure allows identification of possible mitigation measures for risk reduction

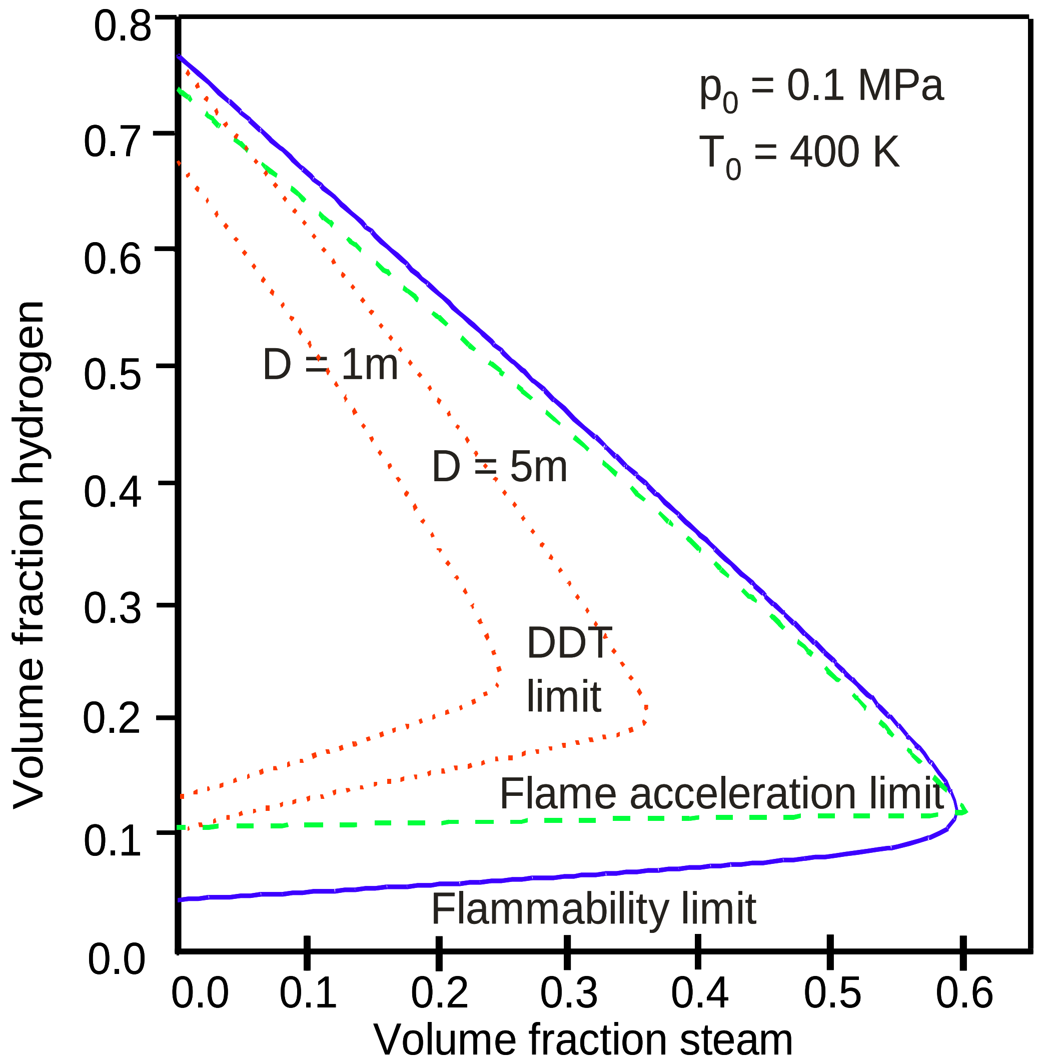
- Exlude severe scenarios by design changes
- Limit hydrogen sources
- Support hydrogen dispersion and mixing processes
- Exclude ignition sources
- Suppress flame acceleration (low confinement and turbulence generation)
- Avoid detonation transition processes (lean mixtures, small scale)
- Confine consequences (strong enclosure)

If this level of defence has been optimized, work on next barrier for accident progression

Accident progression



Mitigation by Steam Inerting



State of the Art in H2 Vehicle Safety
Open issues

- safe venting of compressed hydrogen gas cylinders (35 and 70 MPa),
- optimum arrangement of H2 storage vessels in the vehicle,
- fire safety of hydrogen-powered vehicles with the primary goal to prevent bursting of the high-pressure hydrogen system (flamelets impingement, PRDs,..)
- guidelines for fire fighters in case of fire or accident,
- optimum number and location of hydrogen detectors,
- safety concept in case of a hydrogen leak detection in a running car,
- tolerable H2 leak rates in the vehicle for different operating conditions, including a parked car,
- optimum position and activation criteria for pressure relief devices on the H2 tank,
- procedures to prevent penetration of hydrogen into the passenger compartment,
- effectiveness of forced ventilation for reducing local H2 concentrations in sensitive car areas,
- maximum possible reduction of ignition sources,
- development of standardised safety test procedures for new solid storage materials, such as nanocrystalline powders.
- development of non-destructive testing methods for cryo-vessels and high pressure tanks made from composite materials including highly accelerated lifetime testing.

Some Simplified Methods

Risk Evaluation with FMEA

Wahrscheinlichkeit des **Auftretens** von Prozessfehlern	A
Unwahrscheinlich	1
Sehr gering	2 - 3
Gering	4 - 6
Mäßig	7 -9
Hoch	10

RBZ = A * B * E

Bedeutung der Folgen von Produktfehlern aus Kundensicht	B
Kaum wahrnehmbare Auswirkungen	1
Unbedeutender Fehler, geringe belästigung des Kunden	2 -3
Mäßig schwerer Fehler	4 -6
Schwerer Fehler, Verärgerung des Kunden	7 - 8
Äußerst schwerwiegender Fehler	9 -10

Wahrscheinlichkeit der **Entdeckung** vor Auslieferung an Kunden	E
Hoch	1
Mäßig	2 - 5
Gering	6 - 8
Sehr gering	9
Unwahrscheinlich	10

Some Simplified Methods

Risk Evaluation with FMEA

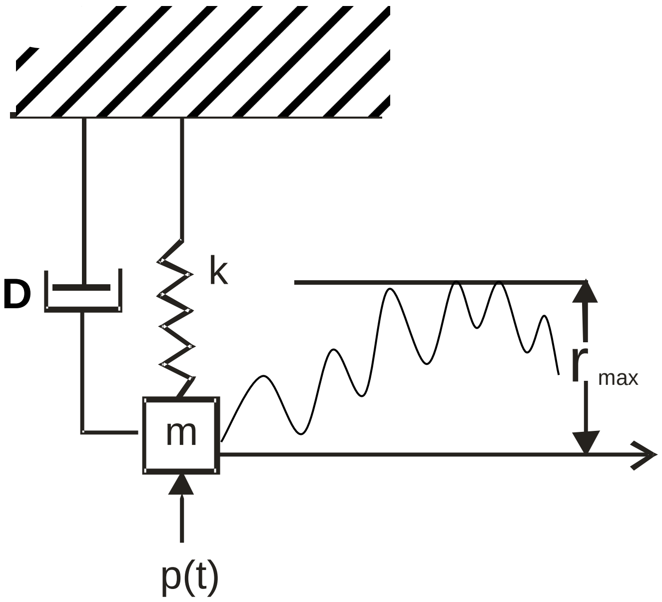
Beispiel einer durchgeführten FMEA-Analyse für eine Membranfiltration

FMEA Membranfiltration														
1	2	3	4	5-8				9	10	11	12-15			
Merkmal bzw. Baugruppe	Fehler	Wirkung	Ursache	A	B	E	RPZ	Abhilfe	Verantw. / Termin	Kontrolle/ Bem.	A	B	E	RPZ
Membranplatten und Permeatsystem	Platten beschädigt	Schlamm tritt ein	Schweißfehler	2	10	1	20	Regulierung 100%						
			Handling bzw. Lagerung und Transport	5	10	6	300	Entdeckung verbessern, sicherheitstechnische Anweisungen						
			Einleitung Faser- und Grobstoffe	2	10	6	120	1mm Siebung vorgeschrieben						
			toxische membranschädigende Stoffe	4	10	6	240	Abwasserzusammensetzung vorschreiben						
	Platten werden dicht	Filtrationsleistung sinkt	Zeitintervalle zu lang	2	5	1	10	weitere Erfahrungswerte sammeln						
			Biofouling	2	5	1	10							
			zu starke hydraulische Belastung, Anlage überlastet	4	5	1	20							
Tragegestell	Korrosion	tragende Bauteile geschwächt	falscher Werkstoff	3	5	8	120	für den jeweiligen Anwendungsfall angepasste Werkstoffe verwenden						
							0							
Antrieb	Ausfall Motor	Reinigung ungenügend	Kurzschluss, Motorschaden	2	6	2	24							
							0							
Reinigungssystem - Luftspülung	Luftspülung fällt aus	Membran verstopft, Deckschichtbildung	Gebläseausfall	2	6	2	24							
			verstopfen der Belüftungsöffnungen	3	6	7	126	saubere Verarbeitung						
	Luftmenge nicht ausreichend	ungenügende Abreinigung	Dimensionierungsfehler	2	6	8	96	Testlauf						
Reinigungssystem - Mediumspülung	Spülpumpe fällt aus	keine Intensivreinigung	Pumpenausfall	2	6	2	24							
	Spülmenge nicht ausreichend	ungenügende Abreinigung	Dimensionierungsfehler	2	6	8	96	Testlauf						
Rollenlagerung	eine Laufrolle blockiert	Lage verändert sich	Lagerschaden, Lebensdauer	7	5	8	280	Wirkleistungsmesser						
	Lagerzapfen korridiert	Lage verändert sich	falsches Material	3	5	8	120	angepasste Werkstoffe						

Some Simplified Methods

Single-DOF-Oscillator model for structural response

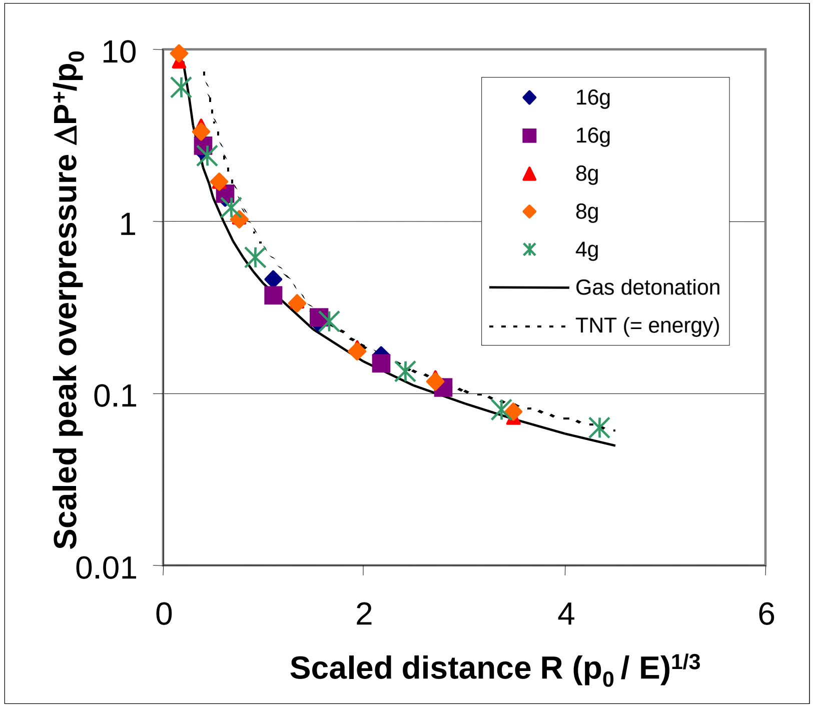
- Simplest model for structural response is SDO model
- Describes ground mode (first harmonic) of structural element which is represented by lumped values for mass, stiffness and damping of motion
- Tool to understand basic effects of transient pressure loads on global displacement of element
- In FEM analysis also higher modes included, but superposition of different effects, results not so transparent

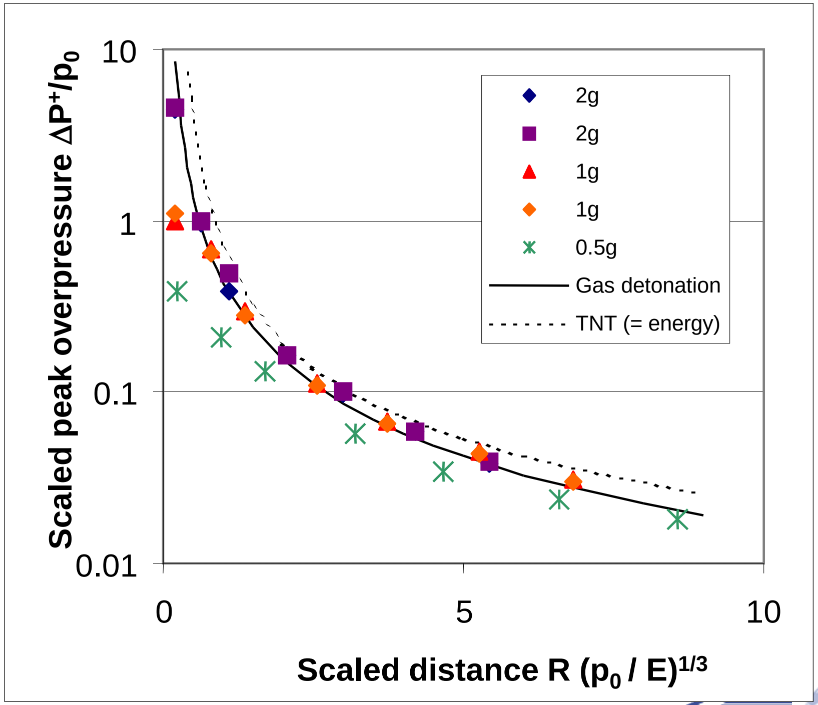


Scaled Peak Overpressures vs Distance

TNT Equivalence, Multi-energy methods,…

- Use of Sachs scaling collapses measured peak overpressures to universal correlation for ≥ 1 g H_2, E = total energy of explosive charge
- Combustion units provide conservative overpressures

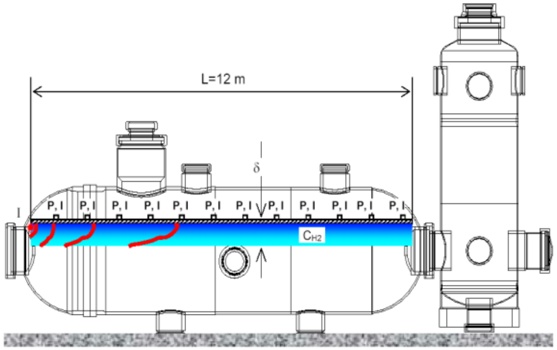




Expanding the State of the Art
(Pre-normative) Research Directions

- **(Partially) Confined Releases**
- **Mitigation**


determined by
- initial PIRT study
- expert questionnaire
- state-of-the-art survey

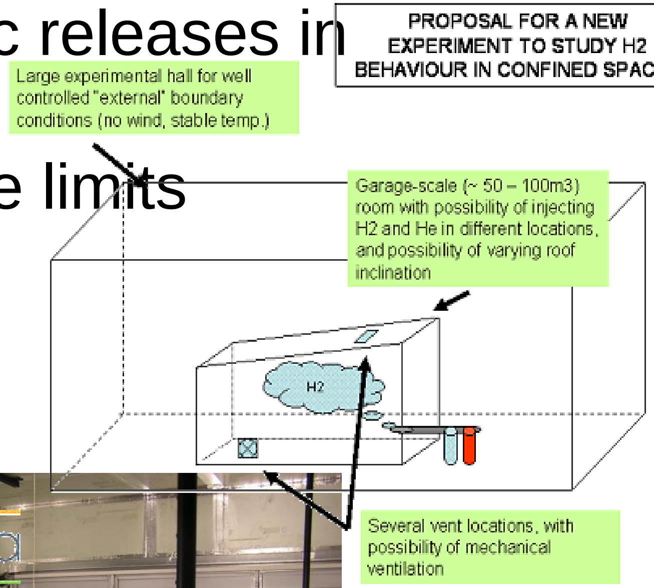


communicate the network's working topics,
orientate the work on intermediate time scale (proposals for experiments, benchmarking, Internal Projects …)

HySafe Internal Project “InsHyde”

Objectives

- Investigation of realistic non-catastrophic releases in (partially) confined areas
- Determination of permeation and release limits
- Systematic assessment of mitigation (including detection) measures (sensors + venting + recombiner...)
- Simulations and experiments for critical releases
- Deriving „Recommendations“, → standards, ...
- Proposing a dedicated project for JTI support “HyGarage” (lead NCSRD)

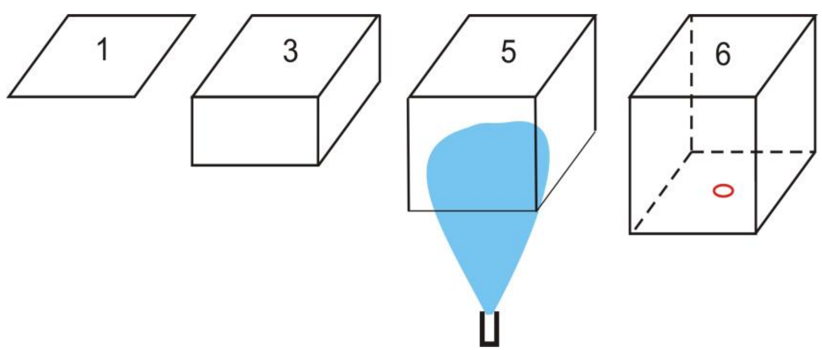


Garage facility at partner CEA

HySafe Internal Project “InsHyde”

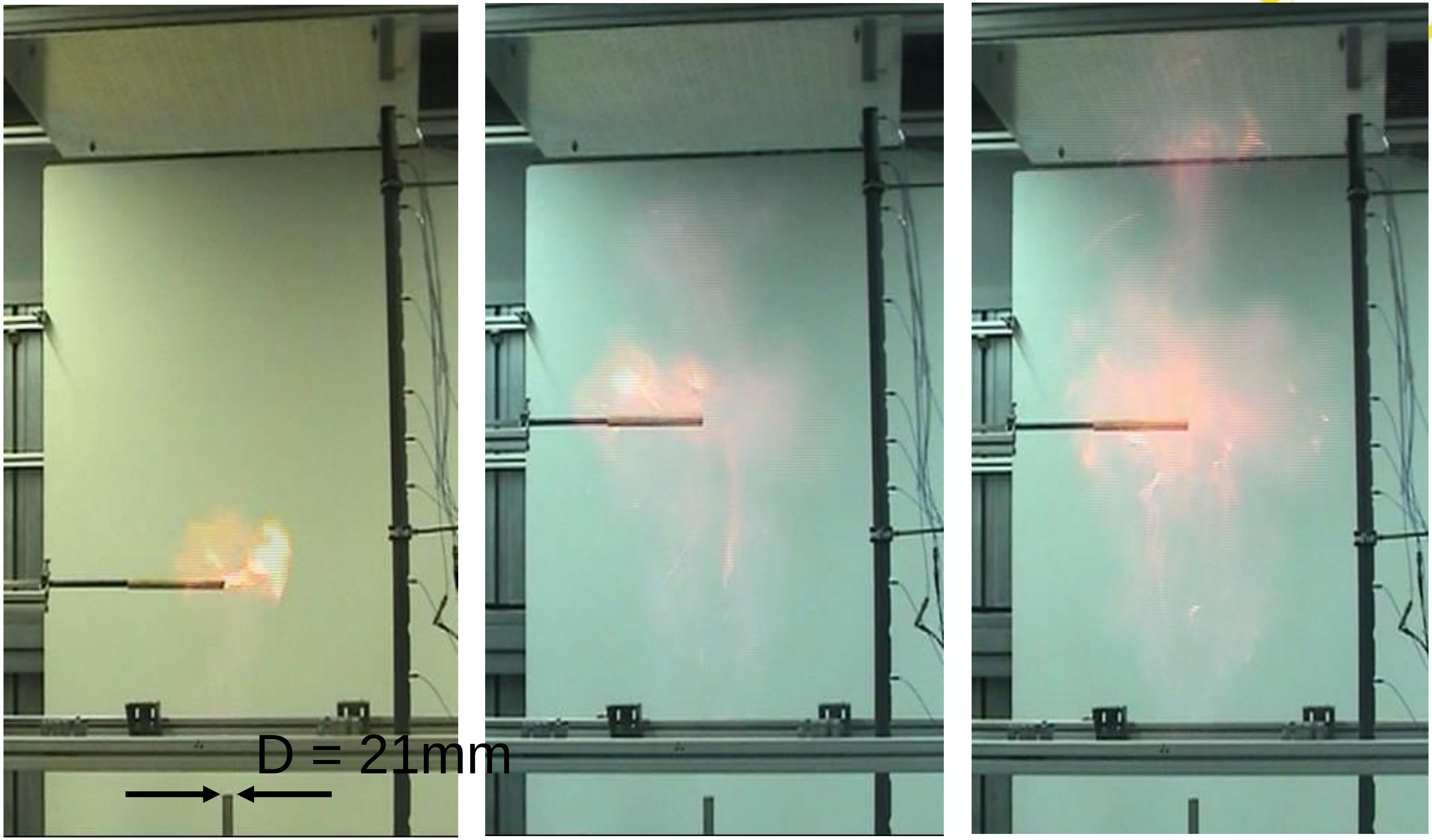
Definition of acceptable inventories

- Released mass of Hydrogen: - 1-10 g (Standard variation)
- Release time: - 0.1-100 s (Jet $\rightarrow$ Plume)
- Ignition time: } - to be chosen in a way, that presumably
- Ignition location: } maximum H_2- combustion occurs
- Ignition energy: - weak, strong
- Complexity of geometry
  a) Obstacles: - different number of wire netting layers $\rightarrow$ turbulence and flame convolution
  b) Enclosure: - different number of restrictive plates (i.e. aluminum)



Obstructed area / Total area	1/6	3/6	5/6	6/6

"InsHyde" Integral tests (10 g)

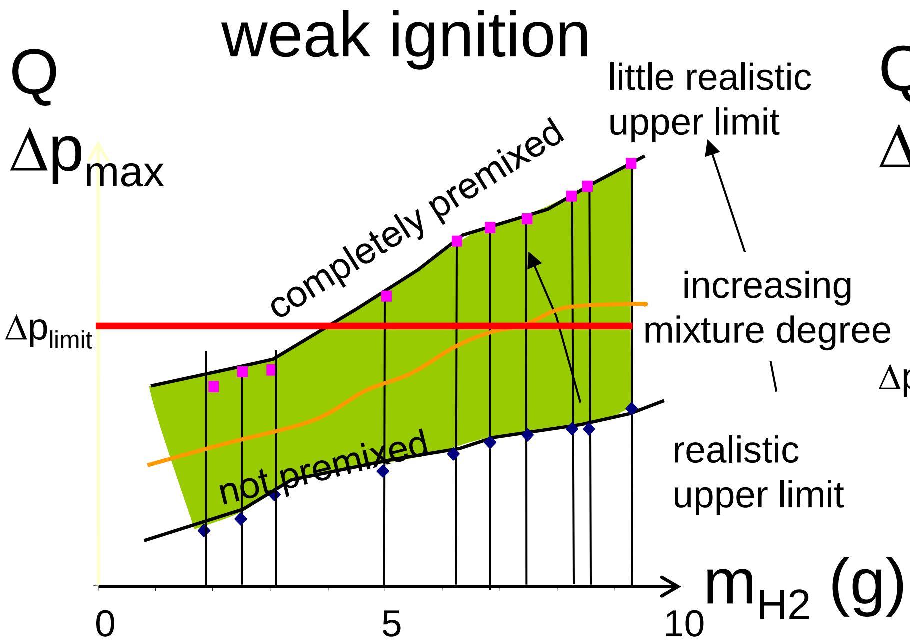


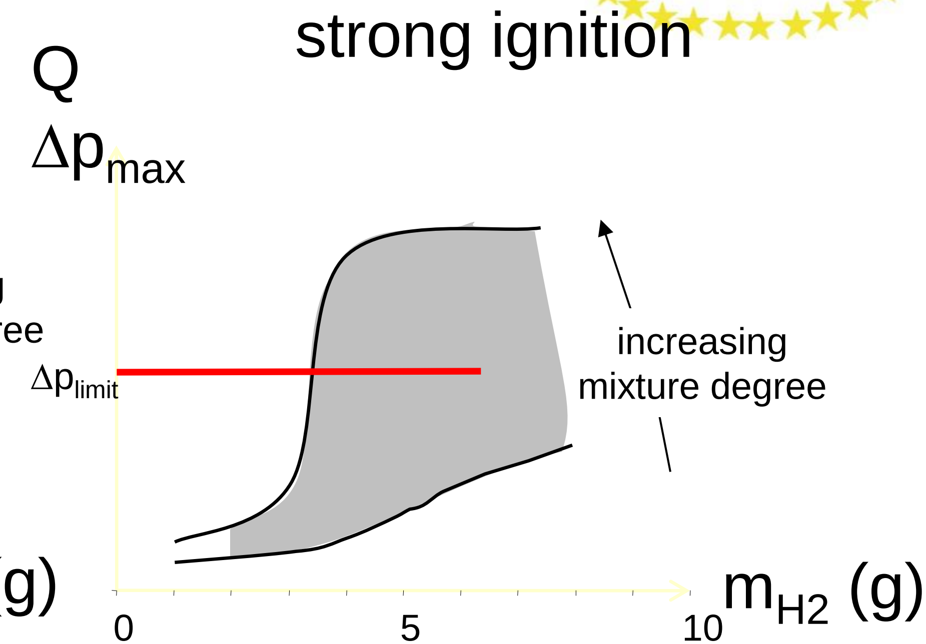
$\dot{m} = 0.15$ g/s, $h_{ign} = 0.45$ m

$\dot{m} = 3.0$ g/s, $h_{ign} = 0.8$ m

$\dot{m} = 6.0$ g/s, $h_{ign} = 0.8$ m

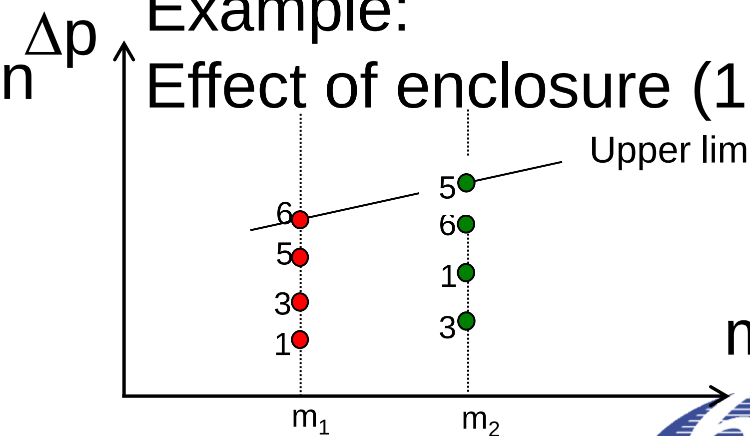
"InsHyde" Some Results





Example:

Effect of enclosure (1-6 Sides



Mixture degree is dependent on

- Release time
- Enclosure
- Obstacles

  → all in Deliverable D113 (to be published)

"InsHyde" – Permeation
Survey on Existing Allowable Rates

- Draft UN ECE regulation (EIHP draft & possibly the basis of the EU Regulation) and superseded versions of draft ISO/DIS15869:
  - For Type 4 containers, the steady state permeation rate < 1.0NmL/hr/L internal vol.
  - The test is conducted at ambient temperature and nominal working pressure.
- ISO/DIS 15869.2 & .3:
  - For Type 4 containers, the steady state permeation rate < 2.0NmL/hr/L water capacity at 35 MPa, and 2.8NmL/hr/L water capacity at 70 MPa.
  - The test is conducted at ambient temperature and nominal working pressure.
- SAE J2579, Jan. 2008:
  - The steady state hydrogen discharge rate due to leakage and permeation from the hydrogen storage system shall not > 75NmL/min at 85^0C and nominal working pressure for a standard passenger vehicle.
  - The rate may be increased in proportion to the enclosure volume for large vehicles.

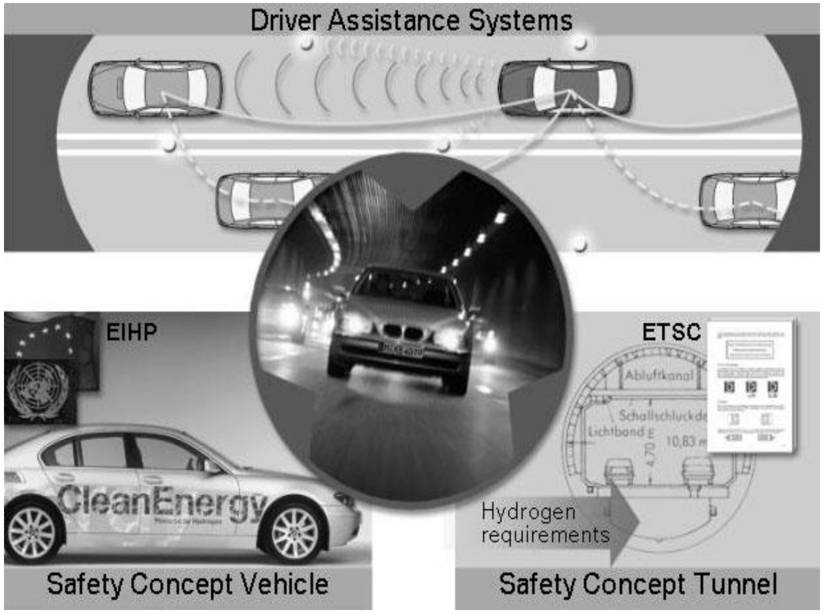
Volvo Technology
Dept 06120
12 2008-09-16

InsHyde: IP1.3 Permeation D74
Paul Adams

VOLVO

→ all in Deliverable D113 (to be published)

HySafe Internal Project "HyTunnel"



- Selection of broadly accepted szenarios.
- Review of available relevant numerical and experimental simulations
- Qualitative assessment on standard mitigation measures effectiveness (benchmark)

i. Experimental part (depending on financing)

ii. Extension of the EC Tunnel „directives"

→ **Improved Tunnel Safety with H_2 as the fuel of the future**

COMMISSION OF THE EUROPEAN COMMUNITIES

Brussels, 30.12.2002
COM(2002) 769 final

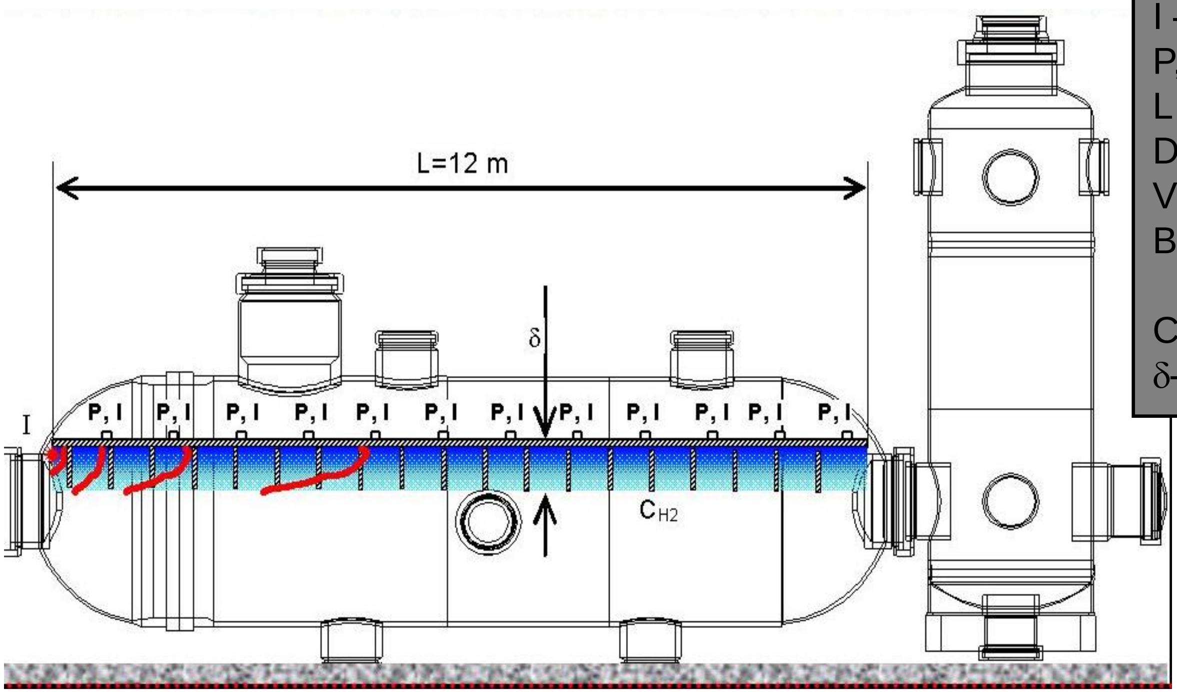
2002/0309 (COD)

Proposal for a

DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

on minimum safety requirements for tunnels in the
Trans-European Road Network

"HyTunnel" - Experimental Layout



I – ignition point;
P, I – pressure and light gauges.
L = 12 m – A1 length;
D = 3.5 m – A1 diameter;
V = 100 m³ (+30 m³)– total volume;
BR = 0.6 (0.3) by obstacle laden grid

C_{H2} –hydrogen concentration;
δ– layer thickness

- Objective: Critical conditions for FA and DDT in semi-confined gas mixture layer
- Expected data: Dependence of critical σ* and λ* on gas layer thickness δ

"HyTunnel" – Main Experiments

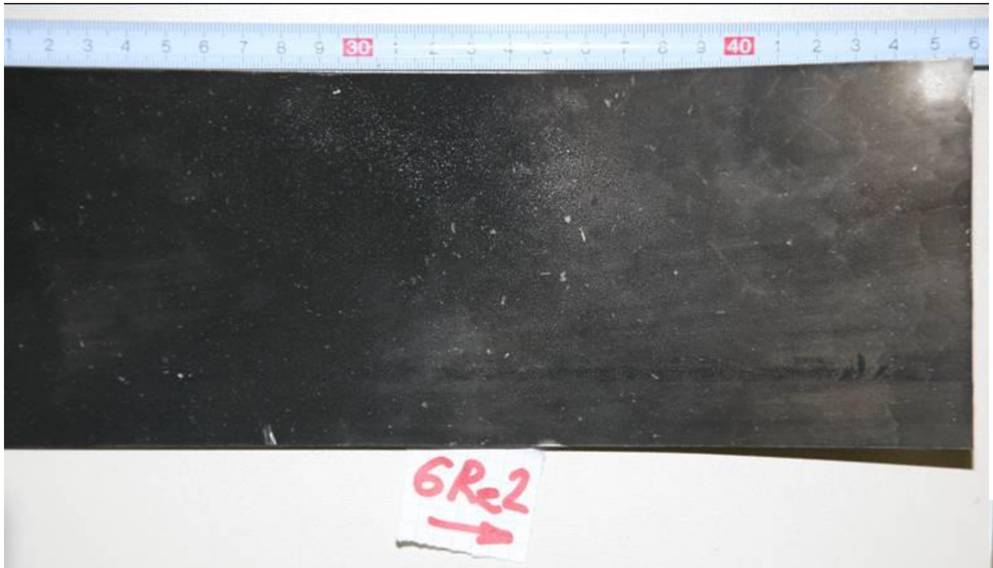
Large scale facility (5.7 x 1.6 x 0.6 m)

- effective venting ratio α = 0.46 (layer thickness δ = 0.15 m)

Diagonal view

Film opening

"HyTunnel" – Smoked-foil records



Detonation cell on the side wall of the box

Detonation cell on the ceiling of the box

Observed averaged cell sizes vary within 1.5 – 1.7 cm

~ corresponds to theoretical expectations

“HyTunnel” - Some results regarding FA and DDT

- Large scale test completed
- Effective flame acceleration (FA) depends on mixture reactivity and gas layer thickness.
  Flame accelerates to sonic velocity:

  for **15% H_2** **$d \geq 0.6$ m**

  for **20% H_2** **$d \geq 0.3$ m**
- **Detonation** in semi-confined geometry at **25% H_2** can occur if gas layer **$d \geq 0.3$ m**
- Critical layer thickness for **detonation propagation**:

  $15 > d/l > 7.5$

“HyTunnel” Simulations

Flammable cloud of a 5kg release

WP18.3 Effect of high purity high pressure hydrogen on structural material

Objectives

Experience from space research/rocket engineering indicates that hydrogen 5.0 with less than 5ppm O_2 contamination
(HPH2, as required for PEM FC) can induce accelerated material damage processes.

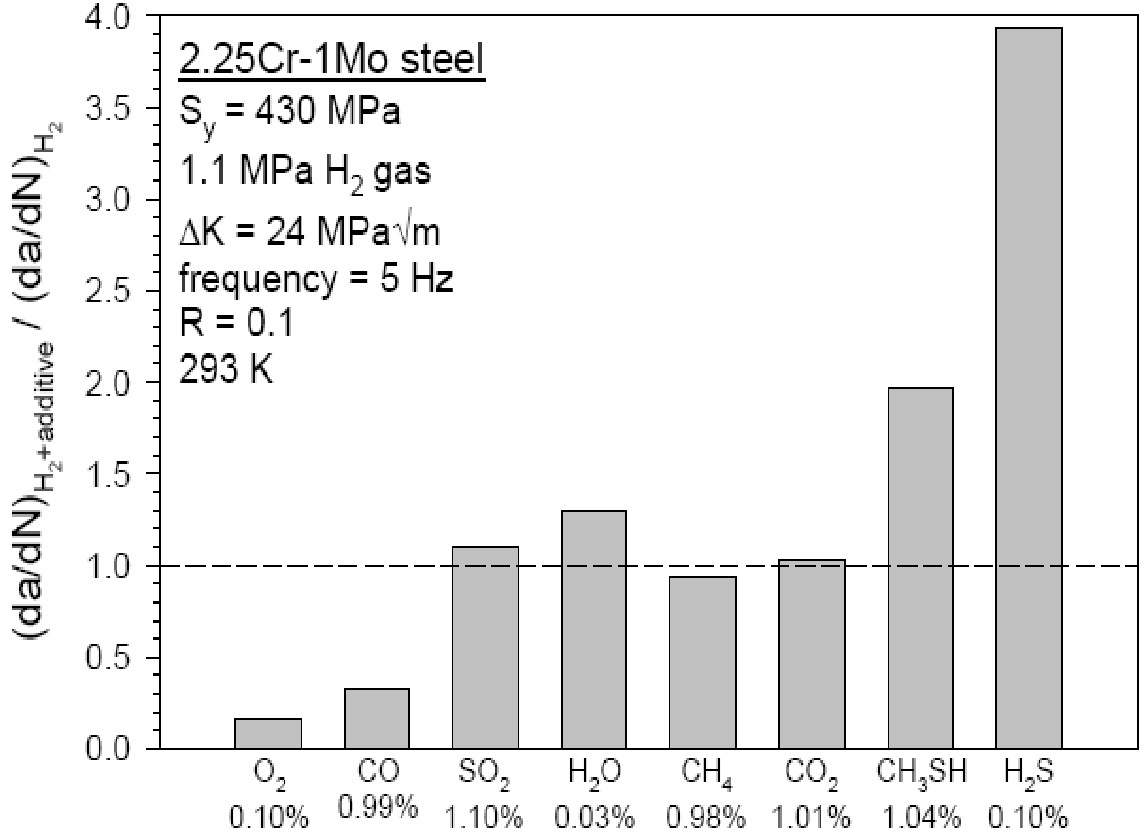
Objectives:

- Investigation of the effect of HPH2 induced cracking
- Recommendations for the safety aspects of the use of HPH2 in fuel cell cars

Lead: **AL** Partners: BAM, DNV, HSE/HSL, INASMET, Risø and Active Supporters: ET, INTA.

WP18.3 High Purity H2

Some results of a literature study



Comparison between pure gas and H_2 with additives [4]

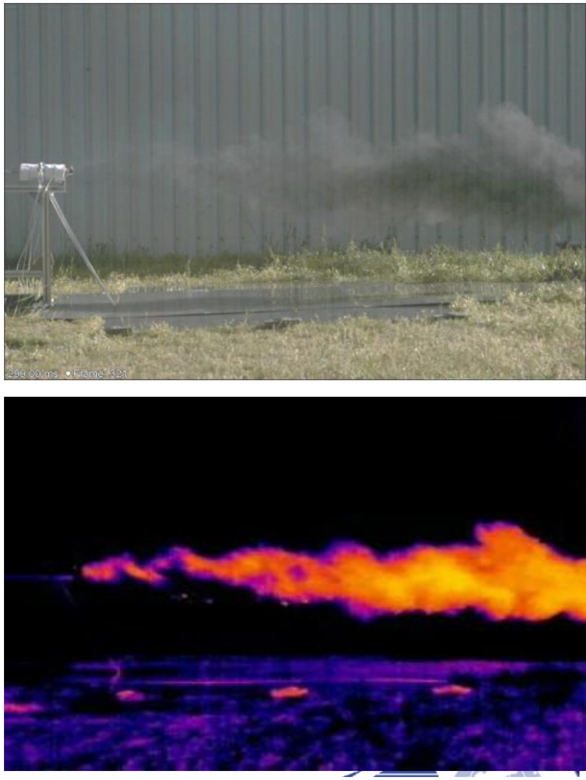
WP18.4 Safety of Nano Storage Material

Fundamental understanding the safety issues regarding nano-scaled solid-state hydrogen storage materials/systems through:

(i) development of standard testing techniques to quantitatively evaluate both materials and systems,

(ii) understand the fundamental science of environmental reactivity of hydrides and

(iii) develop methods and systems to mitigate the risks to acceptable levels.



nano-structured alanate blown out of a heat exchanger tube at 10 bar and 120 °C (frames of a high speed video (left) and of a infrared video (right) at the same instant)

Progress status WP18.4

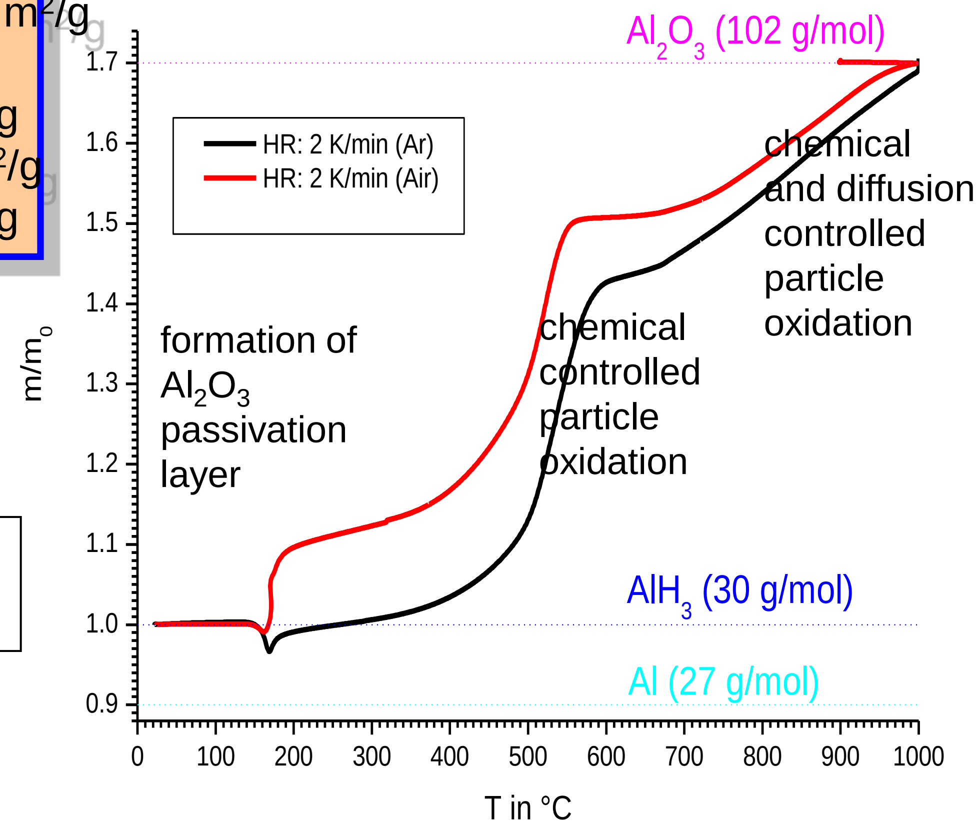
Methods of investigation: decomposition – oxidation

AlH_3 from pyrolysis furnace	2.59 m^2/g
AlH_3 in TGA*	15 to 20 m^2/g
AlH_3 (original crystals)	0.69 m^2/g
ALEX (nano-Al)	12.28 m^2/g
5 µm Aluminum (ALCAN)	1,36 m^2/g

Methods of Thermal Analysis:
DSC, TG, X-Ray

Specific Surface by BET-Analysen and TGA analysis

*estimated from mass increase by oxidation
with a passivation layer of 3 nm



HySafe Internal Project “HyQRA”

Objectives

1) Develop a reference **Quantitative Risk Assessment (QRA)** methodology for hydrogen technologies applying – where necessary - **simplified methods** for acceptable answer times as required for an **engineering tool**

The tool supports the following steps:

a. Hazard identification

b. Frequency estimation

c. Consequence assessments

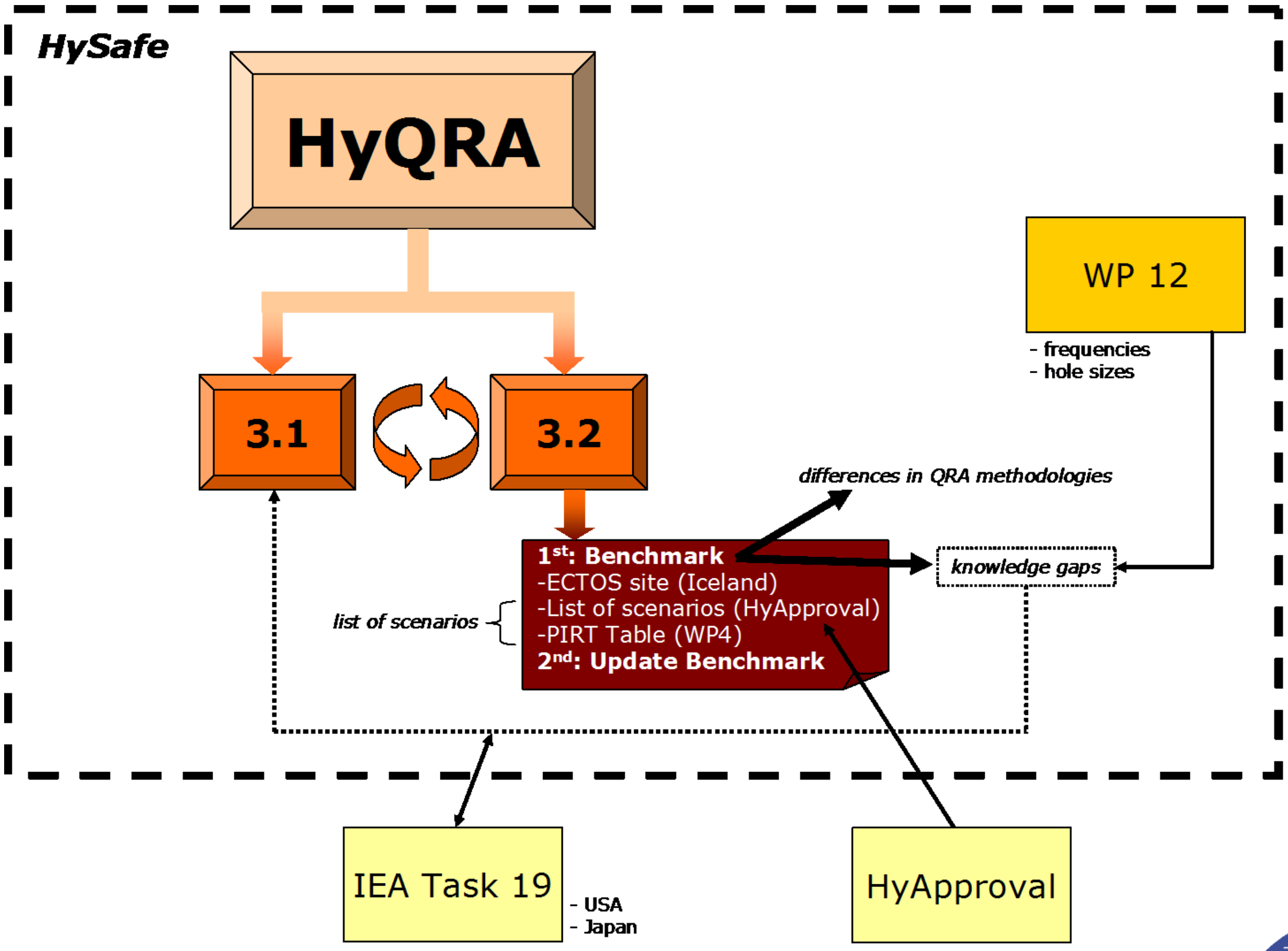
d. Risk estimation

e. Validation of acceptance criteria

f. Assessment of measures for risk reduction

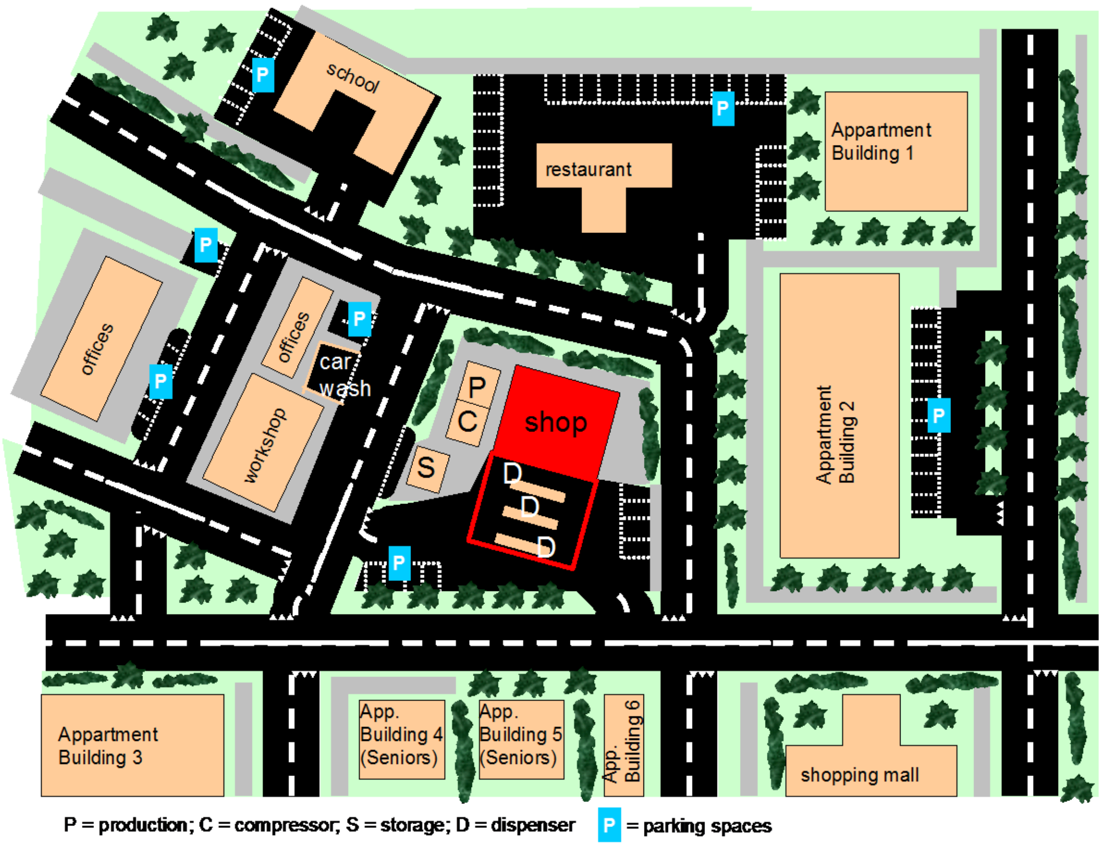
2) Prototypical validation at few relevant cases of the developed methodology

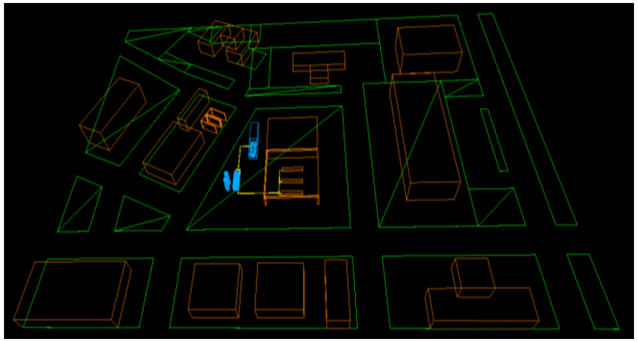
HyQRA
The project structure

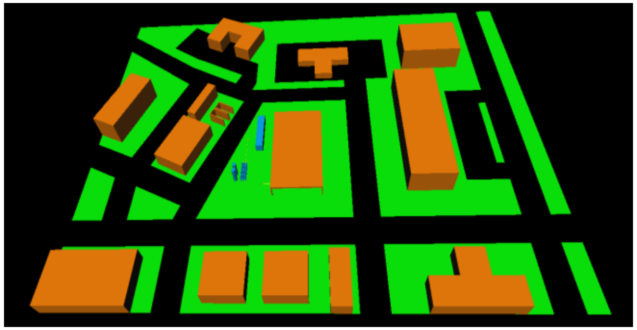


HyQRA Benchmark Base Case

Geometry of the HRS - BBC







State of the Art in Infrastructure Safety

Open issues

- determination of tolerable H2 releases during vehicle repair, which pose no risk to the personnel,
- design of effective and low-cost ventilation systems,
- CFD analysis of leaking hydrogen scenarios, including complex surroundings near the vehicle, extension of the investigations described in [33] and including the special features of a LH2 leak including cold jets,
- control of ignition sources and definition of a realistic conservative ignition model,
- in case of filling stations, the issues of protecting walls and safety distances need to be investigated.

State of the Art in Basic Research
Open issues

- measurement of ignitable space regions, given a certain leak size, shape, and mass flow rate, an extension of the work described in,
- systematic investigation of active and passive safety systems, e.g. ventilators, catalytic recombiners, or flame arrestors,
- modelling of ignition processes under realistic boundary conditions,
- investigation of diffusion flame stability after ignition (limits for lift-off and extinction),
- criteria for flame acceleration and detonation onset in H2-air mixtures with concentration gradients and partial confinement (Note: the criteria described in Section 3.2 are valid for homogeneous and fully confined mixtures; they are, hence, very conservative with respect to practical accident conditions in mobile applications and should be extended to more prototypic conditions).
- basic investigations of the gas behaviour including its reactions at the very low temperatures around 20K and very high pressures
- effect of high purity hydrogen on the relevant materials

Other References

H2 Testing – EIHP2 (www.eihp.org)

EIHP European Integrated Hydrogen Project 2

Welcome | Publications | Workshops | EIHP 1 | Supporters | Members

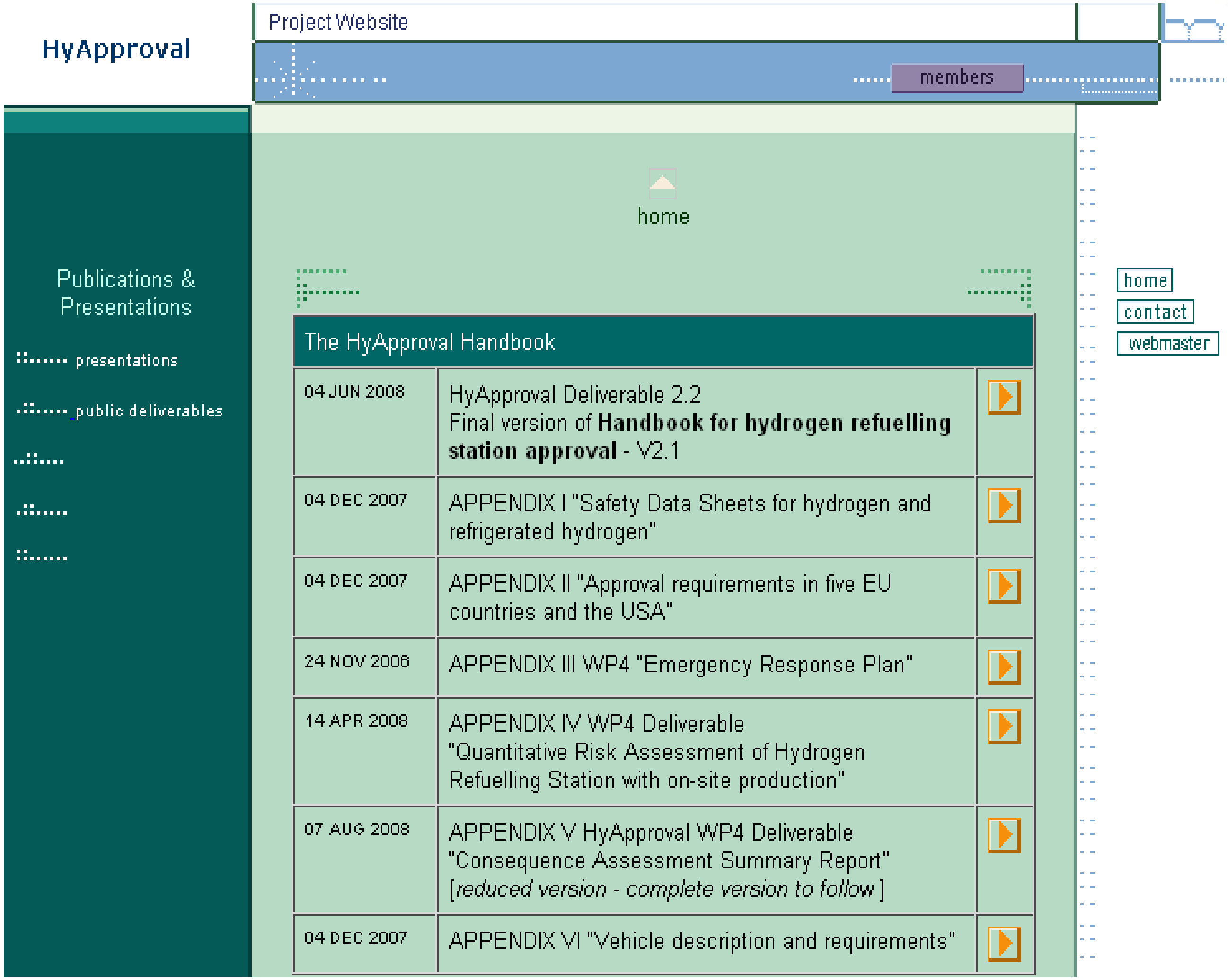
Public Section

Home
Coordinator
Webmaster

EIHP Final Reports [if not mentioned otherwise all in PDF format]
Joint Final Report EIHP2 - Publishable Part, 05APR2004 [0.34 MB] download
WP 2.1 Codes and Standards, by Inger Hugstmyr, Hydro, 22MAR2003 [0.3 MB] download
WP 2.2 Gaseous Hydrogen Vehicle Refuelling Station, by Shell, Air Products, BP, Air Liquide, Vandenborre Hydrogen Systems (Stuart Energy Europe), DNV and Hydro, JAN2004 [1.33 MB] download
WP 2.3 Harmonisation of Components, by BP, 11MAR2004 [0.12 MB] download
WP 2.4 Results from Workshop on "Risk Based Maintenance and Inspection for Hydrogen Refuelling Stations", by DNV, 29JAN2004 [0.44 MB] download
WP 3.1 Identification of Optimum On-Board Storage Pressure for Gaseous Hydrogen City Buses, by Volvo Technology Corporation (lead) and contributing partners: Adam Opel AG, Air Products Plc., DaimlerChrysler AG, Norsk Hydro ASA, Raufoss Alternative Fuel Systems AS, Shell Global Solutions, MAR2004 [0.3 MB] download
WP 3.2 Connectors Test Under High Pressure Hydrogen, by M. Le Digabel, C. Eyraud, N. Botrel, CEA, JAN2004 [0.34 MB] download WP 3.2 Modelling and Simualtion of the Filling of a Gaseous Hydrogen Tank Under Very High Pressure, by C. Perret, CEA, 04FEB2004 [6.28 MB] download

Other References

HRS Handbook – HyApproval (www.hyapproval.org)


HyApproval

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The HyApproval Handbook		
04 JUN 2008	HyApproval Deliverable 2.2 Final version of **Handbook for hydrogen refuelling station approval** - V2.1	
04 DEC 2007	APPENDIX I "Safety Data Sheets for hydrogen and refrigerated hydrogen"	
04 DEC 2007	APPENDIX II "Approval requirements in five EU countries and the USA"	
24 NOV 2006	APPENDIX III WP4 "Emergency Response Plan"	
14 APR 2008	APPENDIX IV WP4 Deliverable "Quantitative Risk Assessment of Hydrogen Refuelling Station with on-site production"	
07 AUG 2008	APPENDIX V HyApproval WP4 Deliverable "Consequence Assessment Summary Report" [*reduced version - complete version to follow*]	
04 DEC 2007	APPENDIX VI "Vehicle description and requirements"	

A simulation contributions to the EC project HyApproval „Handbook for the safe installation/operation of a HRS“ (details on http://www.hyapproval.org) →

Other References

HyPer – Permitting Guidelines for small stationary installations (www.hyperproject.eu)

A PlugPower natural gas fuelled CHP unit powers a greenhouse in Nancy, France.

A PlugPower GasCore© Fuel System in South Africa provides back-up power for telecommunications.

Stationary applications include systems:

- Connected to the power grid on stand alone including remote power
- Fuel Cell systems fuelled by natural gas, liquid hydrocarbon fuels, biogas, hydrogen
- Residential power and heat generation

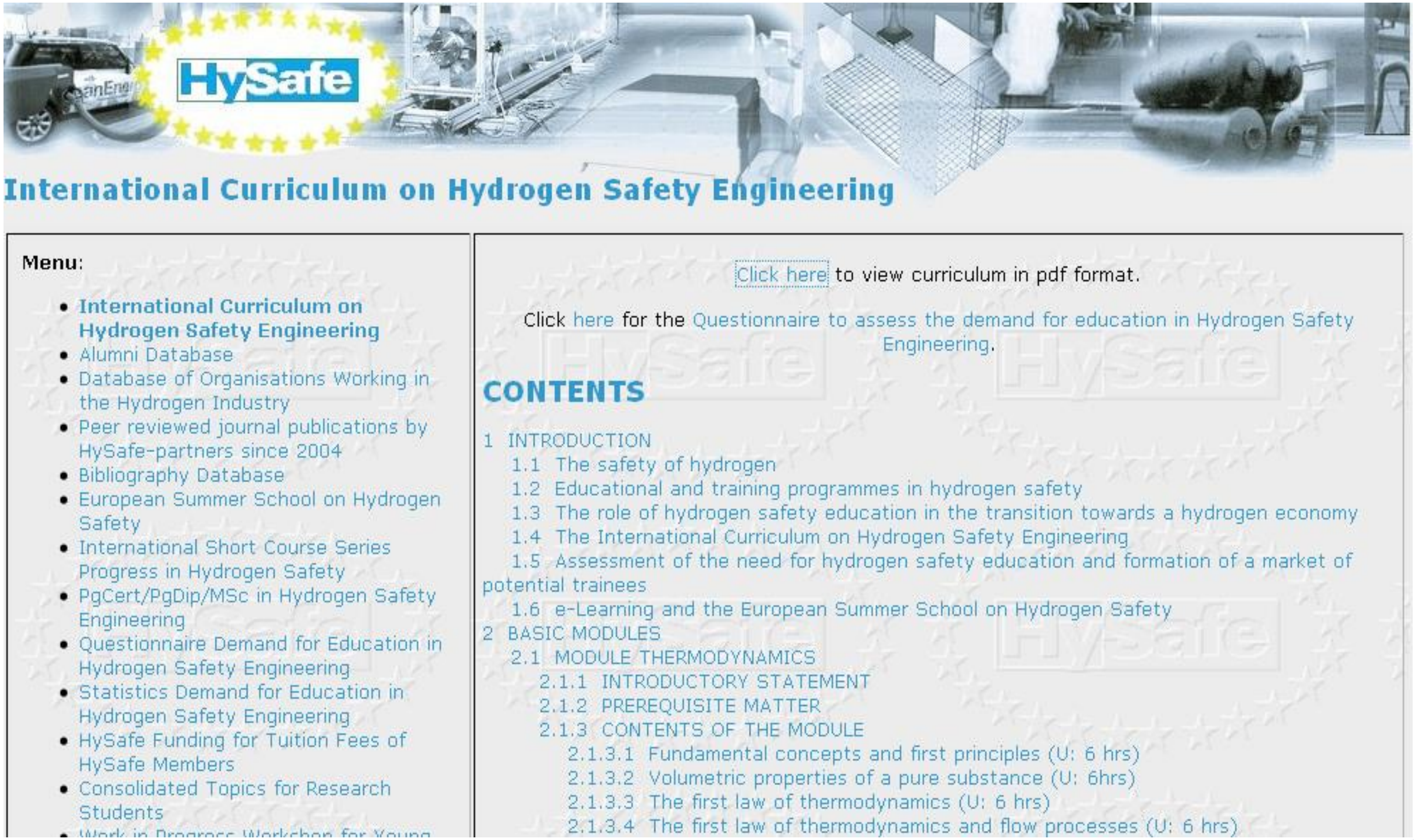
A Vaillant fuel cell heating appliance, Oldenburg, Germany.

A PlugPower GasCore© Fuel System provides power to a telecommunication mast in Scotland, United Kingdom.

- Uninterrupted Power Supply (UPS) and backup systems
- Combined Heat Power Systems (CHP)
- Tri-generation systems (heat used)

State of the Art Education

Online reviewed curriculum (HySafe e-Academy)



International Curriculum on Hydrogen Safety Engineering

Menu:

- **International Curriculum on Hydrogen Safety Engineering**
- Alumni Database
- Database of Organisations Working in the Hydrogen Industry
- Peer reviewed journal publications by HySafe-partners since 2004
- Bibliography Database
- European Summer School on Hydrogen Safety
- International Short Course Series Progress in Hydrogen Safety
- PgCert/PgDip/MSc in Hydrogen Safety Engineering
- Questionnaire Demand for Education in Hydrogen Safety Engineering
- Statistics Demand for Education in Hydrogen Safety Engineering
- HySafe Funding for Tuition Fees of HySafe Members
- Consolidated Topics for Research Students

Click here to view curriculum in pdf format.

Click here for the Questionnaire to assess the demand for education in Hydrogen Safety Engineering.

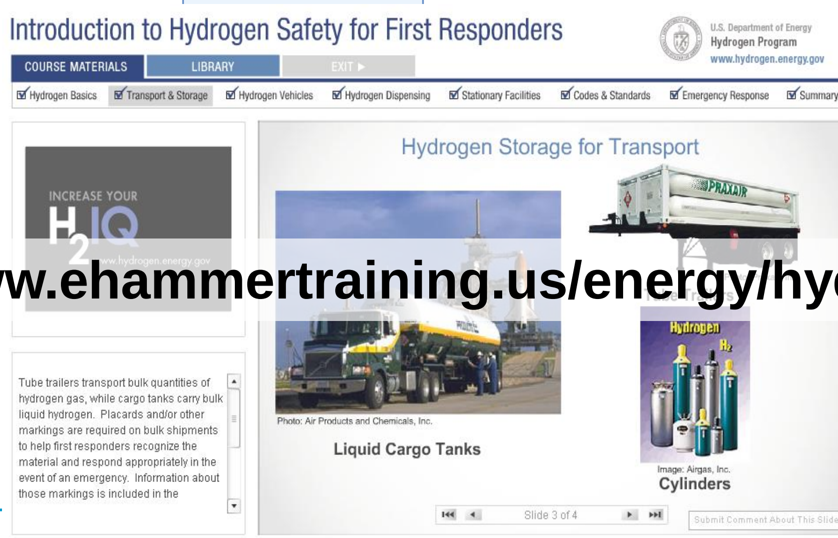
CONTENTS

Other Education and Training Offers

PGC and Summer School (HySafe e-Academy)

for details see

http://www.hysafe.net/eAcademy



http://www.ehammertraining.us/energy/hydrogen/controller.cfm

Invitation to the 3rd Int. Conf. on Hydrogen Safety

September 16-18th, 2009

Ajaccio, Corse, France

HySafe

HIA HYDROGEN IMPLEMENTING AGREEMENT

STORHY

Italian National Firecorps

AUTO21 Safety and Infrastructure Study of Hydrogen Fuelled Vehicles

H2 Codes and Systems for Hydrogen Safety

IPHE International Partnership for the Hydrogen Economy

HyFLEET:CUTE

HELP Hydrogen Executive Leadership Panel

NATURALHY

Hydrogen Safety, Codes and Standard Program

Canadian Hydrogen Safety Program

CCS Global SINCE 1977

ISO

HySafe ICHS

Contact: ICHS@hysafe.org

INTERNATIONAL CONFERENCE ON HYDROGEN SAFETY

Support

NoE HySafe is co-funded by the European Commission within the 6th Framework Programme (2002-2006); Contract n°: SES6-CT-2004-502630.

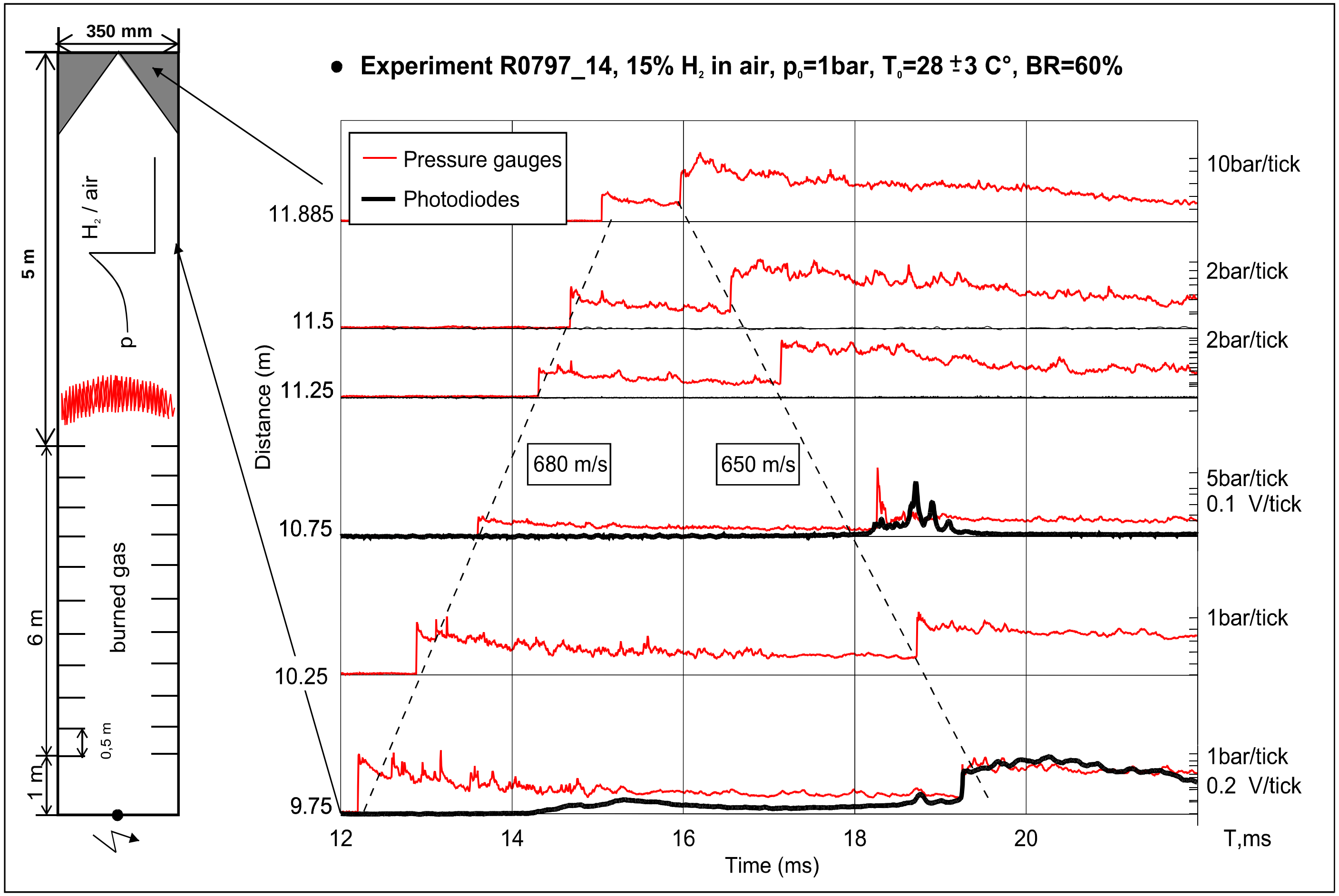
The network is contributing to the implementation of the Key Action "Integrating and strengthening the ERA" within the Energy, Environment and Sustainable Development.

Thanks to all HySafe colleagues…

… and thank you for your attention.

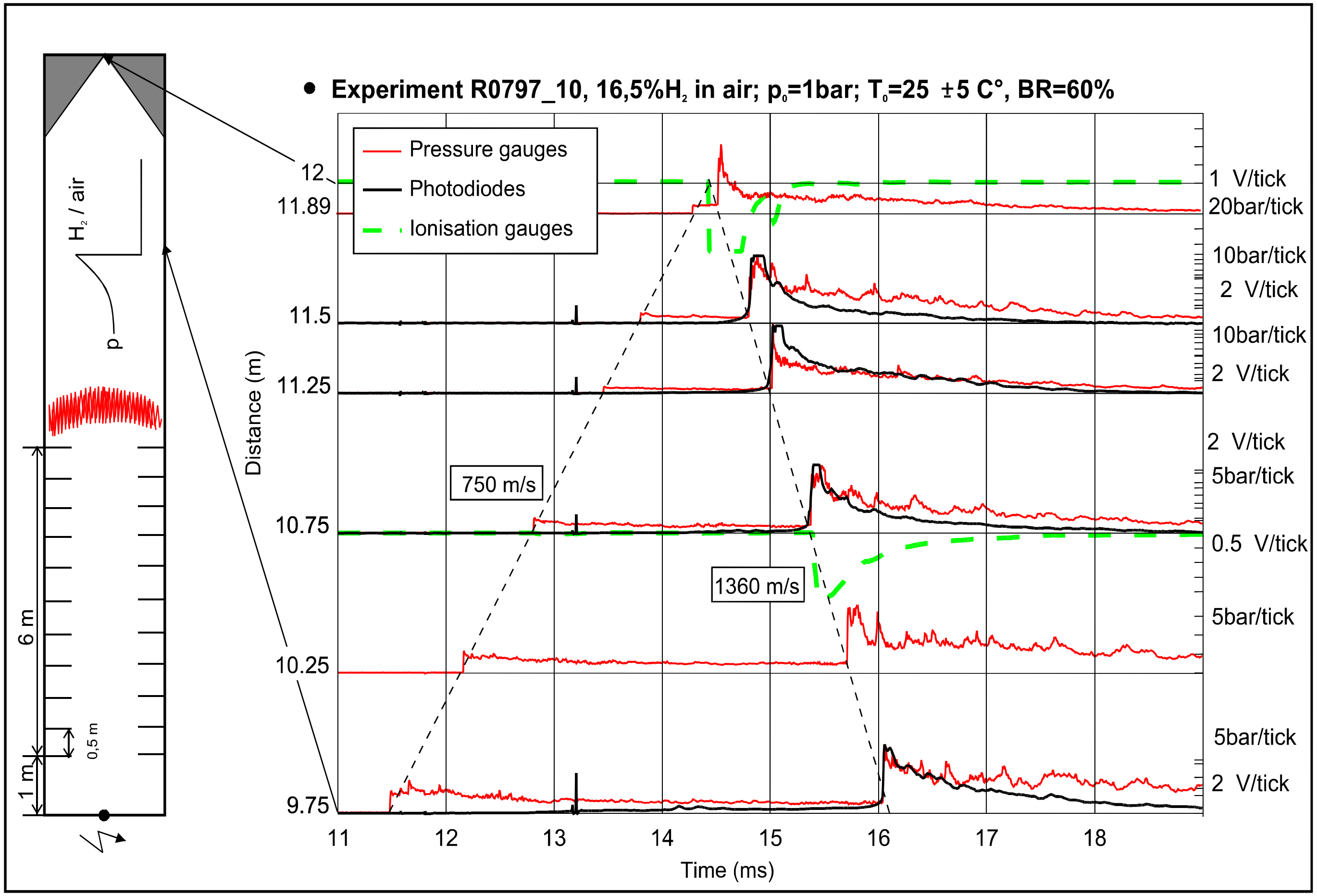
TURBULENT DEFLAGRATION EXPERIMENT WITHOUT DDT

- Partially obstructed tube with conus, 15 % hydrogen in air



TURBULENT DEFLAGRATION EXPERIMENT WITH DDT

- Partially obstructed tube with conus, 16.5 % hydrogen in air



BLAST LOADED ELASTIC OSCILLATOR (1)

- Equation of Motion

$$m\ddot{x} = \sum_i F_i$$

$$= -kx + \Delta p^{+} e^{-\frac{t}{T_{load}}}$$

$$m\ddot{x} + kx = \Delta p^{+} e^{-\frac{t}{T_{load}}}$$

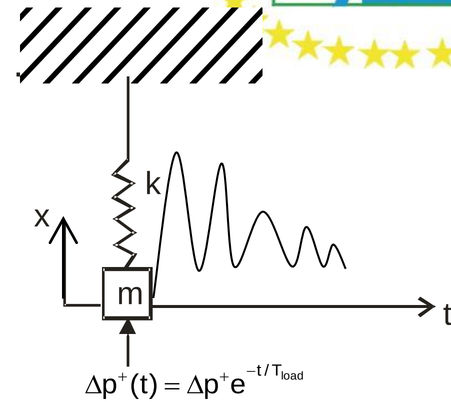
with $x(t=0) = 0$

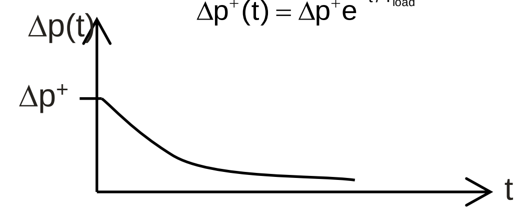
$\dot{x}(t=0) = 0$

Static maximum deflection

$$\ddot{x} = 0$$

$$x_{max} = \Delta p^{+}/k$$





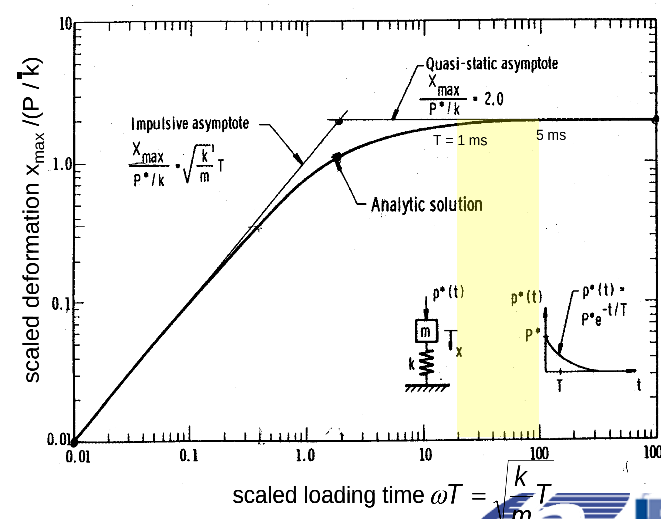
- Solution

$$\frac{x(t)}{\Delta p^{+}/k} = \frac{(\omega T_{load})^2}{1+(\omega T_{load})^2}\left[\frac{\sin\omega t}{\omega T_{load}} - \cos\omega t + e^{-t/T_{load}}\right]$$

where $\omega = (k/m^{1/2}) = \text{oscillatorperiod} = \frac{2\pi}{T_{osc}}$

- Damage is determined by maximum displacement x_{max}, can be found from solution by setting $\dot{x}(t) = 0$
- Scaled displacement = f(scaled loading time)

$$\frac{x_{max}}{\Delta p^{+}/k} = f(\omega T_{load})$$



BLAST LOADED ELASTIC OSCILLATOR (2)

- Asymptotes for maximum deflection /deformation can be computed from energy balances
- Quasistatic loading real m ($T_{load} >> T_{osc}$)
  - strain energy = work on structure

$$\tfrac{1}{2} k x_{max}^2 = \Delta p^+ \cdot x_{max}$$

$$\frac{x_{max}}{\Delta p^+ / k} = 2$$

dynamic maximum deflection is two times static deflection (DLF = 2)

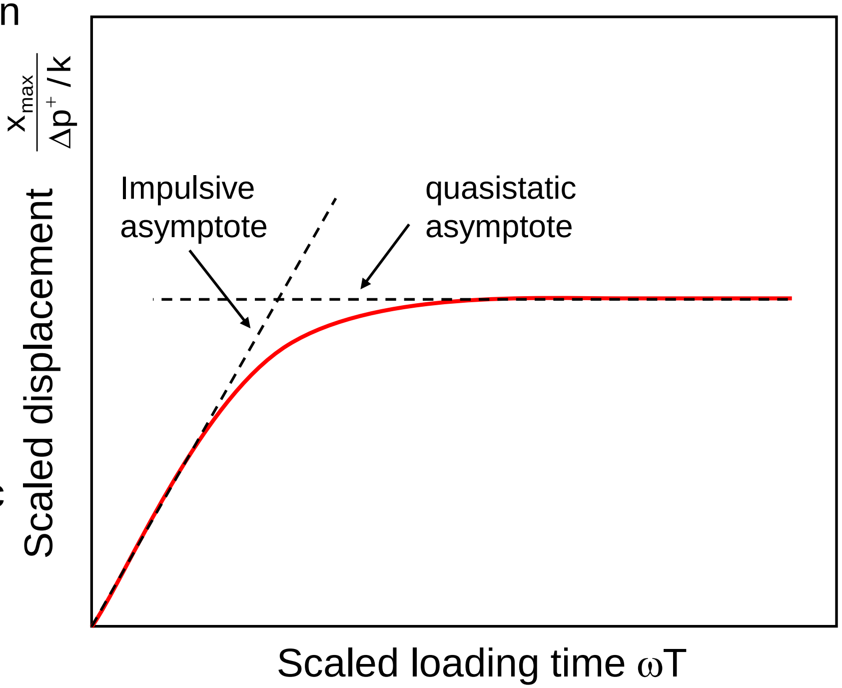
- Impulsive loading real m ($T_{load} << T_{osc}$)
  - kinetic energy (t=0) = strain energy

$$\frac{1}{2} m v_0^2 = \frac{1}{2} k x_{max}^2$$

$$\frac{I^2}{2m} = \frac{1}{2} k x_{max}^2 \qquad I = \int_0^\infty \Delta p^+ e^{-t/T_{load}} = \Delta p^+ \cdot T_{load}$$

$$\frac{x_{max}}{\Delta p^+ / k} = \left(\frac{k}{m}\right)^{1/2} T_{load} = \omega T_{load} \quad \text{or} \quad x_{max} = \left(\frac{1}{k m^{1/2}}\right) \cdot I$$

maximum deformation is proportional to blast wave impulse I



- Often oscillator response is presented with inverted ordinate and unscaled load parameters Δp^+ and T_{load}

- Quasistatic asymptote

$$\frac{\Delta p^+}{k x_{max}} = \frac{1}{2}$$

$$\Delta p^+ = \frac{k x_{max}}{2}$$

Maximum deflagration x_{max} is only proportional to applied peak overpressure Δp^+, indipendent of load duration

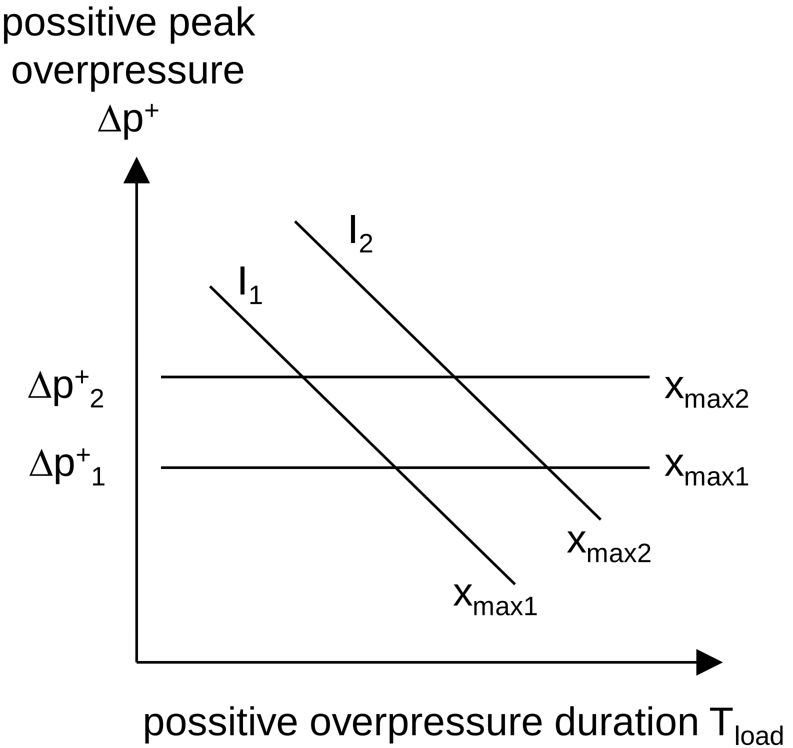
- Impulsive asymptote

$$\frac{\Delta p^+}{x_{max}} = \frac{1}{\omega T_{load}}$$

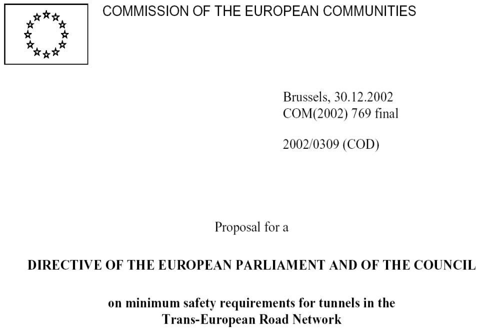
$$\Delta p^+ = (km)^{\frac{1}{2}} x_{max} \frac{1}{T_{load}}$$

$$\Delta p^+ T_{load} = I \sim x_{max}$$

Maximum deflagration x_{max} is proportional to applied impulse



Internal Project “HyTunnel”


COMMISSION OF THE EUROPEAN COMMUNITIES

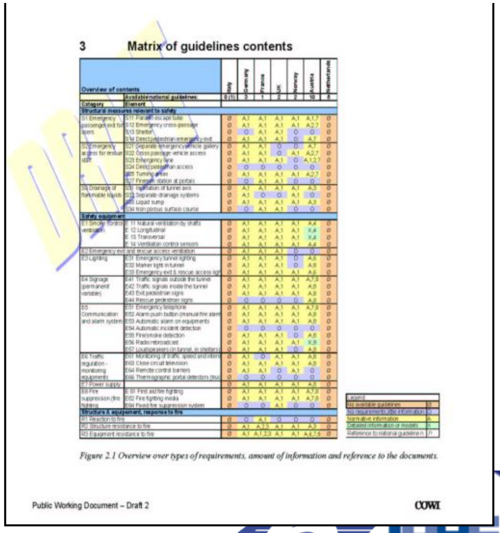
Brussels, 30.12.2002
COM(2002) 769 final

2002/0309 (COD)

Proposal for a

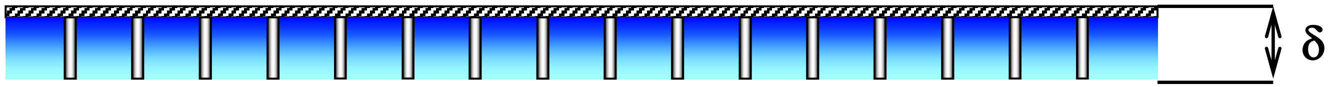
DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

on minimum safety requirements for tunnels in the Trans-European Road Network



- Accidents in public focus
- Heterogenous regulations
- Costly and long term investments

"HyTunnel" - Some Experimental Work



Tunnel 2D-geometry of gas mixture with one solid wall is assumed to be semi-confined volume with venting ratio a = 0.5

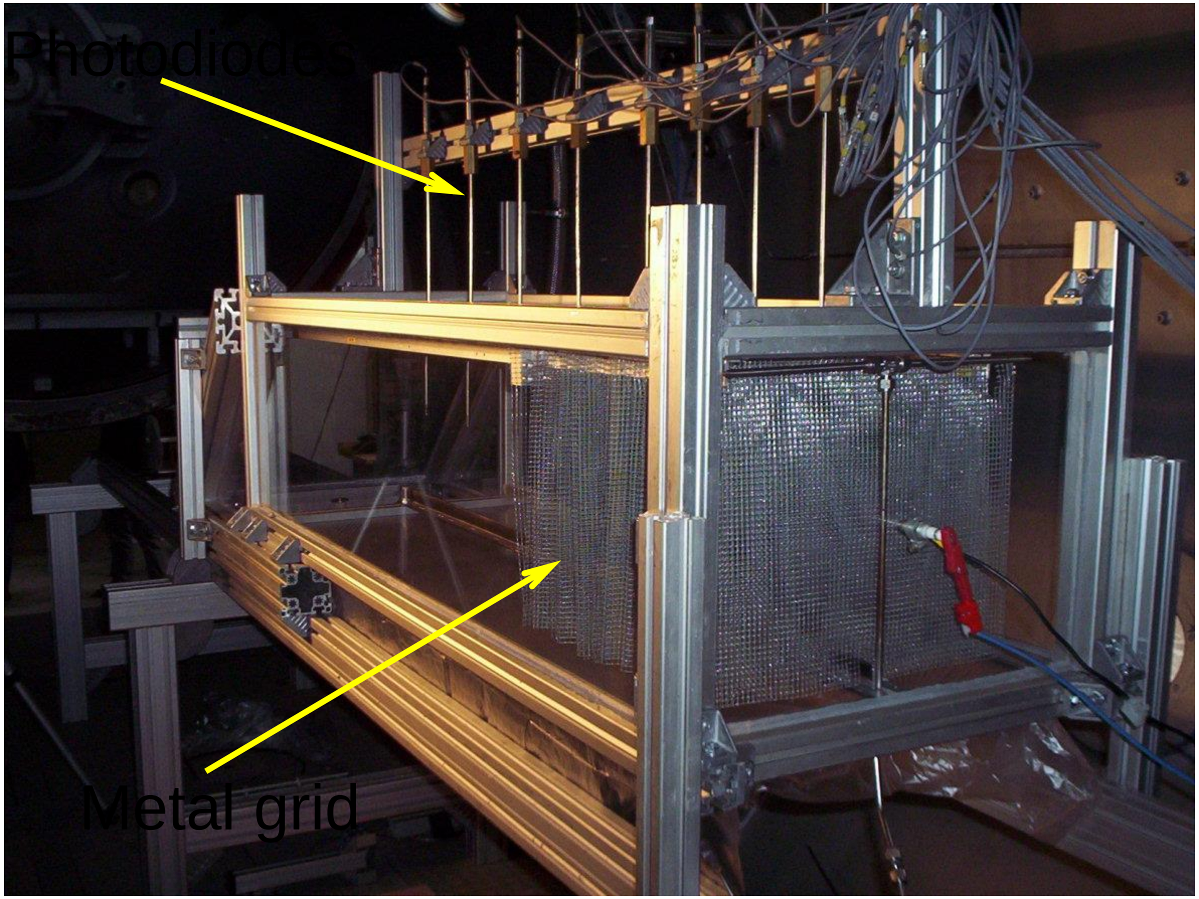
- **FA criterion: $s/s_0 \sim 1+2 \cdot a$**
- **FA estimation for different a:**

  a = 40% => fast deflagration in 25% H2/air

  a = 50% => fast deflagration in 30% H2/air
- **DDT estimation for different d:**
- **DDT criterion: d/l ~ ?**

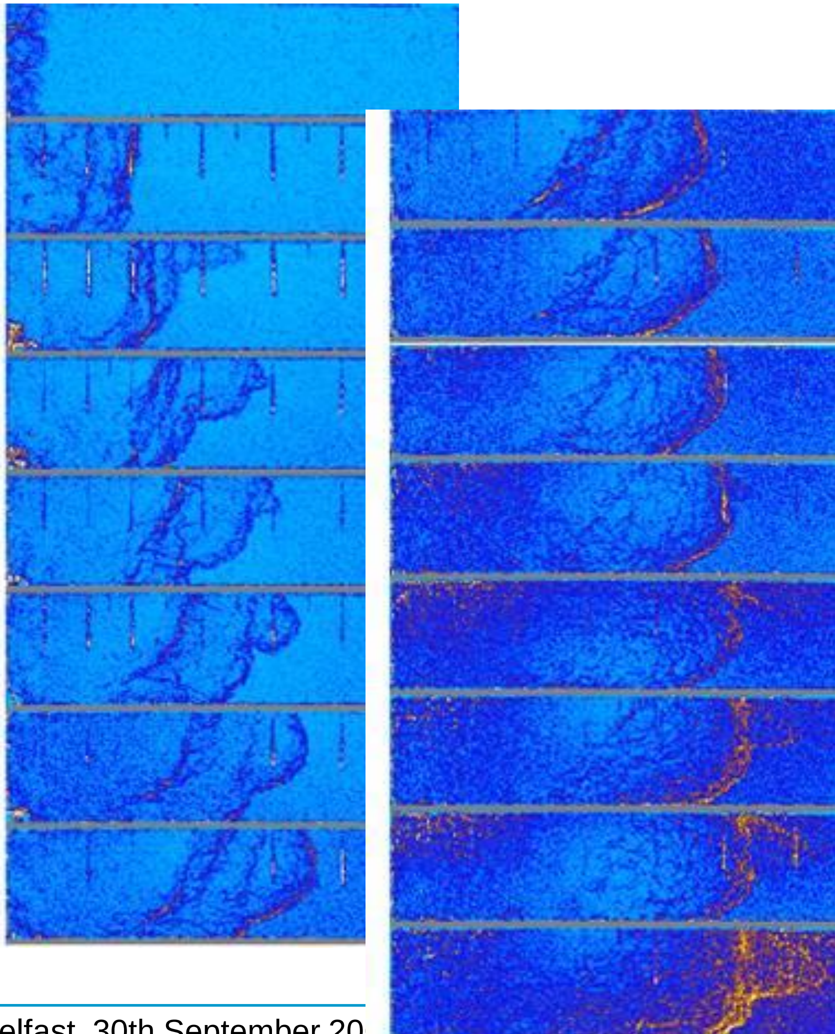
“HyTunnel” - Pretests

Small scale facility (1.6 x 0.5 x 0.4 m)

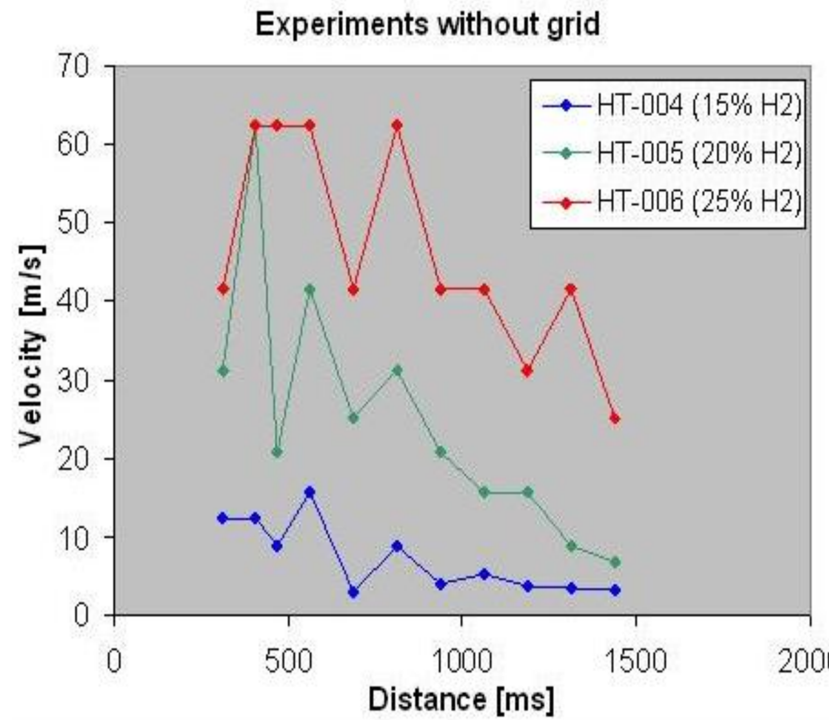


"HyTunnel" – Small Scale Tests Results

BOS 15 % H_2/air w/o obstacles



Flame velocity vs. distance



HyApproval – HRS

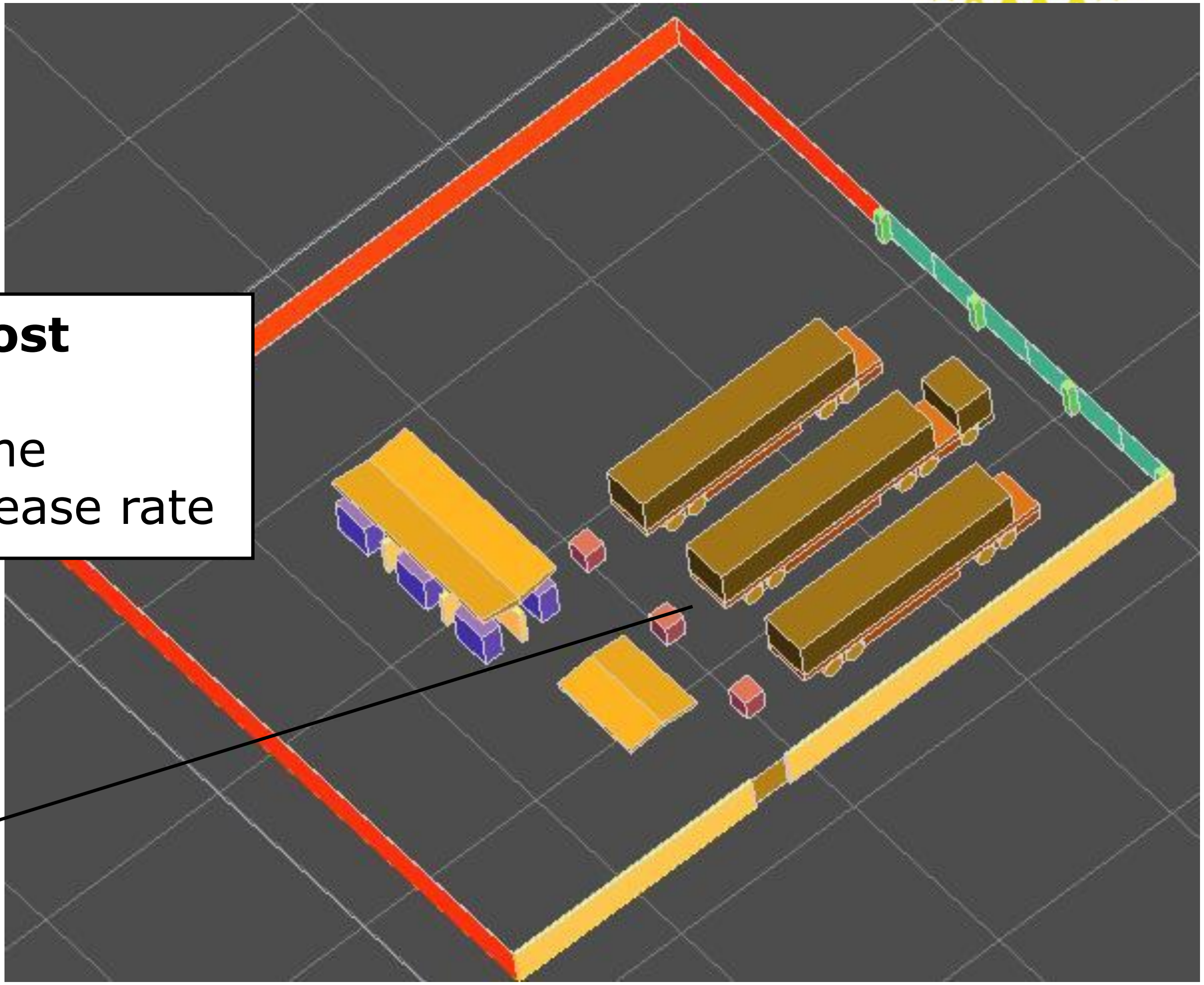
Worst Case Numerical Simulation

Scenario T1:
Trailer hose disconnection

Assume all contents lost

- 250 kg H_2 released
- ~ 10 min release time
- ~ 1.3 kg/s initial release rate

Leak location

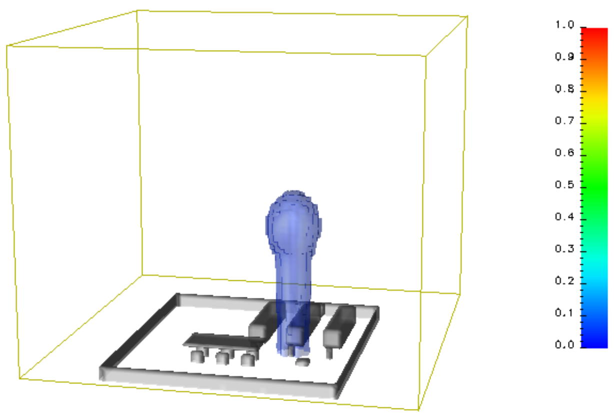


CGH2 Refuelling Station Side View (Luxembourg refuelling station)

Scenario T1: Hydrogen concentration

Iso-surface 4% H_2

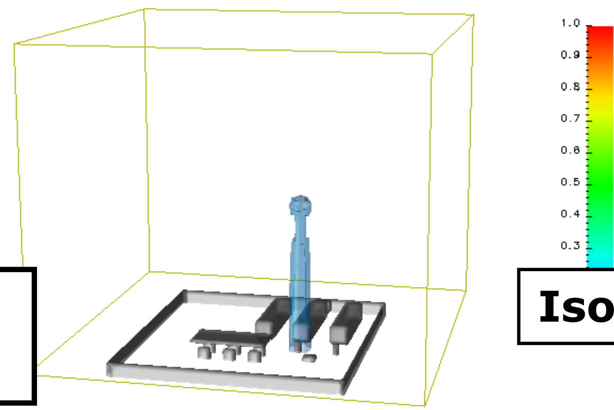
Concentration Comp. #1



ace 15% H2

Iso-surface 15% H_2

Concentration Comp. #1

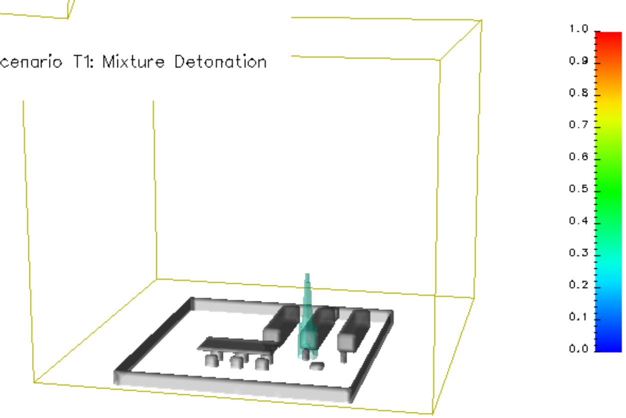


Concentration distribution at 6.8 s after the beginning of the release

COM3D v. 3.2.0

Scenario T1: Mixture Detonation

Iso-surface 30% H_2



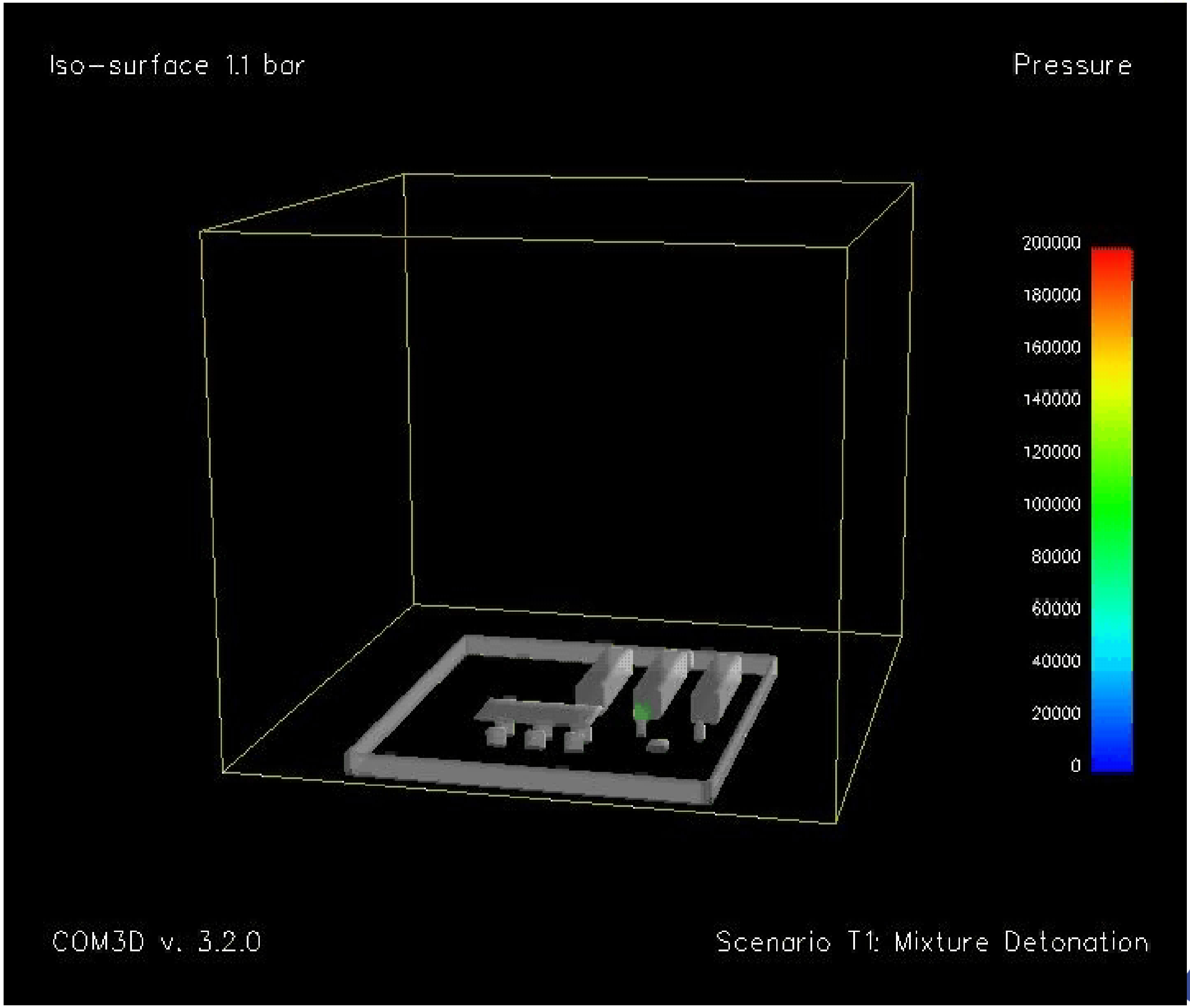
COM3D v. 3.2.0

Scenario T1: Mixture Detonation

Concentration distribution is imported from GASFLOW

Grid was modified from 60x60x50 to 120x120x100 (with total $1.44 \cdot 10^6$ cells)

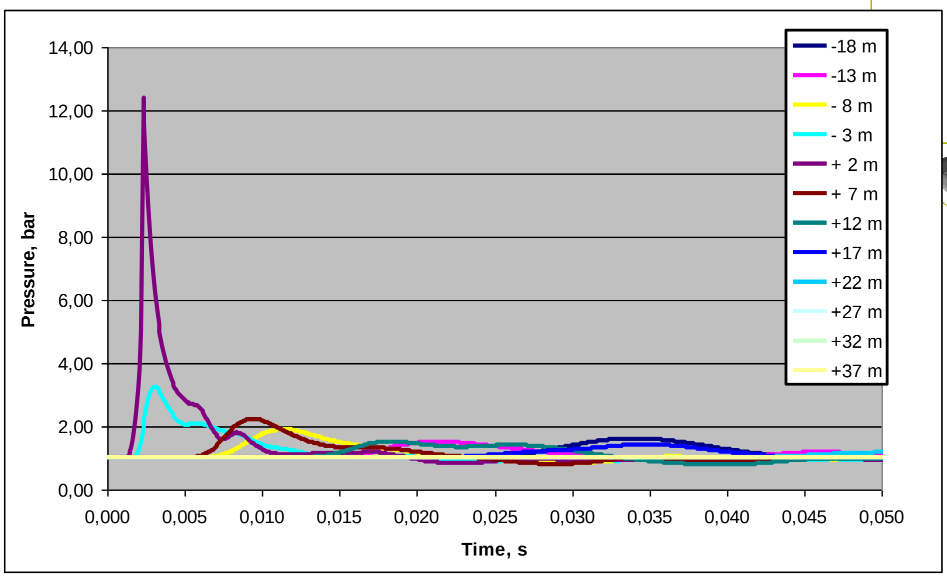
Scenario T1: Pressure wave evolution during detonation

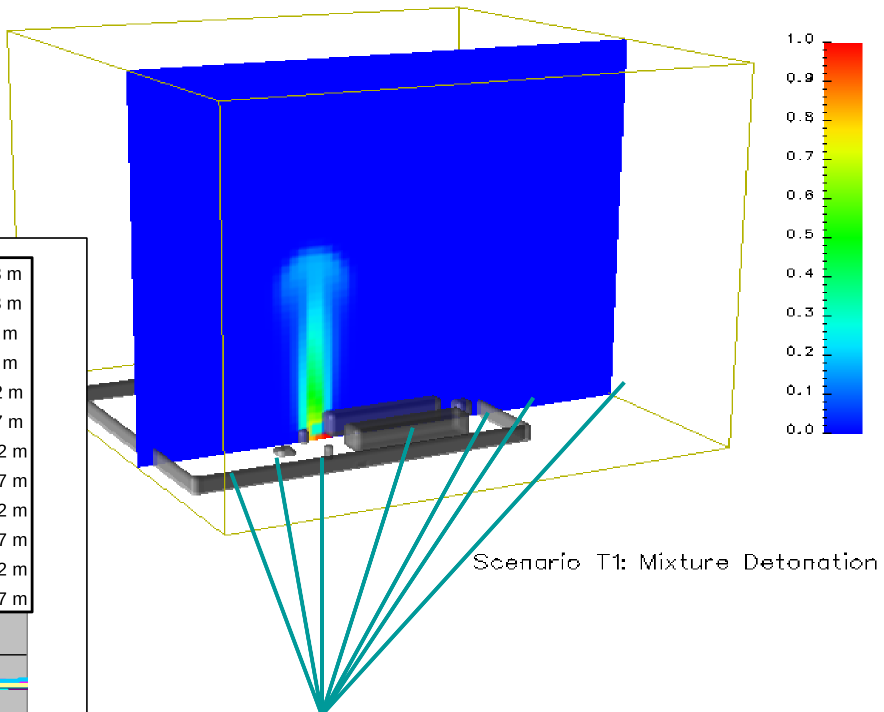


Scenario T1: Pressure loads

Recordings of the pressure wave resulted from the detonation of the H2 release at 6.8 s

'Transducer' line along trailer



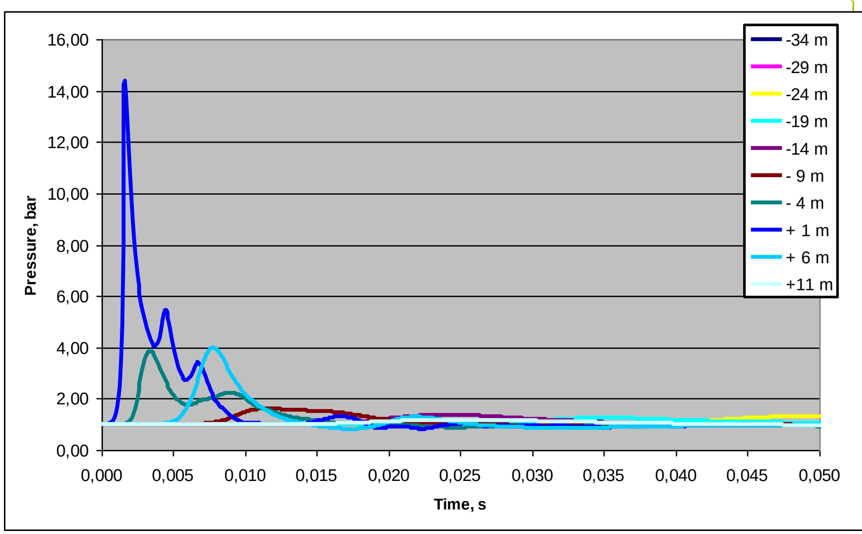


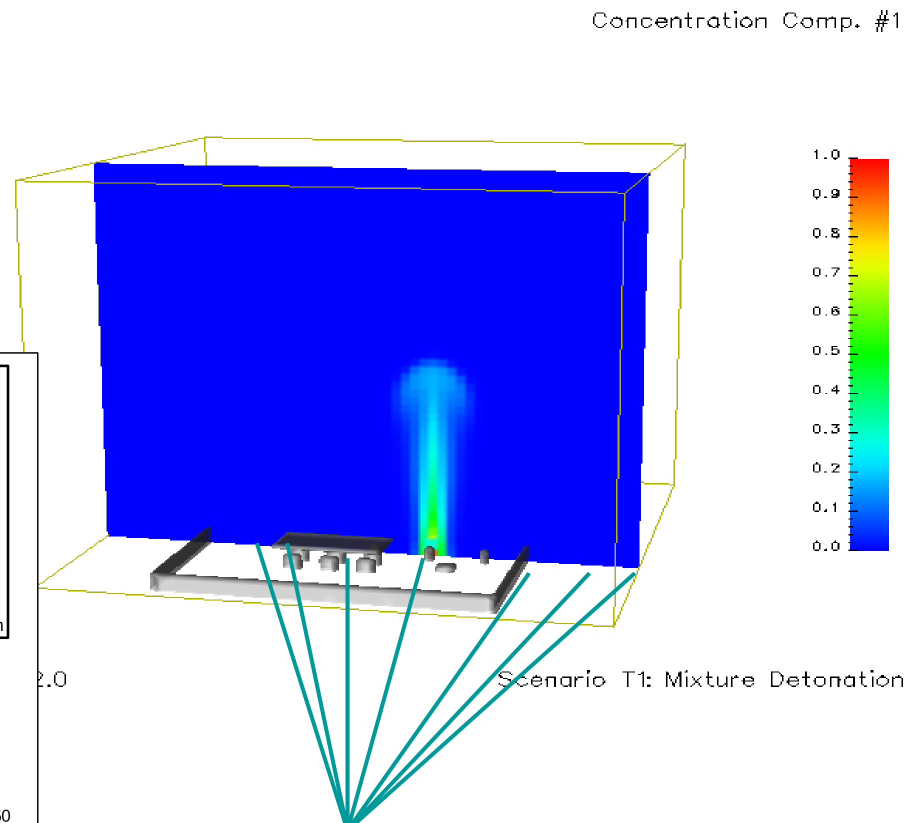
Pressure 'transducers'

Scenario T1: Pressure loads

Recordings of the pressure wave resulted from the detonation of the H2 release at 6.8 s

‘Transducer’ line between trailers and storage





Pressure ‘transducers’