MECHANISTIC SAFETY ANALYSIS OF HYDROGEN BASED ENERGY SYSTEMS

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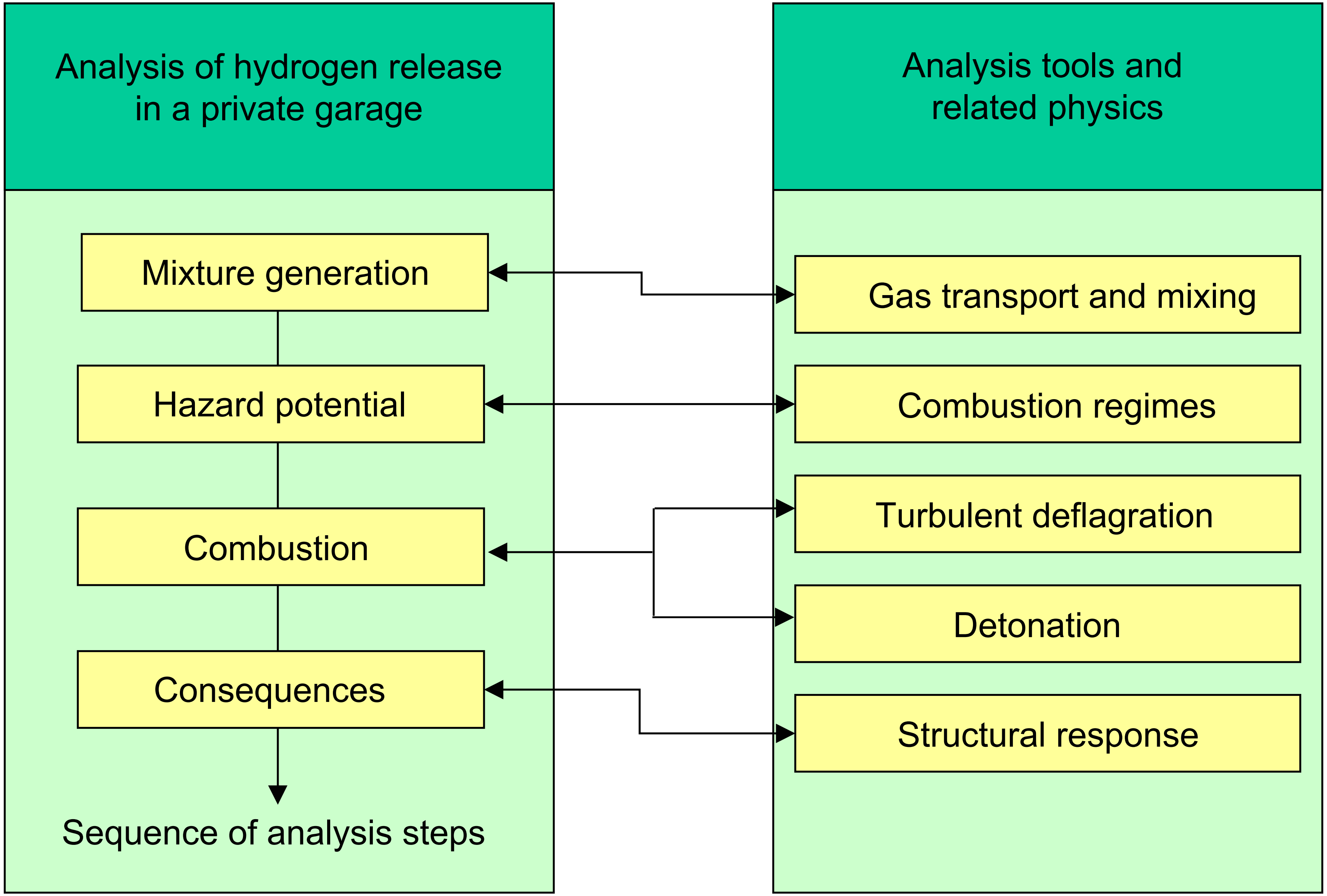
CONTENT OF PRESENTATION

- Presentation consists of two topics which are treated in parallel



Analysis of hydrogen release in a private garage

Mixture generation

Hazard potential

Combustion

Consequences

Sequence of analysis steps

Analysis tools and related physics

Gas transport and mixing

Combustion regimes

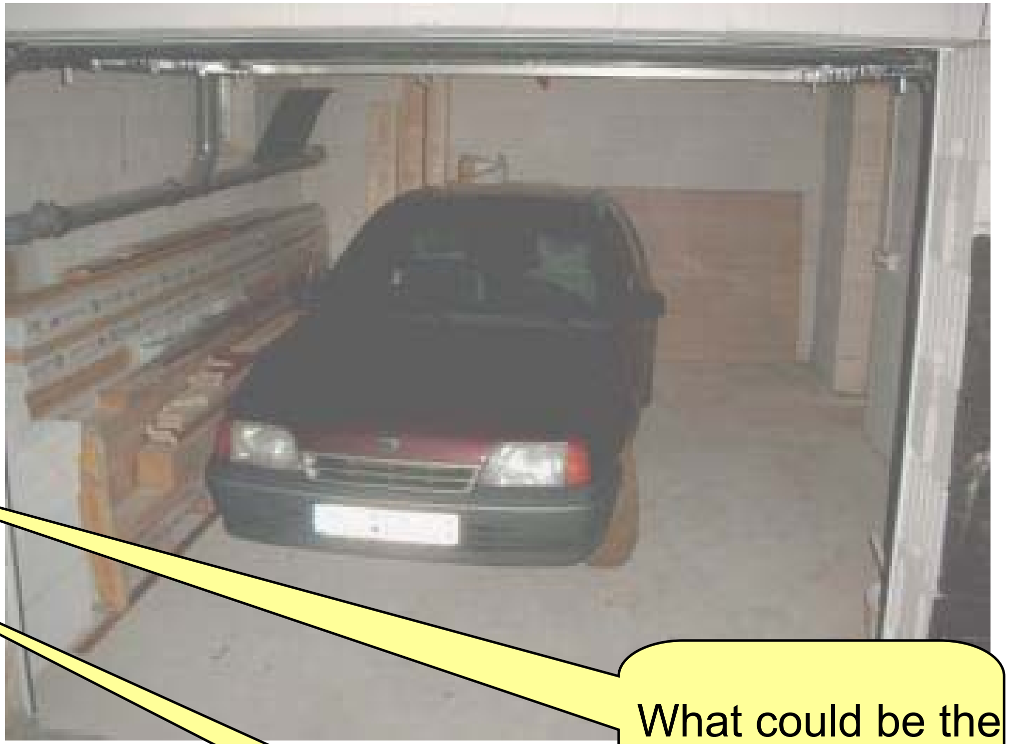
Turbulent deflagration

Detonation

Structural response

OUR EXAMPLE FOR HYDROGEN ANALYSIS

- Oil peak behind us, hydrogen fueled cars in widespread use
- Returned from a trip late at night
- There was some small collision but apperently no domage to LH$_2$-system
- Park car in private garage
- But at night the questions come ….



What could be the consequences?

What would happen in case of a hydrogen leak?

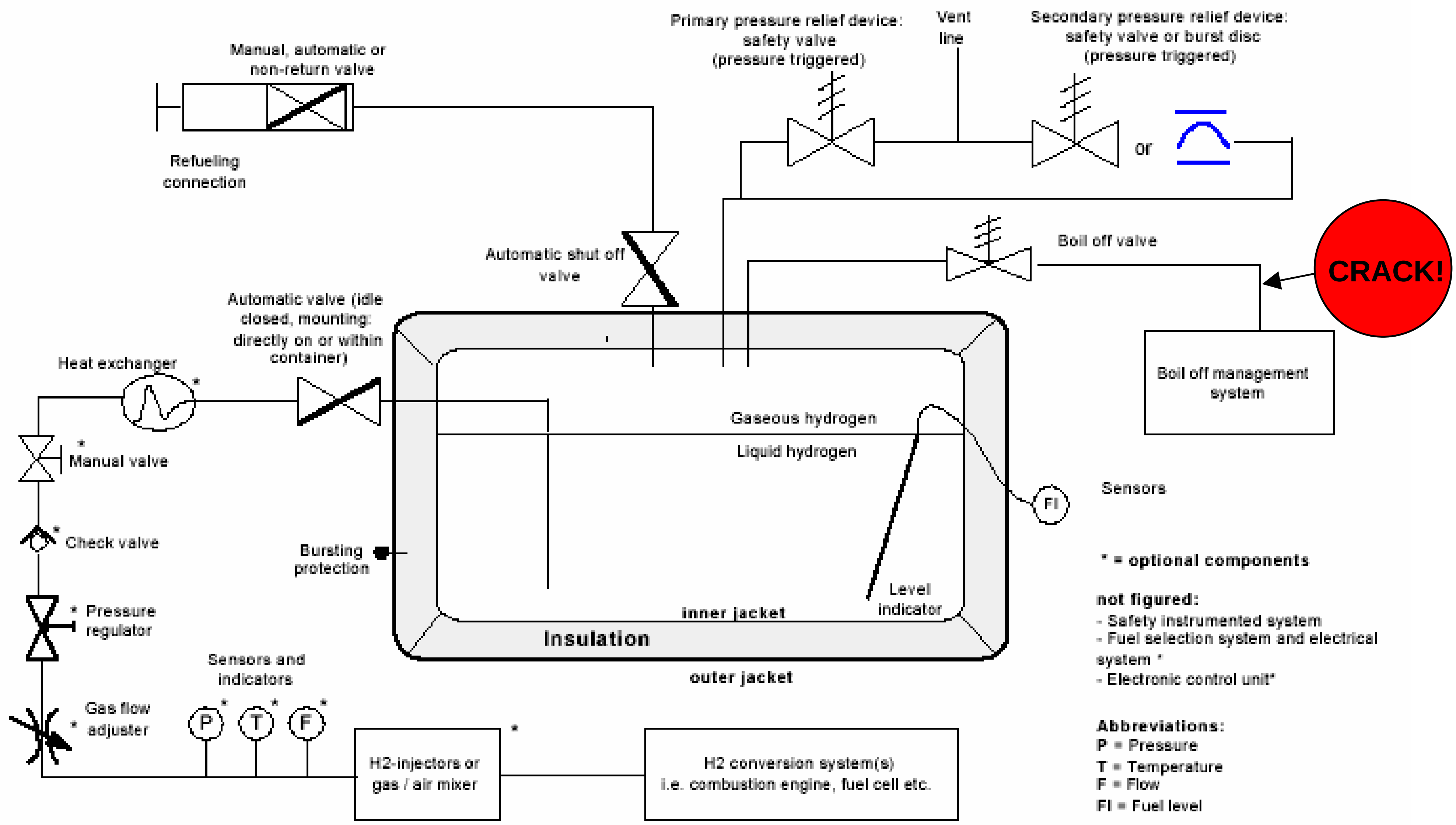
What mixtures could develop?

Could they be flammable?

How fast could the burn be?

What would be the pressure loads?

GENERIC ARCHITECTURE OF AN LH_2-TANK SYSTEM



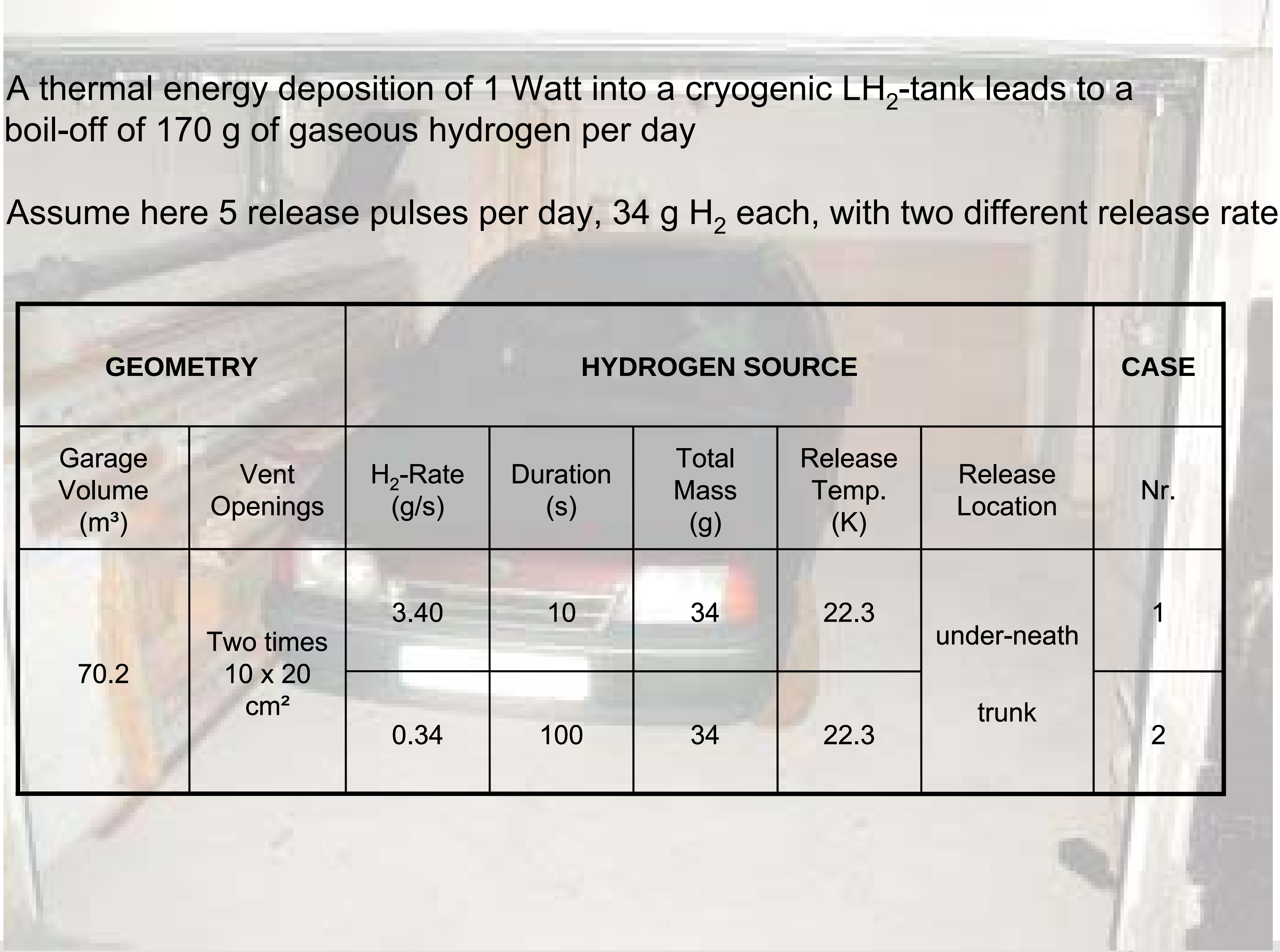
* = optional components

not figured:
- Safety instrumented system
- Fuel selection system and electrical system *
- Electronic control unit*

Abbreviations:
P = Pressure
T = Temperature
F = Flow
FI = Fuel level

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

INVESTIGATED GARAGE SCENARIOS

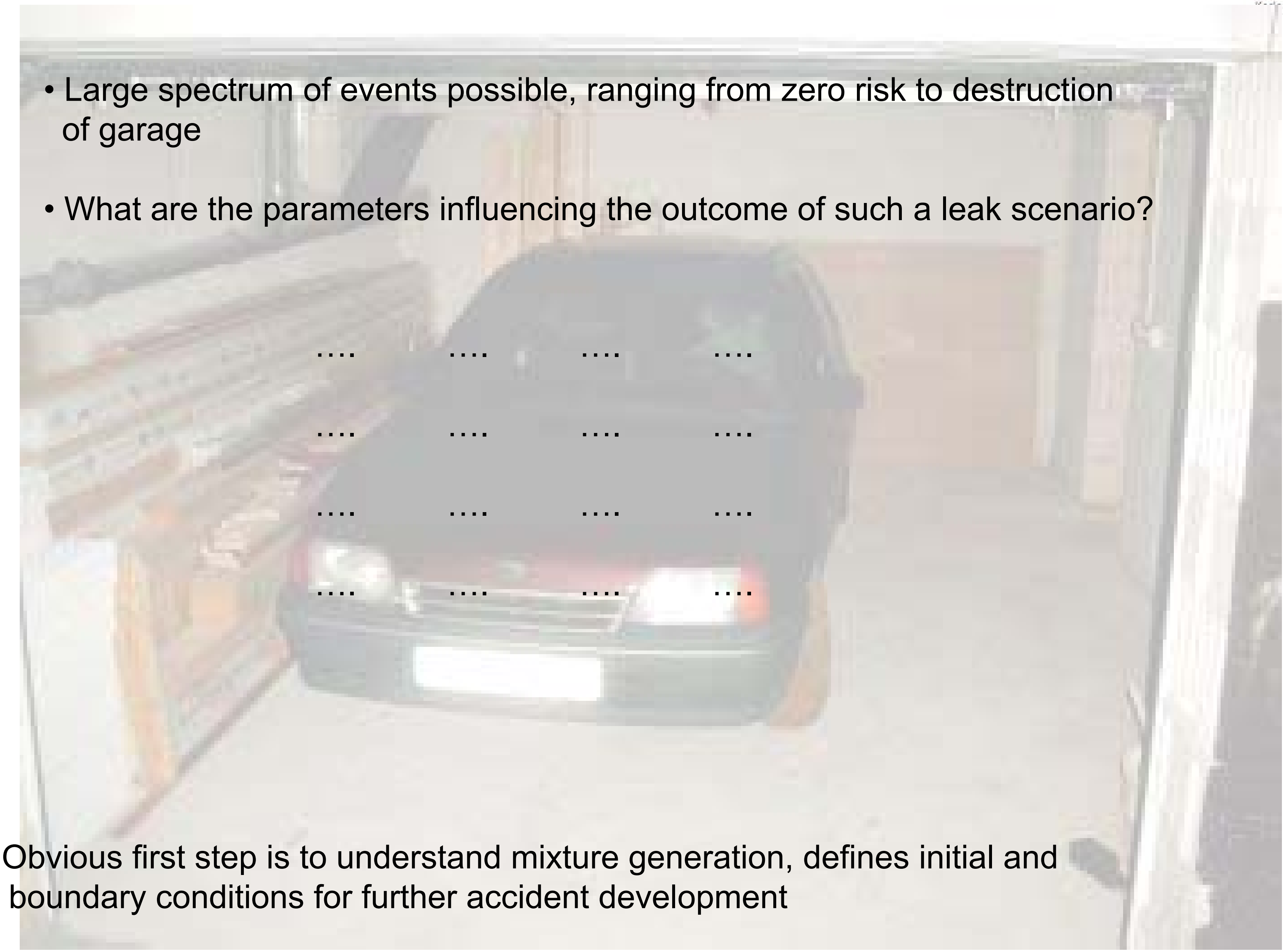


- A thermal energy deposition of 1 Watt into a cryogenic LH_2-tank leads to a boil-off of 170 g of gaseous hydrogen per day

- 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?

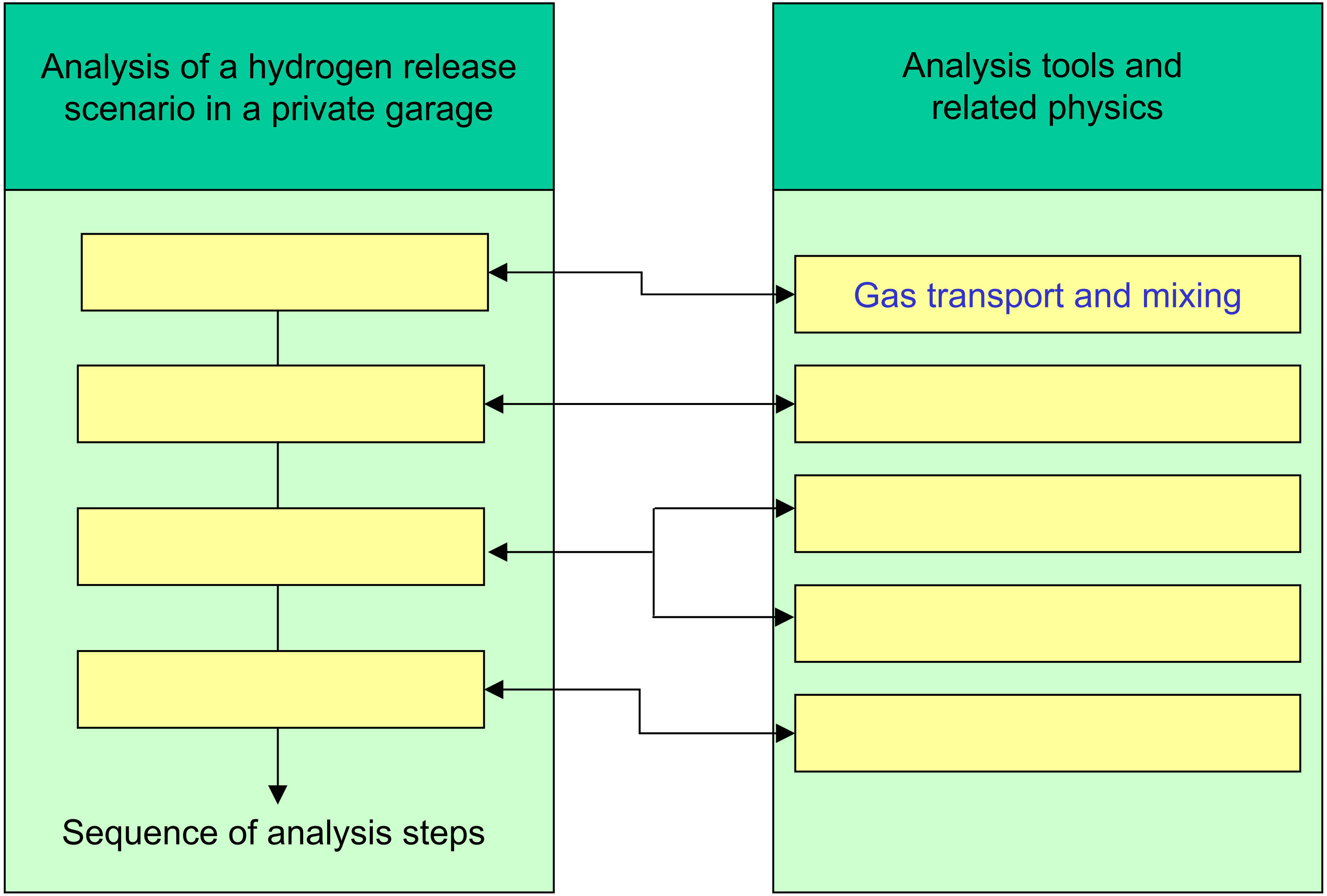
…. …. …. ….

…. …. …. ….

…. …. …. ….

…. …. …. ….

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



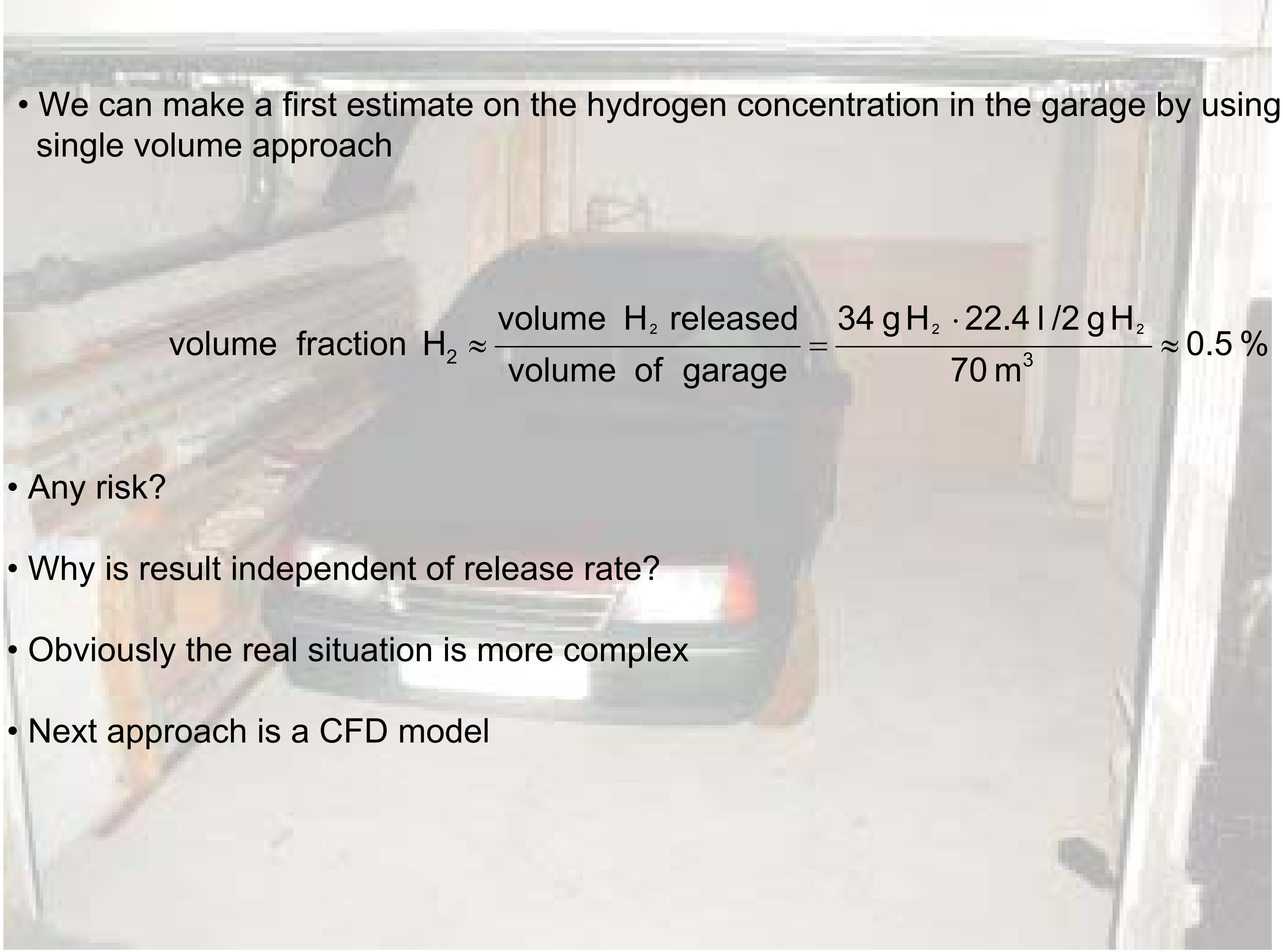
Analysis of a hydrogen release scenario in a private garage

Analysis tools and related physics

Gas transport and mixing

Sequence of analysis steps

AN INITIAL ESTIMATE ON HYDROGEN CONCENTRATION

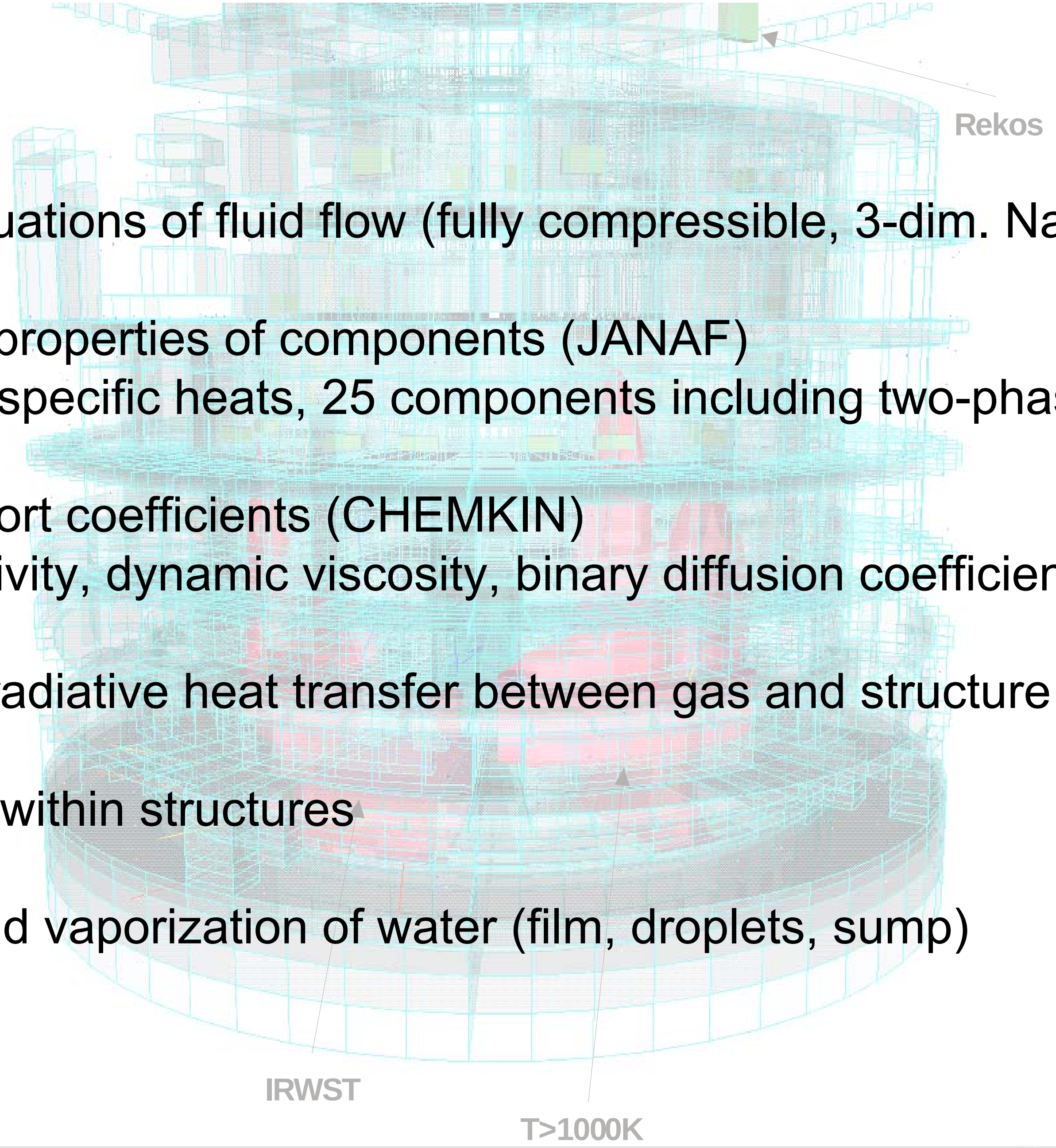


- We can make a first estimate on the hydrogen concentration in the garage by using a single volume approach

$$\text{volume fraction } H_2 \approx \frac{\text{volume } H_2 \text{ released}}{\text{volume of garage}} = \frac{34\,\text{g}\,H_2 \cdot 22.4\,\text{l}/2\,\text{g}\,H_2}{70\,\text{m}^3} \approx 0.5\,\%$$

- Any risk?
- Why is result independent of release rate?
- Obviously the real situation is more complex
- Next approach is a CFD model

Physical models of 3d code GASFLOW (1)



- Conservation equations of fluid flow (fully compressible, 3-dim. Navier- Stokes)

- Thermophysical properties of components (JANAF)
  (internal energy, specific heats, 25 components including two-phase water)

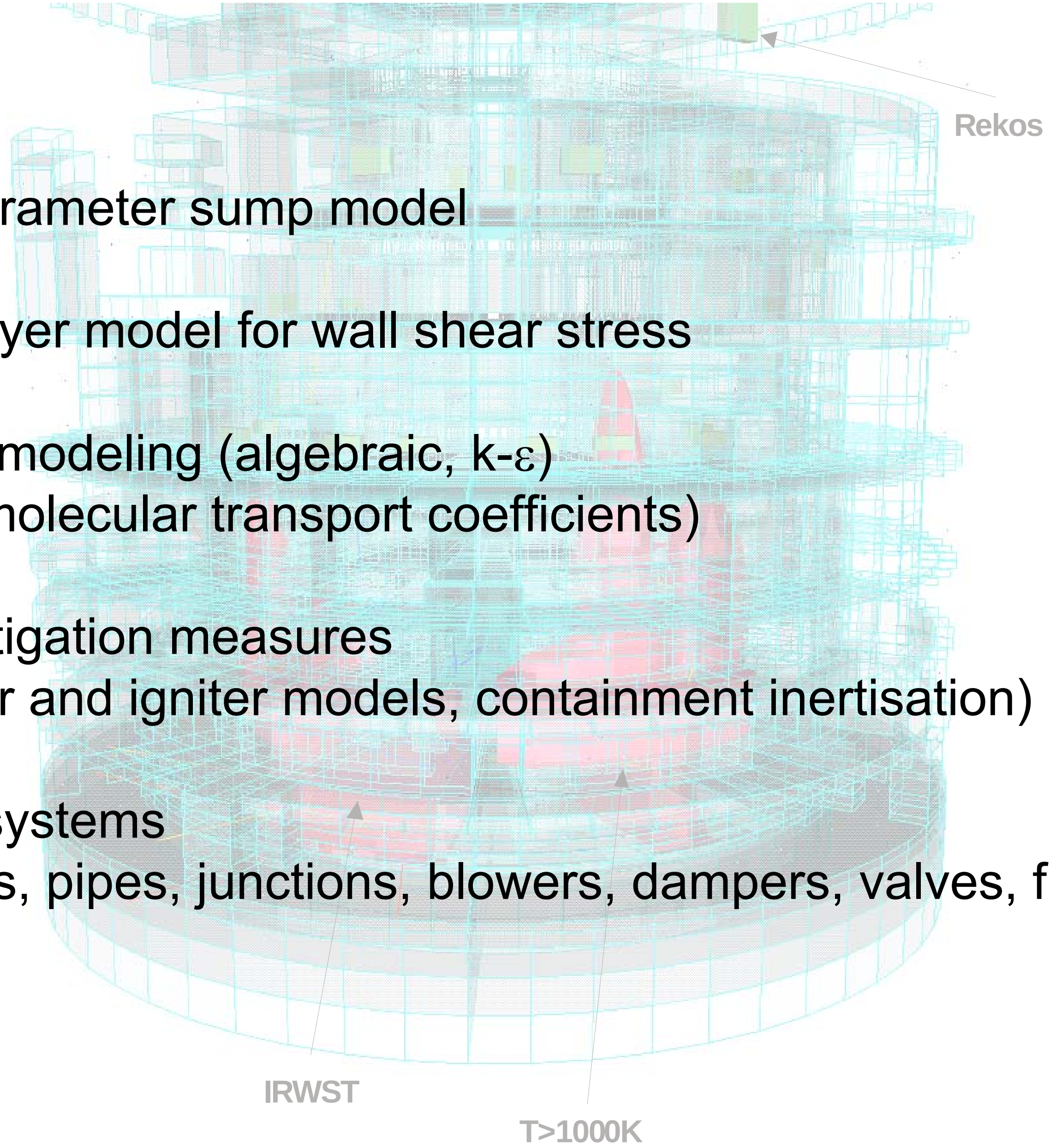
- Molecular transport coefficients (CHEMKIN)
  (thermal conductivity, dynamic viscosity, binary diffusion coefficients)

- Convective and radiative heat transfer between gas and structure

- Heat conduction within structures

- Condensation and vaporization of water (film, droplets, sump)

Physical models of 3d code GASFLOW (2)



- Lumped- parameter sump model
- Boundary layer model for wall shear stress
- Turbulence modeling (algebraic, k-ε)
  (effects on molecular transport coefficients)
- Accident mitigation measures
  (Recombiner and igniter models, containment inertisation)
- Ventilation systems
  (1-dim. ducts, pipes, junctions, blowers, dampers, valves, filters, etc)

GASFLOW EQUATIONS

- **Fully compressible Navier-Stokes, expressed in integral form for finite volume discretisation**

• Mass conservation

Total mass:

$$\frac{\partial}{\partial t}\int_V \rho \, dV = \oint_S \rho \mathbf{u} \mathbf{A} \, dS + \int_V S_\rho \, dV$$

convection   sources (inflow, droplet depletion)

Component α :

$$\frac{\partial}{\partial t}\int_V \rho_\alpha \, dV = \oint_S \rho_\alpha \mathbf{u} \mathbf{A} \, dS - \oint_S (\mathbf{J}_\alpha \mathbf{A}) \, dS + \int_V S_{\rho,\alpha} \, dV$$

convection   diffusion   chem. reaction two-phase change

• Momentum conservation

$$\frac{\partial}{\partial t}\int_V \rho \mathbf{u} \, dV = \oint_S \rho \mathbf{u}^2 \mathbf{A} \, dS - \oint_S p \, d\mathbf{S} + \int_V \rho \mathbf{g} \, dV - \oint_S (\tau \mathbf{A}) \, dS$$

momentum flux   pressure gradient   gravity   viscous stresses

$$- \oint_S (\mathbf{D}_d \mathbf{A}) \, dS + \int_V \mathbf{S}_m \, dV$$

drag from internal surfaces & flow restrictions   momentum sources

• Internal energy conservation

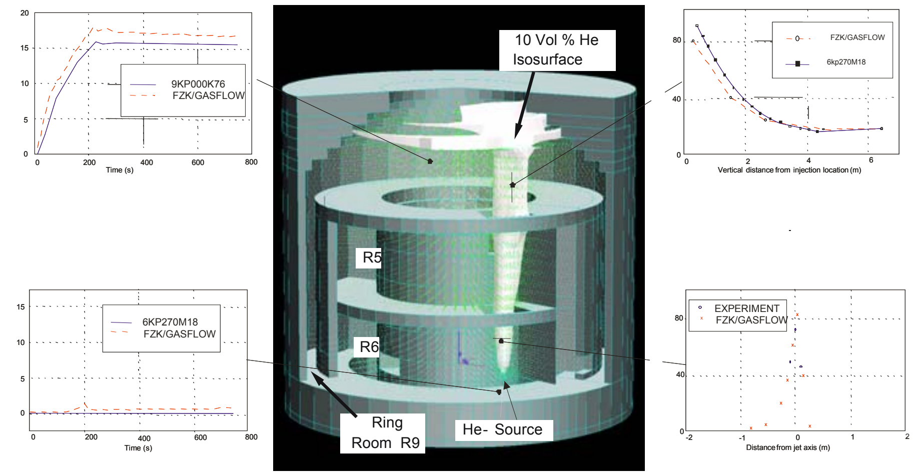
$$\frac{\partial}{\partial t}\int_V \rho e \, dV = \oint_S \rho e \, \mathbf{u} \, \mathbf{A} \, dS - \oint_S p(\mathbf{u}\mathbf{A}) \, dS - \int_V \left(\frac{p}{V} \frac{\partial V_{HO}}{\partial t} \right) dV$$

convection   pV work   pV work due to phase change

$$- \oint_S (\mathbf{q}\mathbf{A}) \, dS + \int_V S_e \, dV \qquad e = \sum_\alpha x_\alpha e_\alpha$$

energy flux (thermal, conductivity, ...)   energy sources (combustion, phase change, heat transfer)

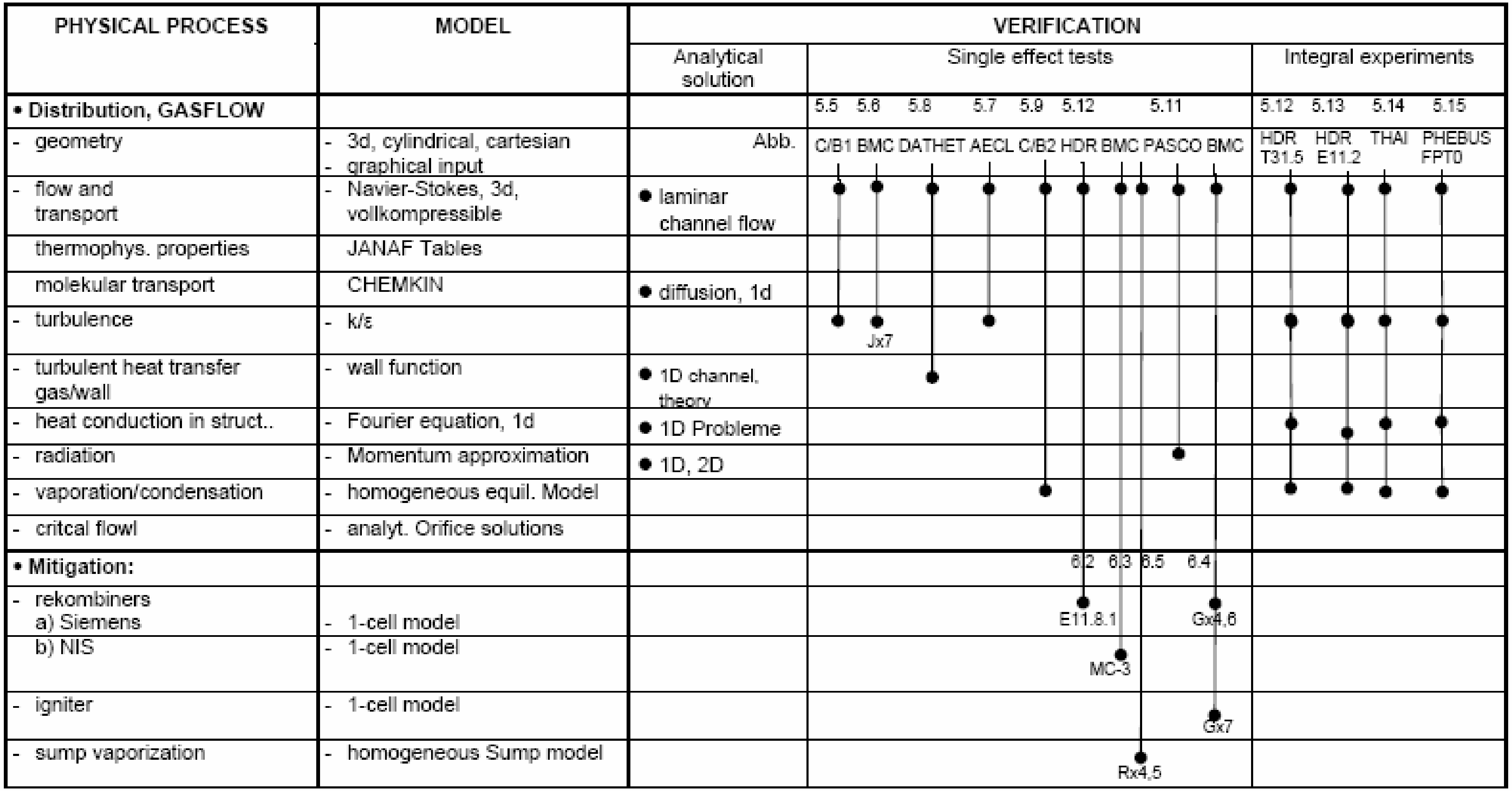
- **Vertical He-jet into air (42 m/s) for 200 s**



J.R. Travis et al, Report FZKA-5994 (1998)

GASFLOW VERIFICATION

- 3d code GASFLOW used and developed at FZK for hydrogen distribution simulation. Large verification matrix:

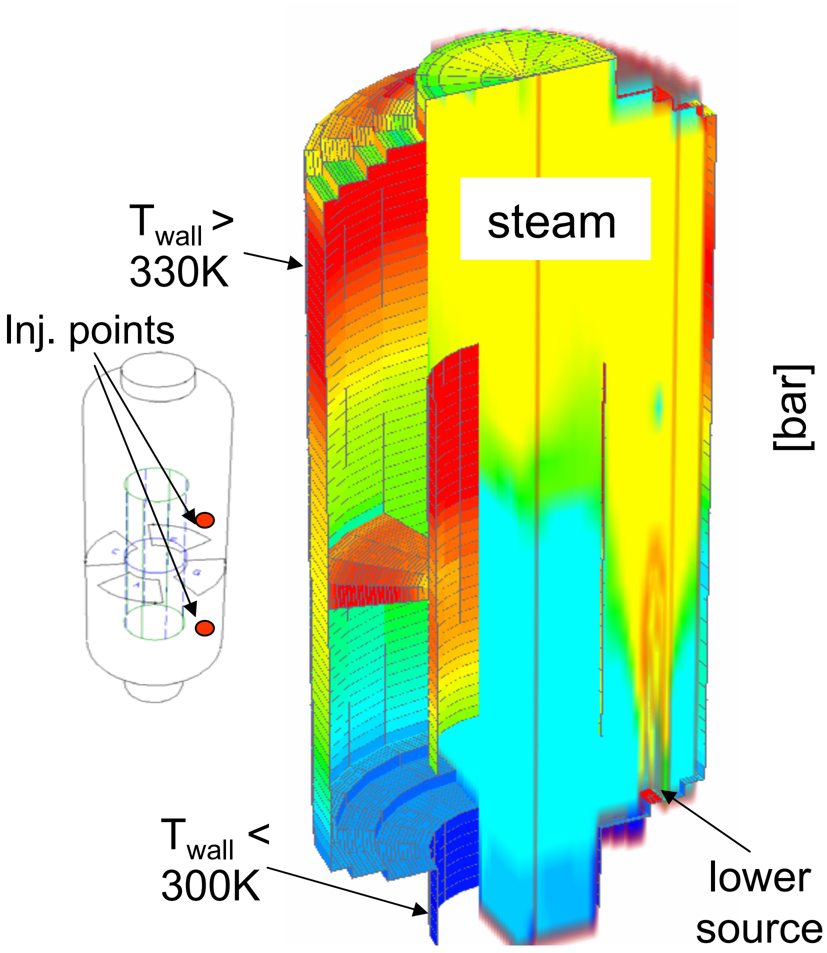


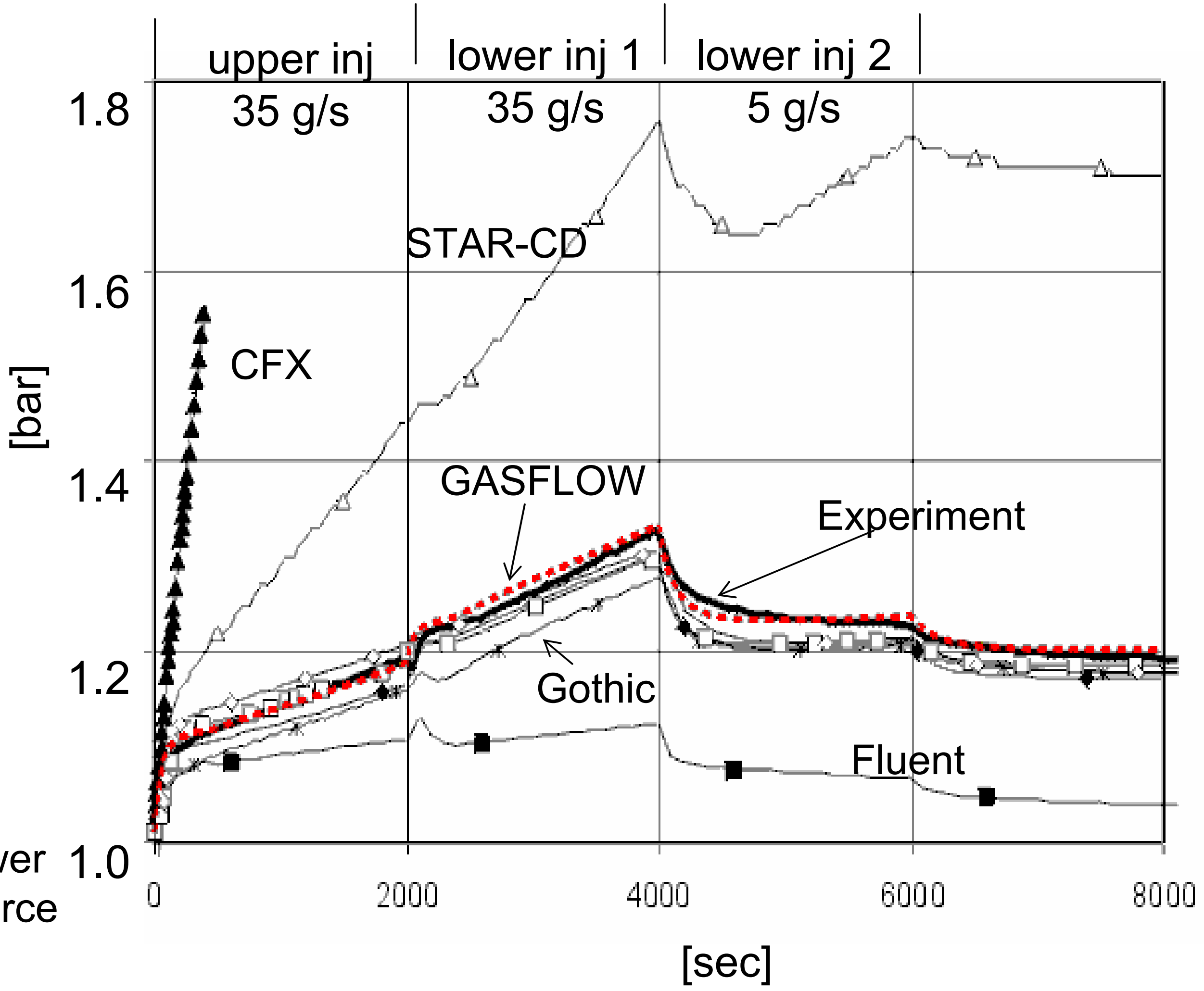
PHYSICAL PROCESS	MODEL	VERIFICATION														
		Analytical solution	Single effect tests										Integral experiments			
• Distribution, GASFLOW			5.5	5.6	5.8	5.7	5.9	5.12			5.11		5.12	5.13	5.14	5.15
- geometry	- 3d, cylindrical, cartesian - graphical input	Abb.	C/B1	BMC	DATHET	AECL	C/B2	HDR	BMC		PASCO	BMC	HDR T31.5	HDR E11.2	THAI	PHEBUS FPT0
- flow and transport	- Navier-Stokes, 3d, vollkompressible	● laminar channel flow	●	●	●	●	●	●	●	●	●	●	●	●	●	●
thermophys. properties	JANAF Tables															
molekular transport	CHEMKIN	● diffusion, 1d														
- turbulence	- k/ε		●	● Jx7		●							●	●	●	●
- turbulent heat transfer gas/wall	- wall function	● 1D channel, theory			●											
- heat conduction in struct..	- Fourier equation, 1d	● 1D Probleme											●	●	●	●
- radiation	- Momentum approximation	● 1D, 2D									●					
- vaporation/condensation	- homogeneous equil. Model						●						●	●	●	●
- critcal flowl	- analyt. Orifice solutions															
• Mitigation:								6.2	6.3	6.5		6.4				
- rekombiners a) Siemens	- 1-cell model							● E11.8.1				● Gx4,6				
b) NIS	- 1-cell model								● MC-3							
- igniter	- 1-cell model											● Gx7				
- sump vaporization	- homogeneous Sump model									● Rx4,5						

Report FZKA-7085 (2005), www.fzk.de/hbm

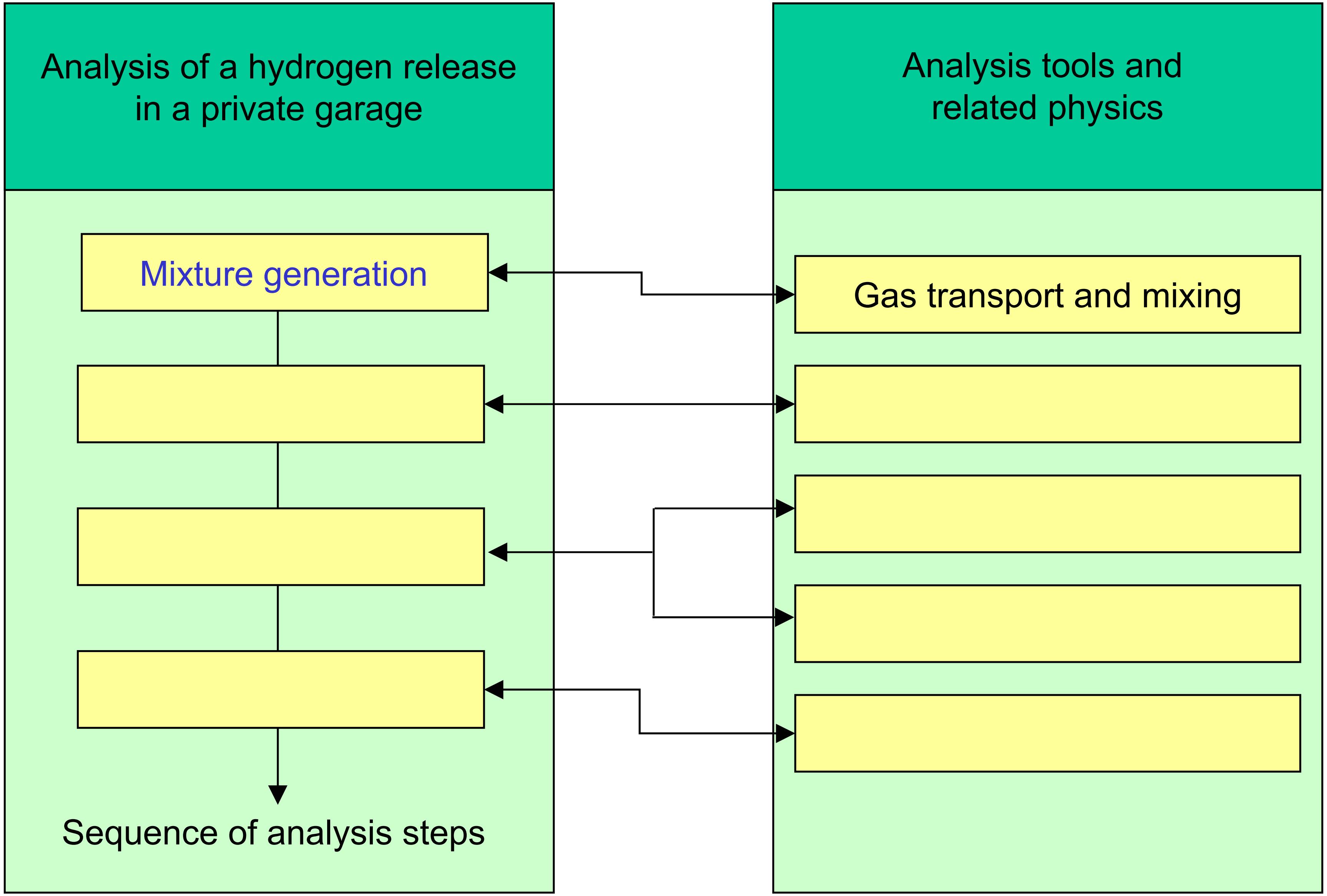
EXAMPLE FOR RECENT GASFLOW VERIFICATION

- German national benchmark, test TH7 in Thai facility with condensation
- Blind pressure prediction of CFD codes





P. Royl, IKET



Analysis of a hydrogen release in a private garage

Mixture generation

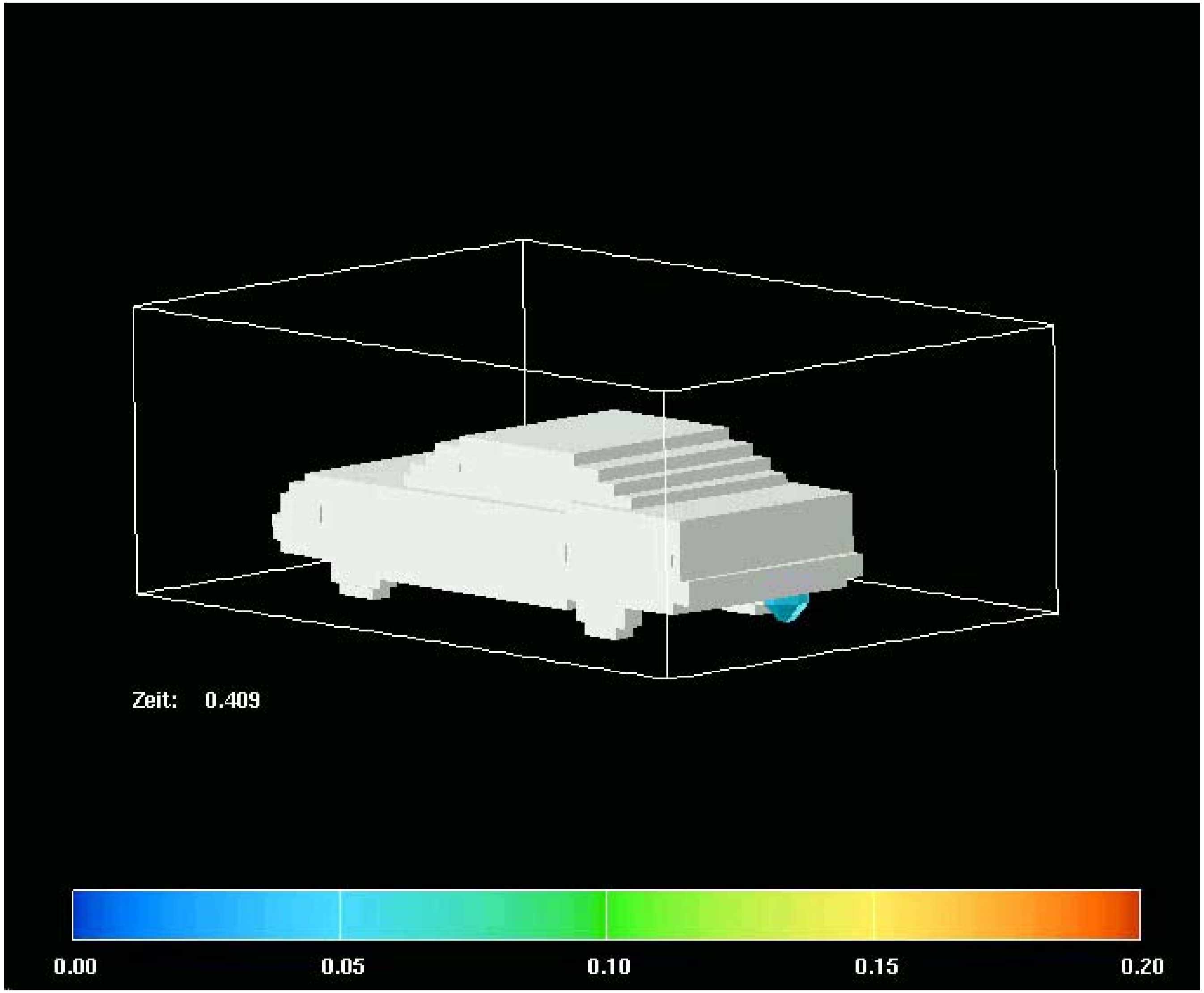
Sequence of analysis steps

Analysis tools and related physics

Gas transport and mixing

GASFLOW SIMULATION OF GARAGE SCENARIO

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

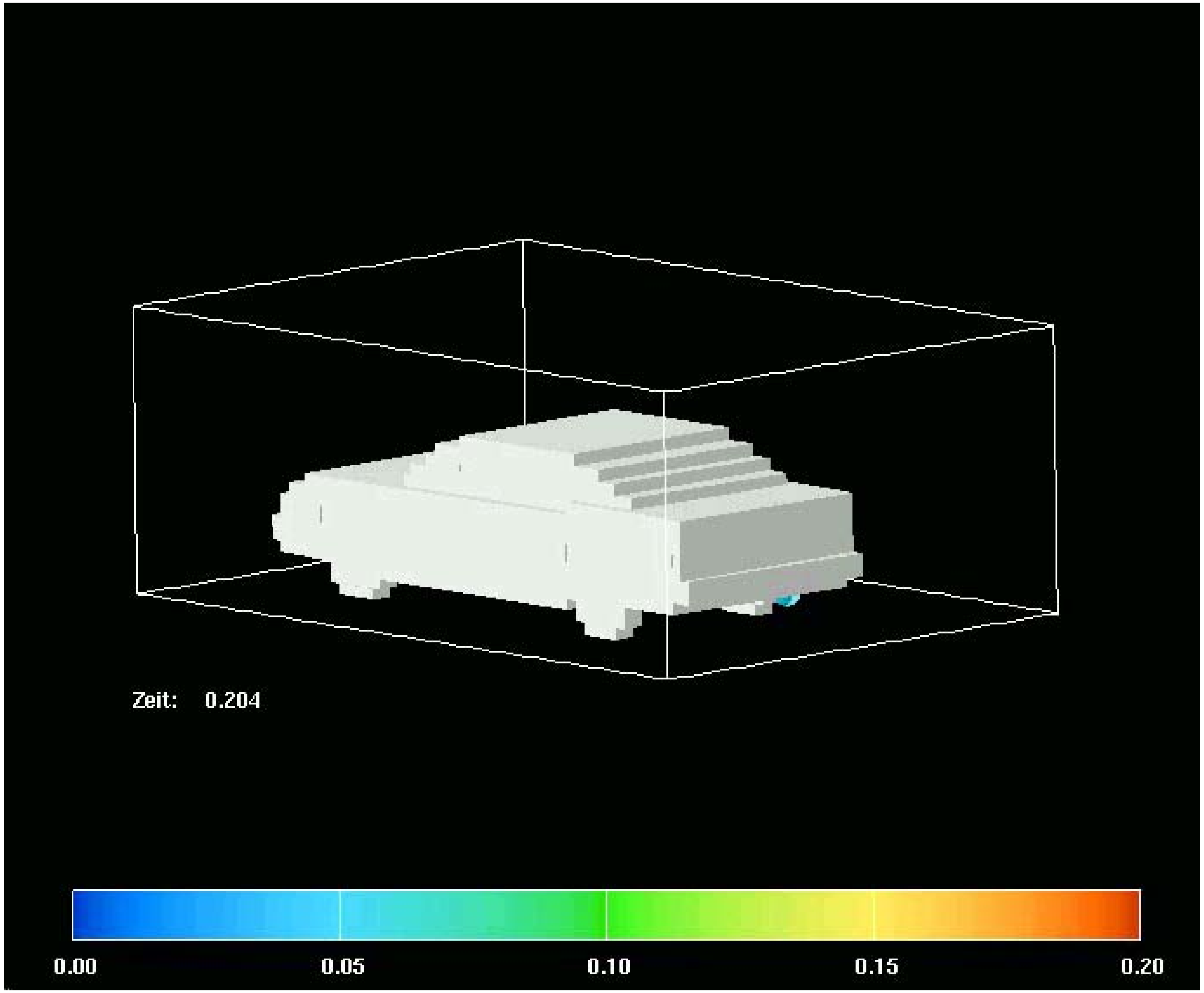


volume fraction H_2

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

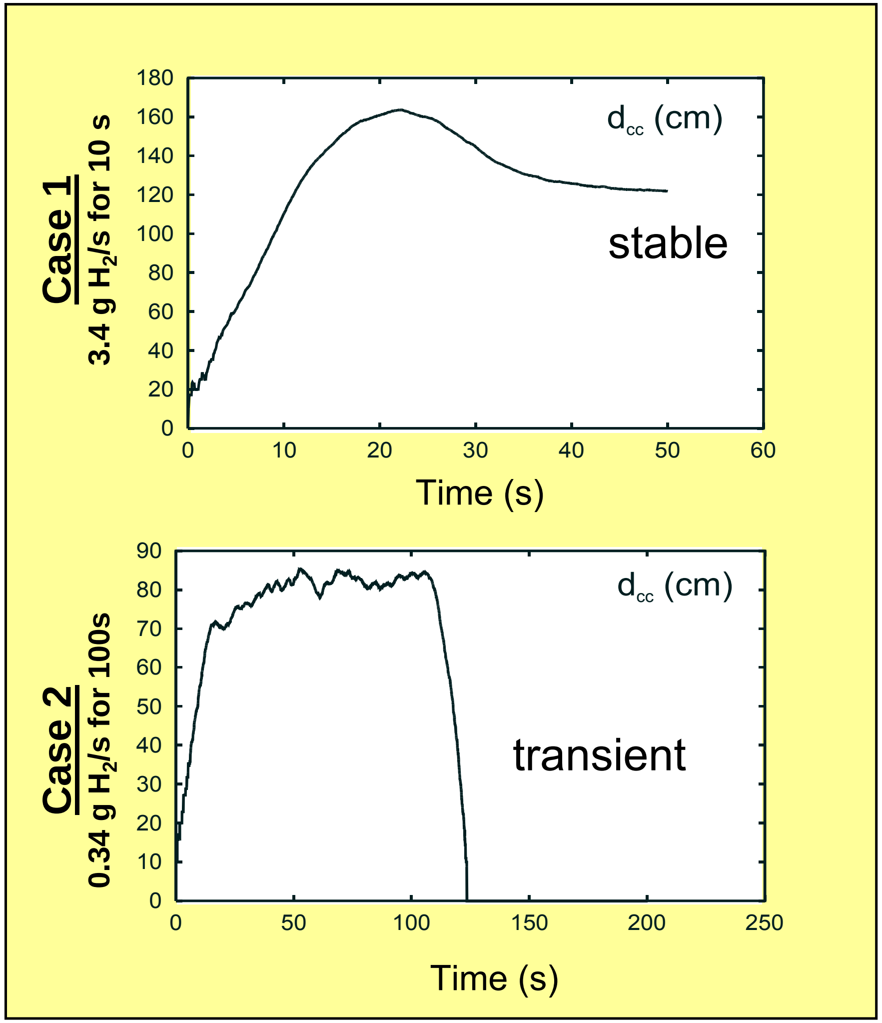


volume fraction H_2

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

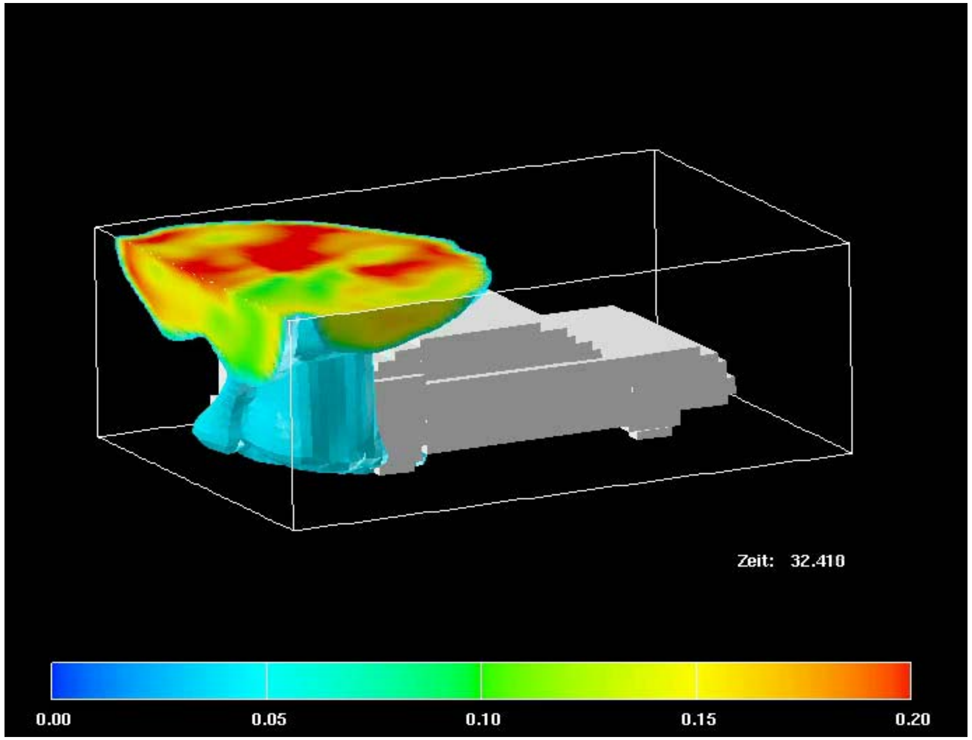
RESULTING HYDROGEN CLOUD IN GARAGE

- Computed dimension of combustible H_2-air cloud in garage (4…75% H_2)
- Characteristic size of combustible cloud expressed as $d_{CC} = (V_{cc})^{1/3}$
- Combustible cloud size strongly dependent on release rate, is result of balance between source strength and sinks, or release rate and mixing mechanisms

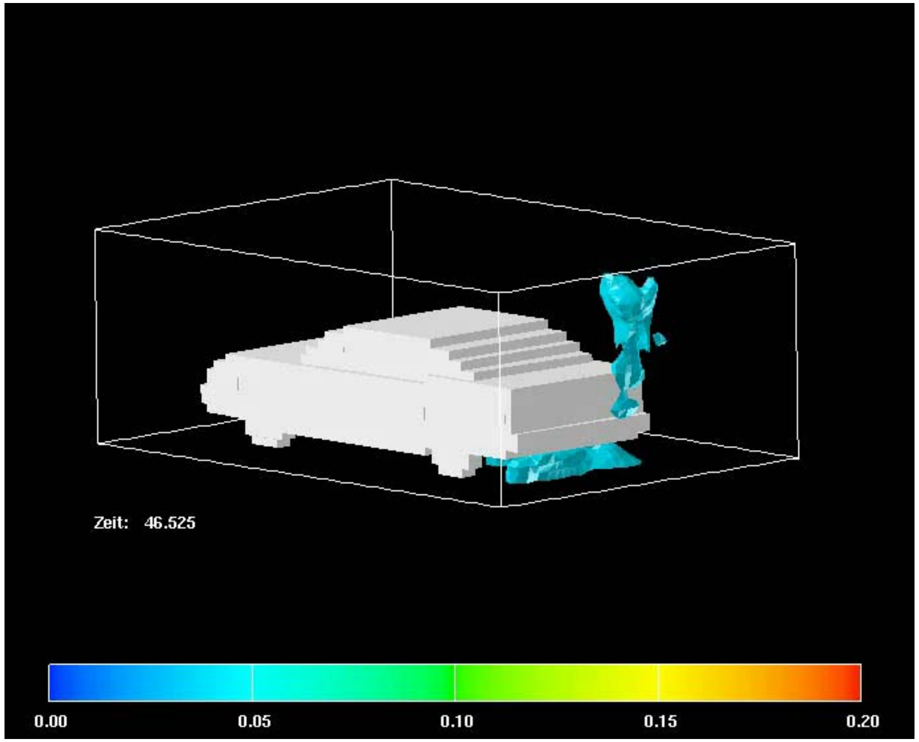


WHAT IS RISK FROM COMBUSTIBLE CLOUD?

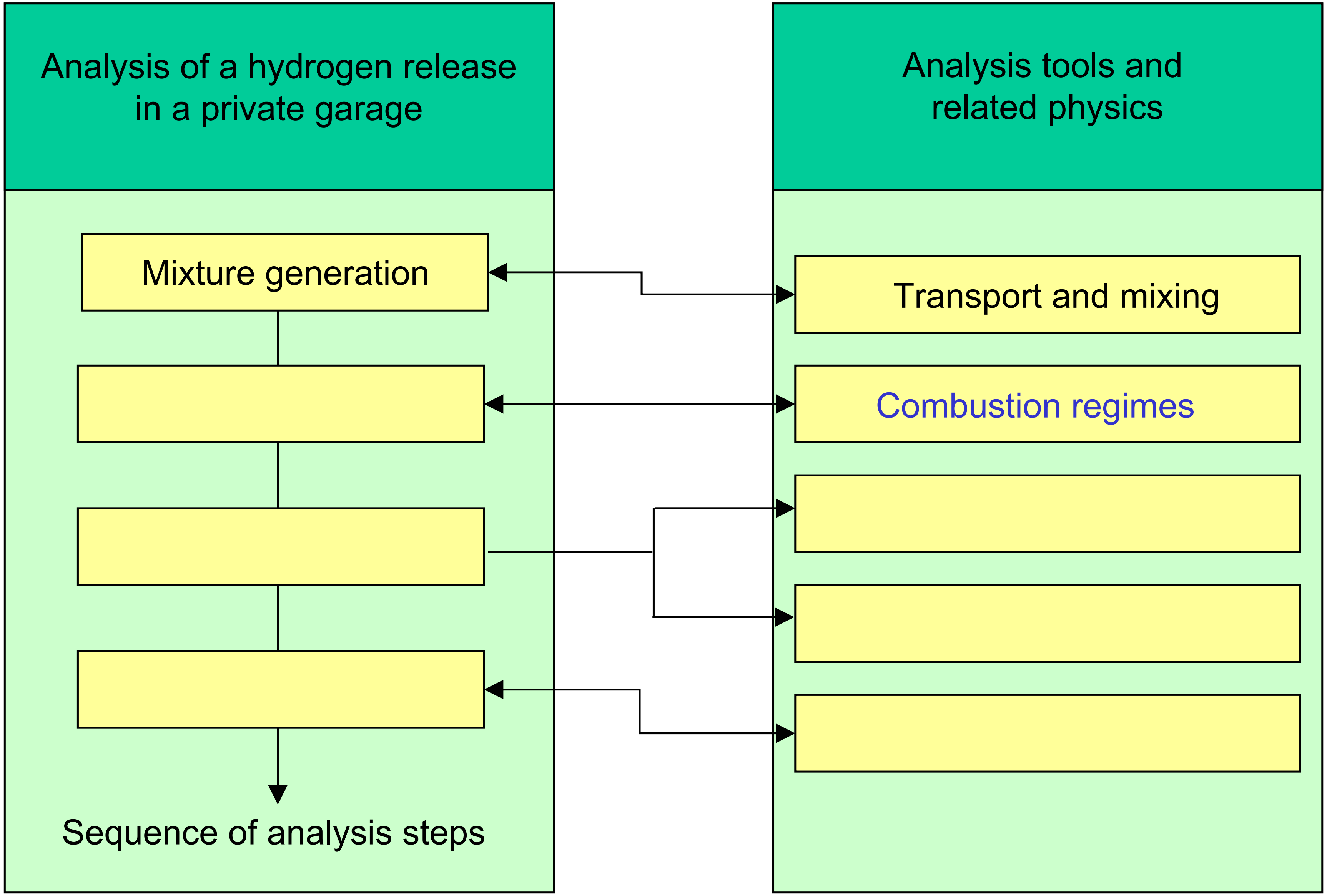
- How would you judge the hazard in both cases?
- Who would switch on lights in the garage?
- What physical quantities determine hazard potential of a combustible H_2-air cloud?



Case 1



Case 2



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Mixture generation

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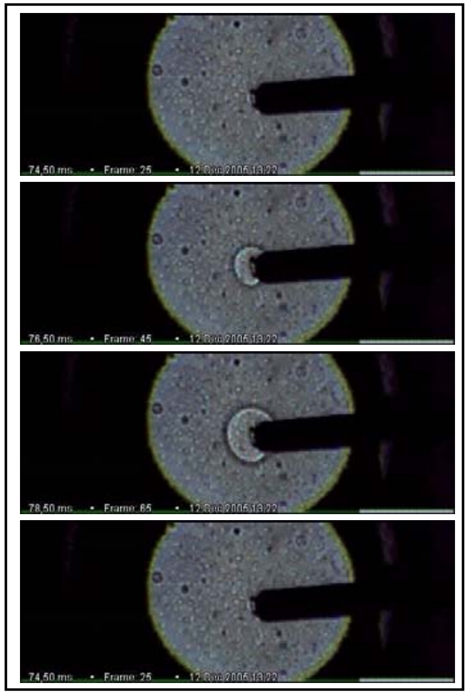
Transport and mixing

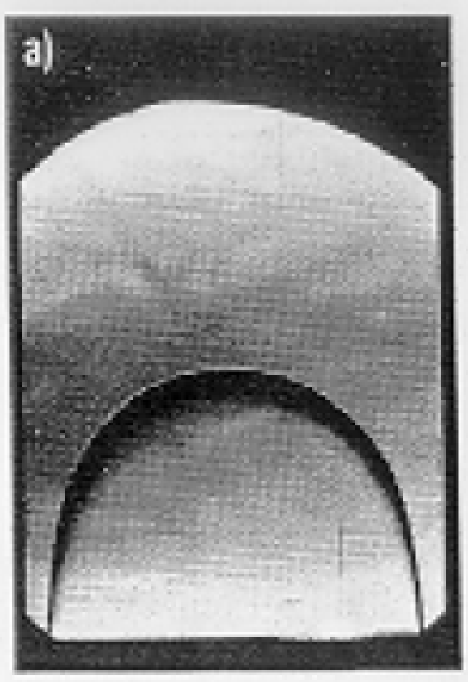
Combustion regimes

COMBUSTION REGIMES

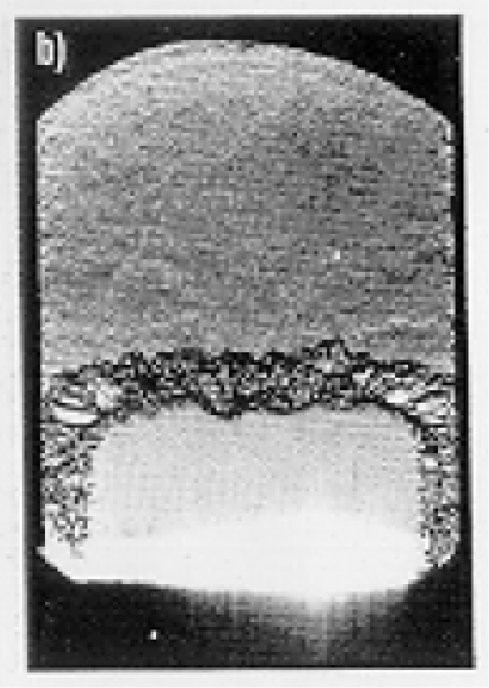
- H_2 – air mixtures can burn in different modes / combustion regimes



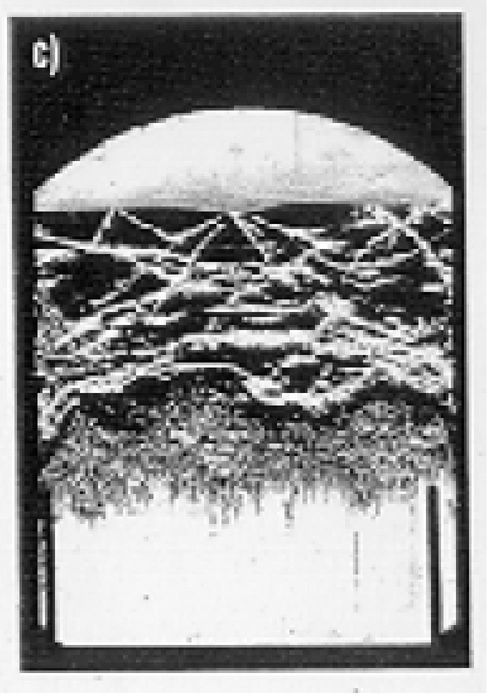
Inert, no stable
flame propagation
$v_{fl} = 0$



Laminar deflagration
$v_{fl} \approx 1$ m/s, Ma << 1



Fast turbulent deflagration
$v_{fl} \approx 300$ m/s, Ma ≈ 1



Detonation
$v_{fl} \approx 1500$ m/s, Ma >> 1

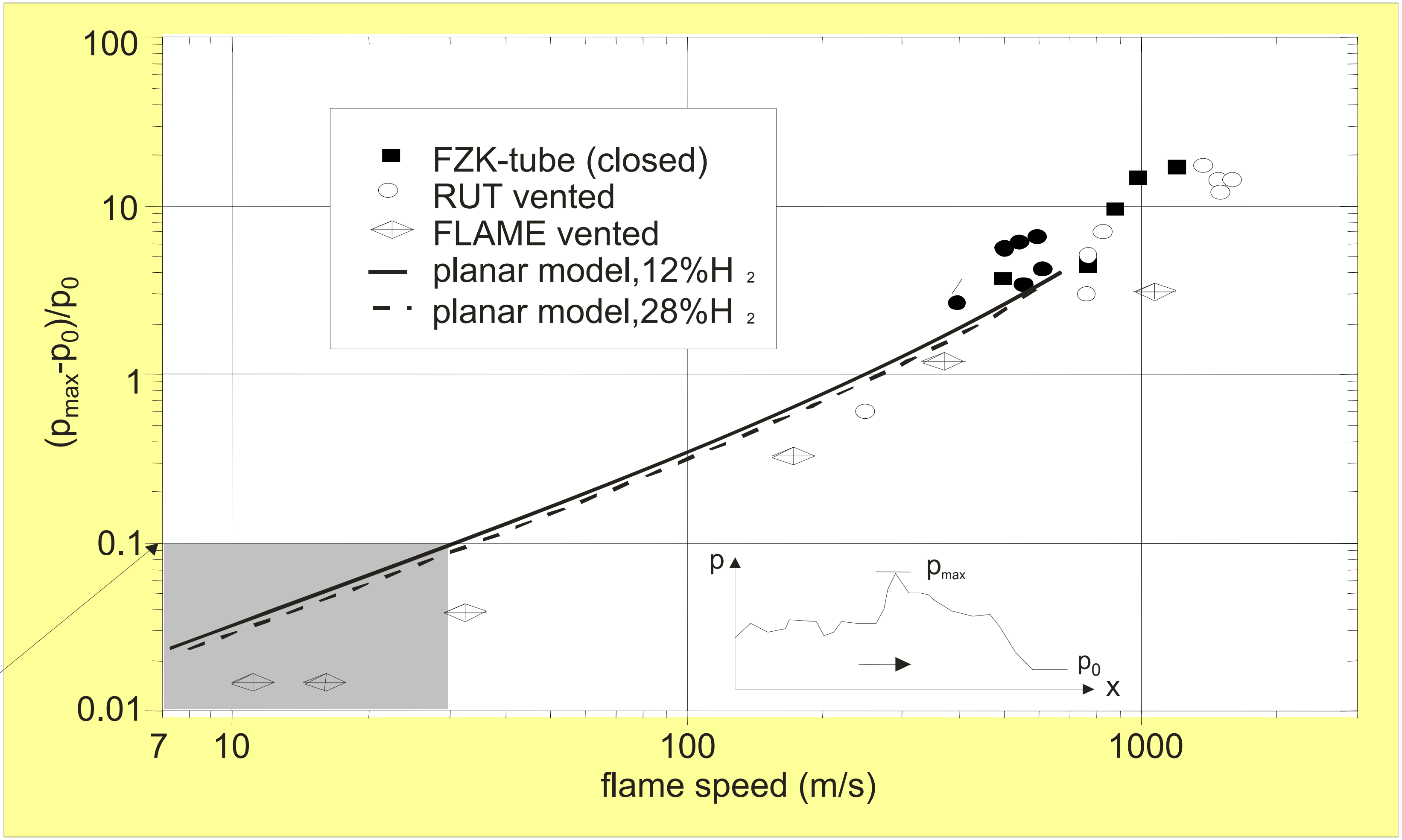
- Change of mode possible by transition process

Ignition

Flame acceleration

Deflagration-to-detonation transition (DDT)

PEAK OVERPRESSURES FROM HYDROGEN-AIR FLAMES

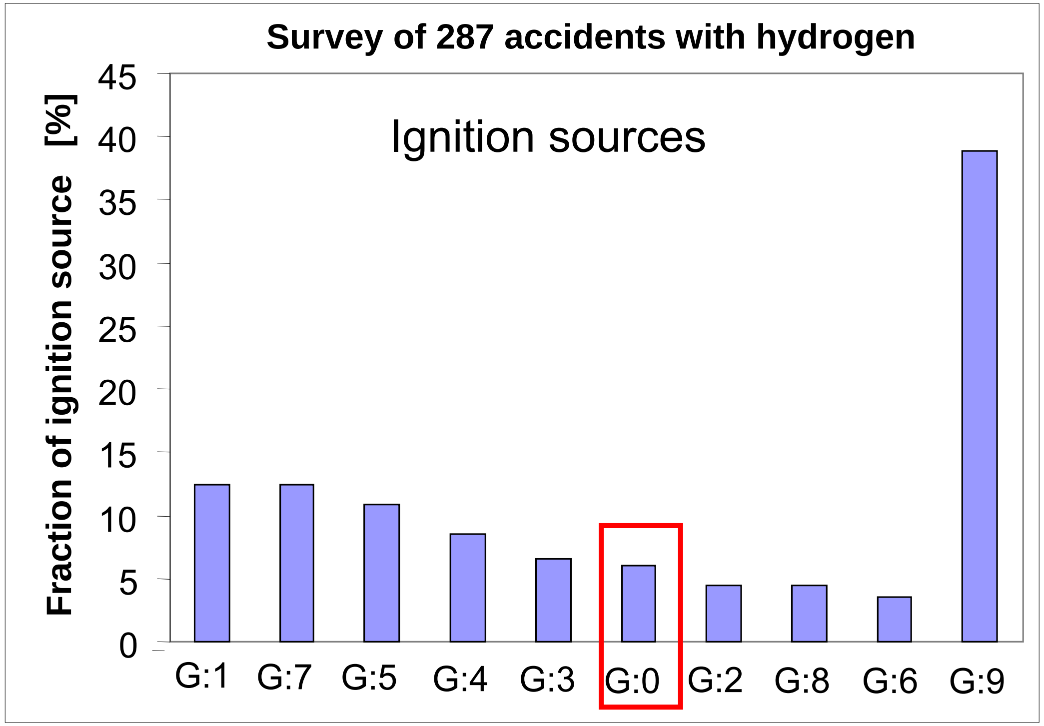


Maximum acceptable static load for typical inner containment structures (1 ton / m^2)

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

IGNITION

- Combustion requires an ignition source and a burnable mixture
- Many potential ignition sources exist
- More than 90% of incidents with GH_2 lead to ignition, cause often unknown
- Ignition difficult to exclude in a hydrogen safety analysis, conservatively the presence of an ignition source may be assumed
- Controlling factor is then flammability of mixture, well known for H_2-air



G:1 open fire
G:2 mechanical spark
G:3 electrical spark
G:4 hot surface
G:5 static discharge

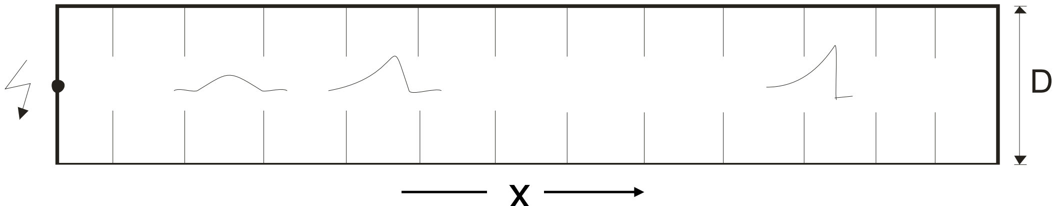
G:6 catalytic surface
G:7 self-ignition
G:8 others
G:9 unknown
G:0 no ignition

Kreiser et al, Report Univ. Stuttgart IKE 2-116 (1994)

FLAME ACCELERATION

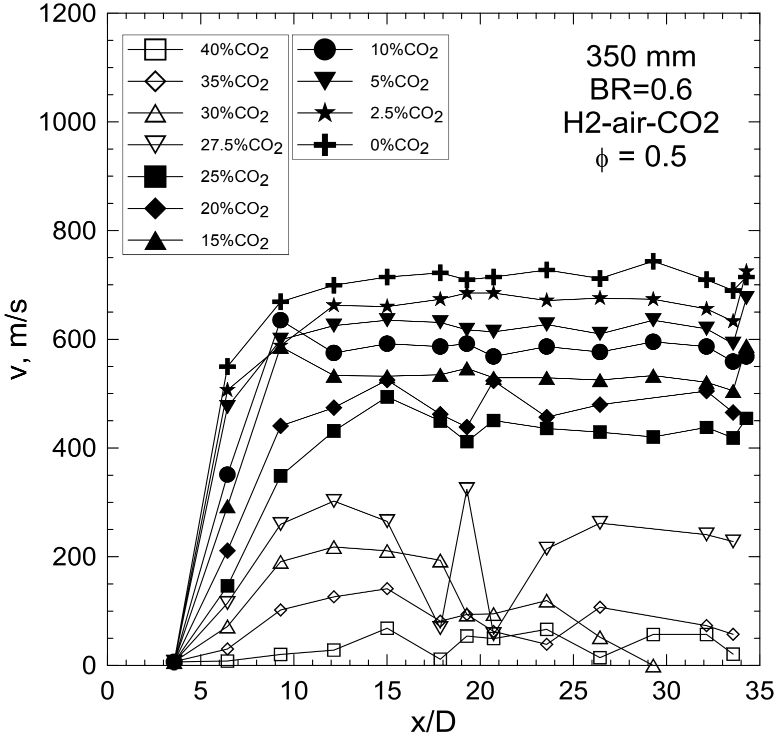
- Conservative conditions for flame acceleration in hydrogen mixtures were investigated in closed obstructed tubes, e.g. FZK 12m-tube

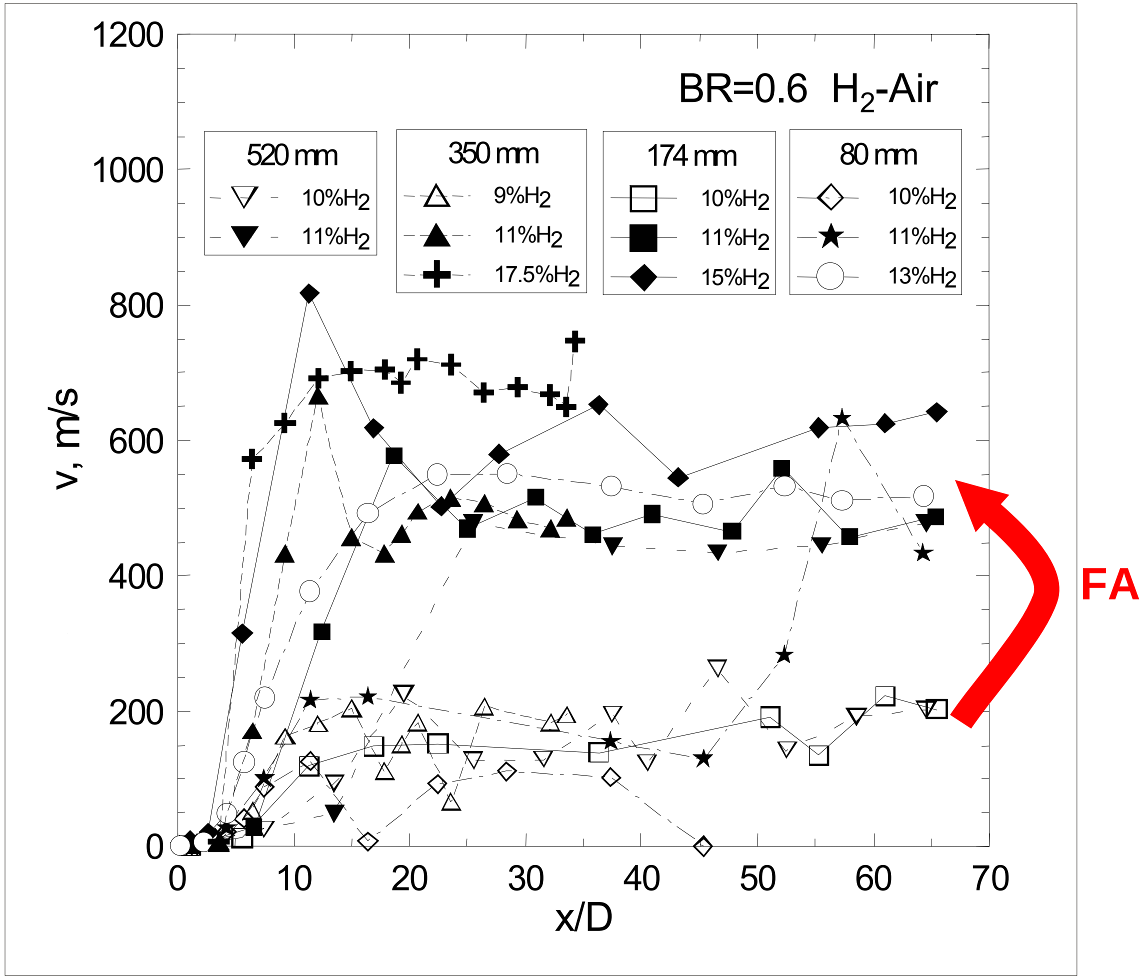
RESULTS OF FLAME ACCELERATION EXPERIMENTS



- 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





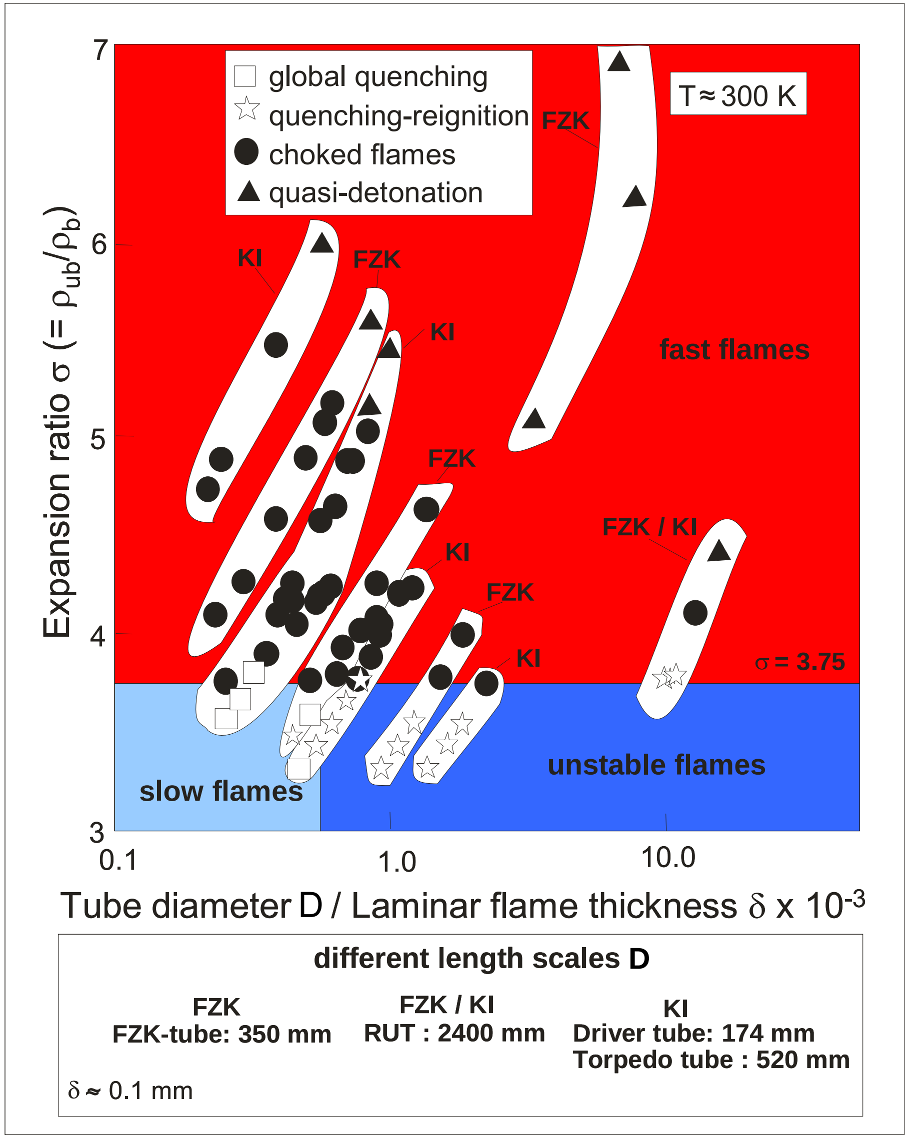
FLAME ACCELERATION CRITERION

- 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 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)

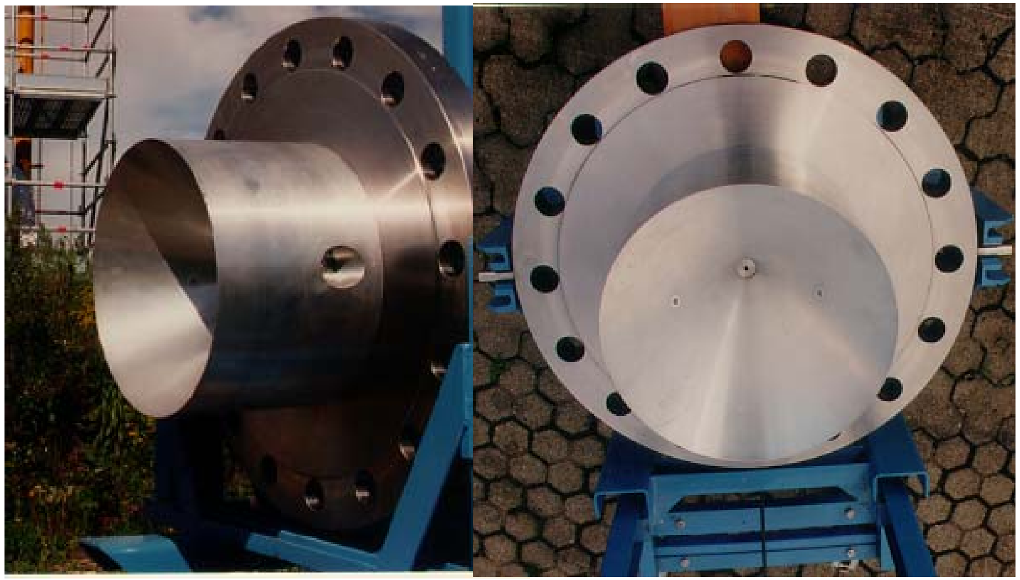


In lecture notes

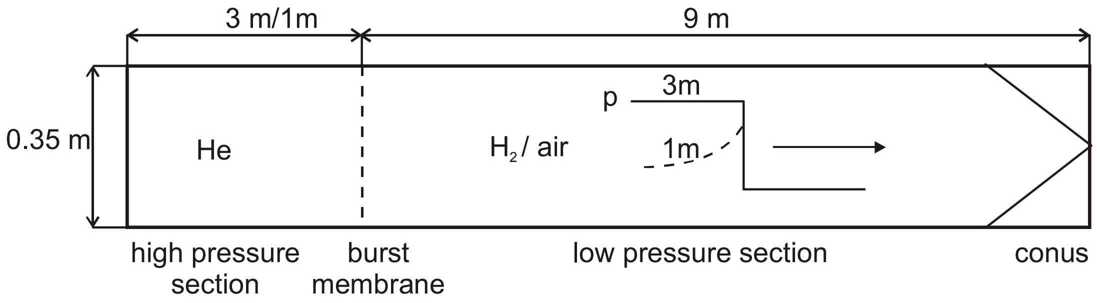
DEFLAGRATION-TO DETONATION TRANSITION

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

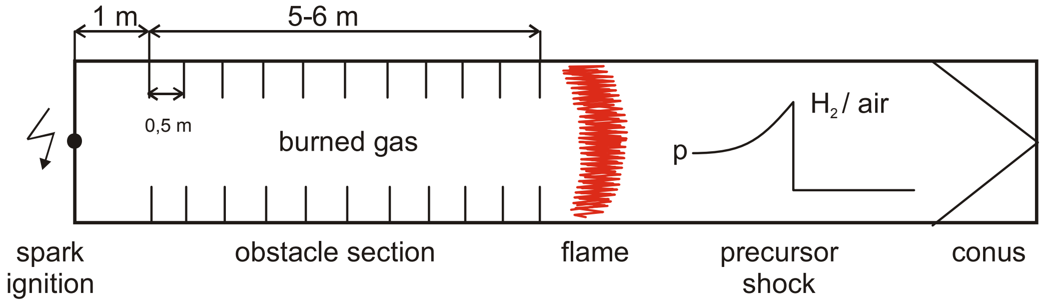
- Present here one example for DDT with pressure wave emitted from an obstructed region and focussed in a conus



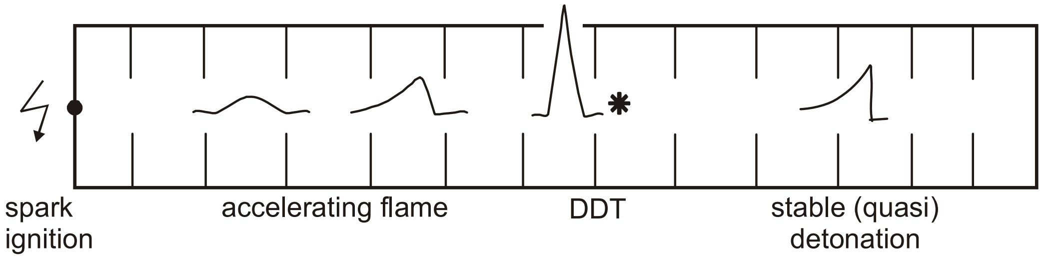
- **Shock tube with conus (idealized mode A)**



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

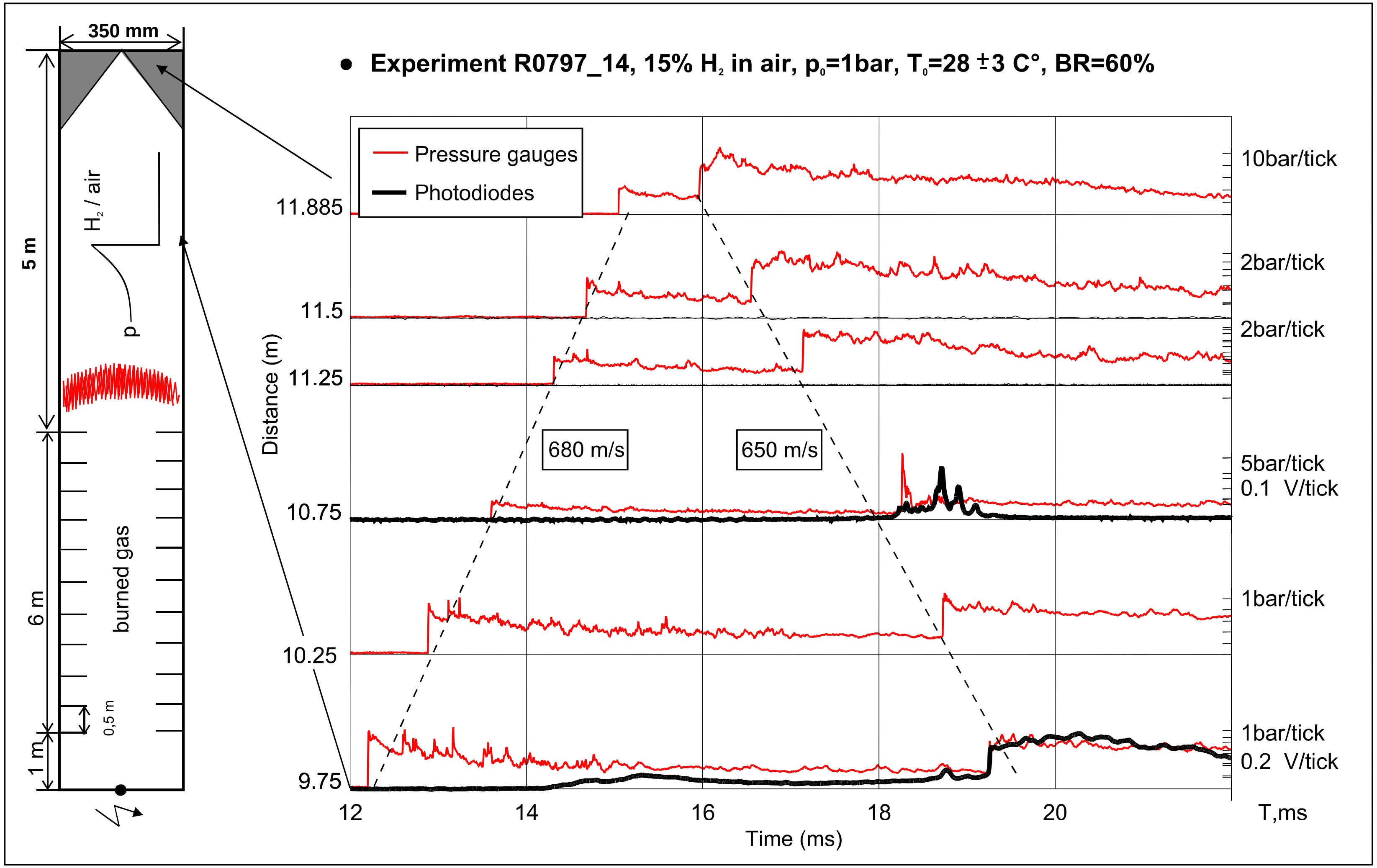


- **Fully obstructed tube (prototypic mode B)**



TURBULENT DEFLAGRATION EXPERIMENT WITHOUT DDT

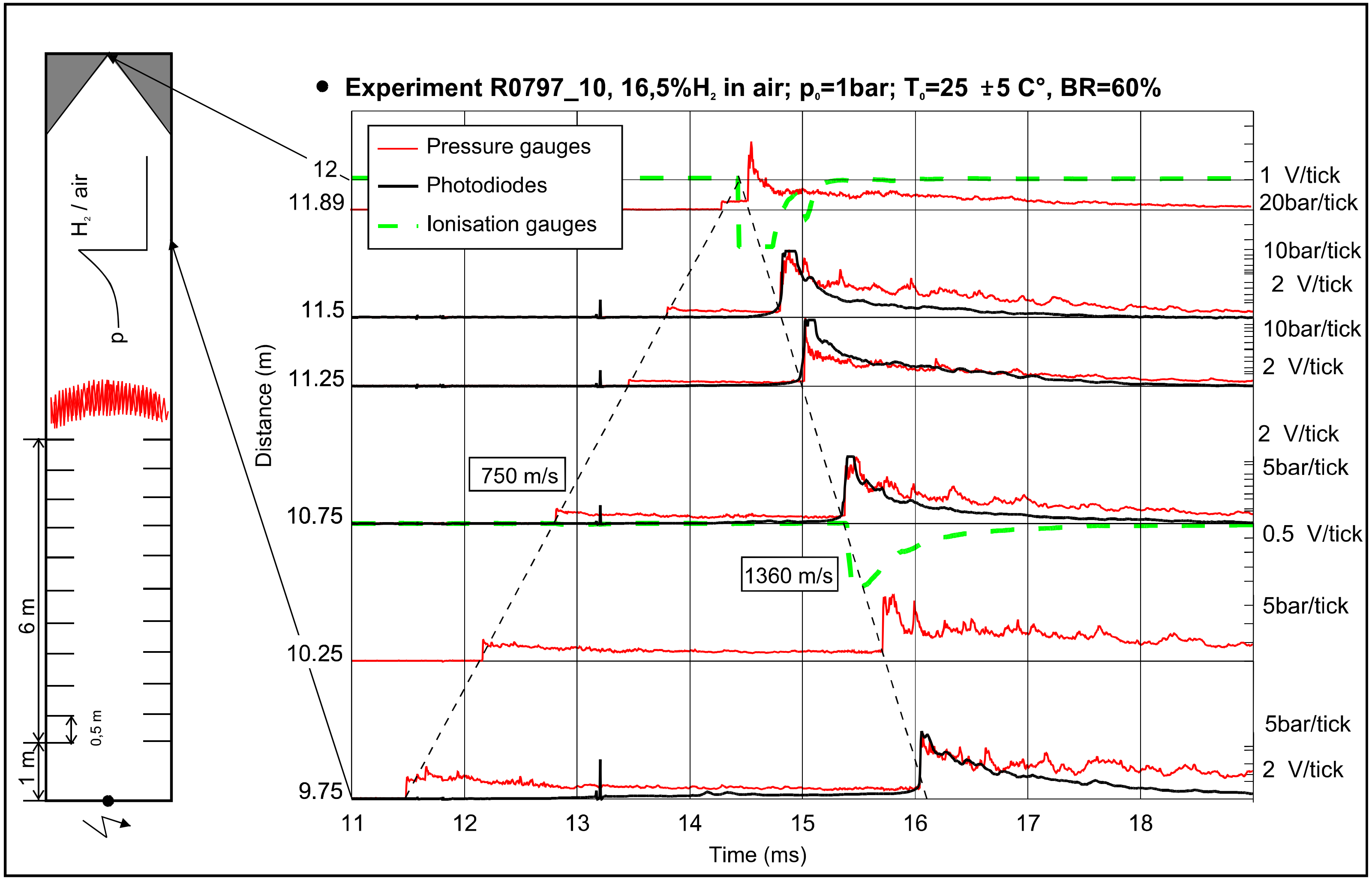
- Partially obstructed tube with conus, 15 % hydrogen in air



- **Experiment R0797_14, 15% H_2 in air, p_0=1bar, T_0=28 ±3 C°, BR=60%**

TURBULENT DEFLAGRATION EXPERIMENT WITH DDT

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



Experiment R0797_10, 16,5%H_2 in air; p_0=1bar; T_0=25 ±5 C°, BR=60%

- Result: focussing of pressure waves emitted from a fast turbulent flame can trigger a detonation on other parts of the system

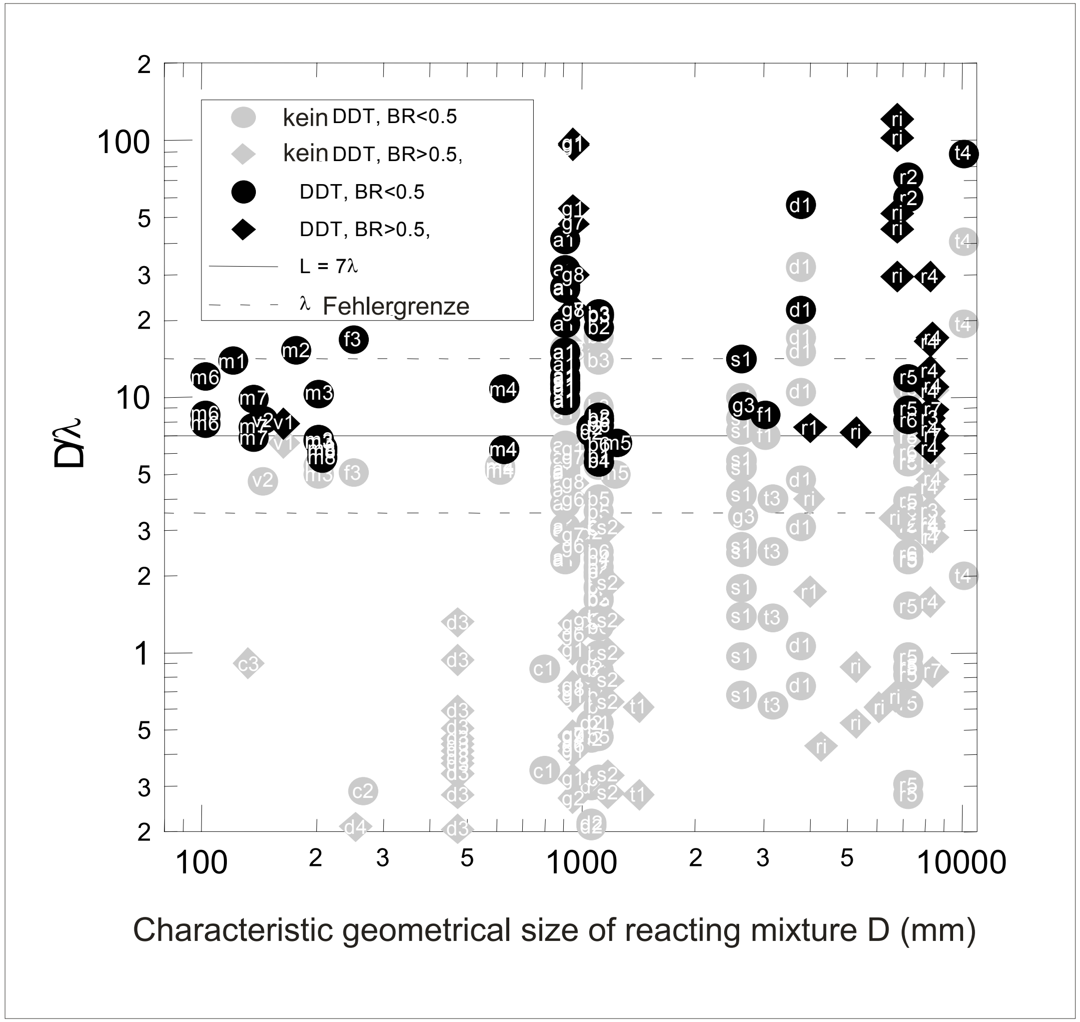
CRITERION FOR DDT

- 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/λ > 7

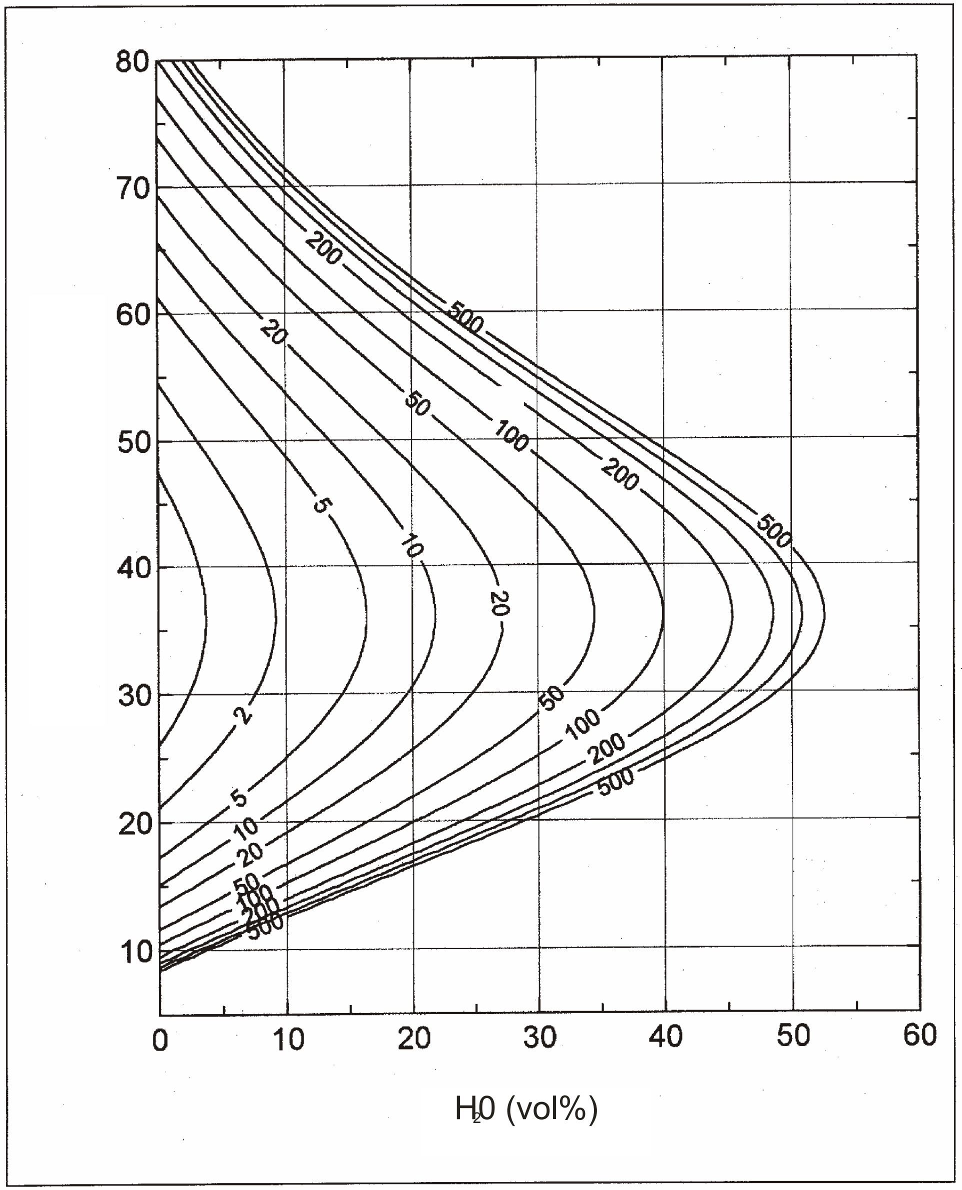
- Current uncertainty in detonation cell size λ ≈ factor 2

- In accident scenarios D/λ can vary by orders of magnitude, criterion has therefore predictive capability



DETONATION CELL SIZES

- Detonation cell sizes (in cm) of H_2-air-steam mixtures at 375 K and 1 bar initial pressure. Dry hydrogen concentration is defined as H_2 / (H_2 + air)



State of the Art Report by a Group of Experts „Flame Acceleration and Deflagration – to – Detonation Transition in Nuclear Safety“, Nuclear Safety NEA/CSNI/R(2000)7, August 2000

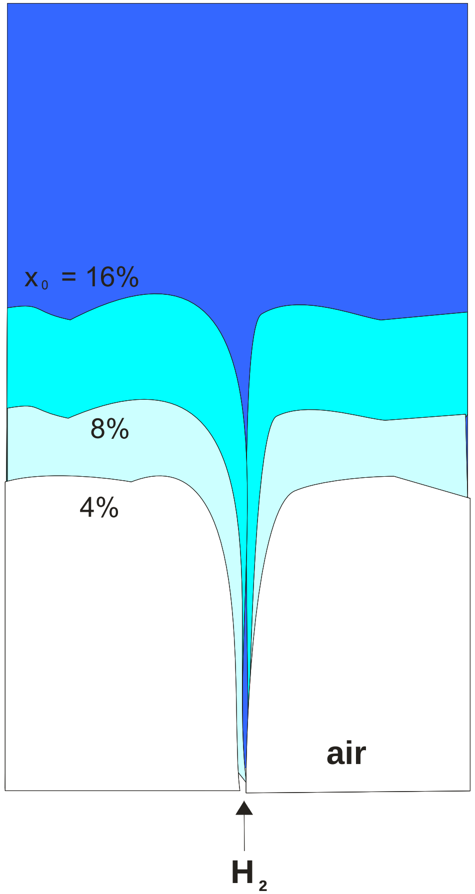
SUMMARY OF CRITERIA

- Criteria for possible occurrence of fast combustion regimes were evaluated from many experiments with various H_2-mixturs on different scales

Flame acceleration

$$\sigma_{index} = \frac{\sigma_{(average\ mixture)}}{\sigma_{critical}\ (T)}$$

$$= \begin{cases} < 1 \text{ excluded} \\ > 1 \text{ possible} \end{cases}$$

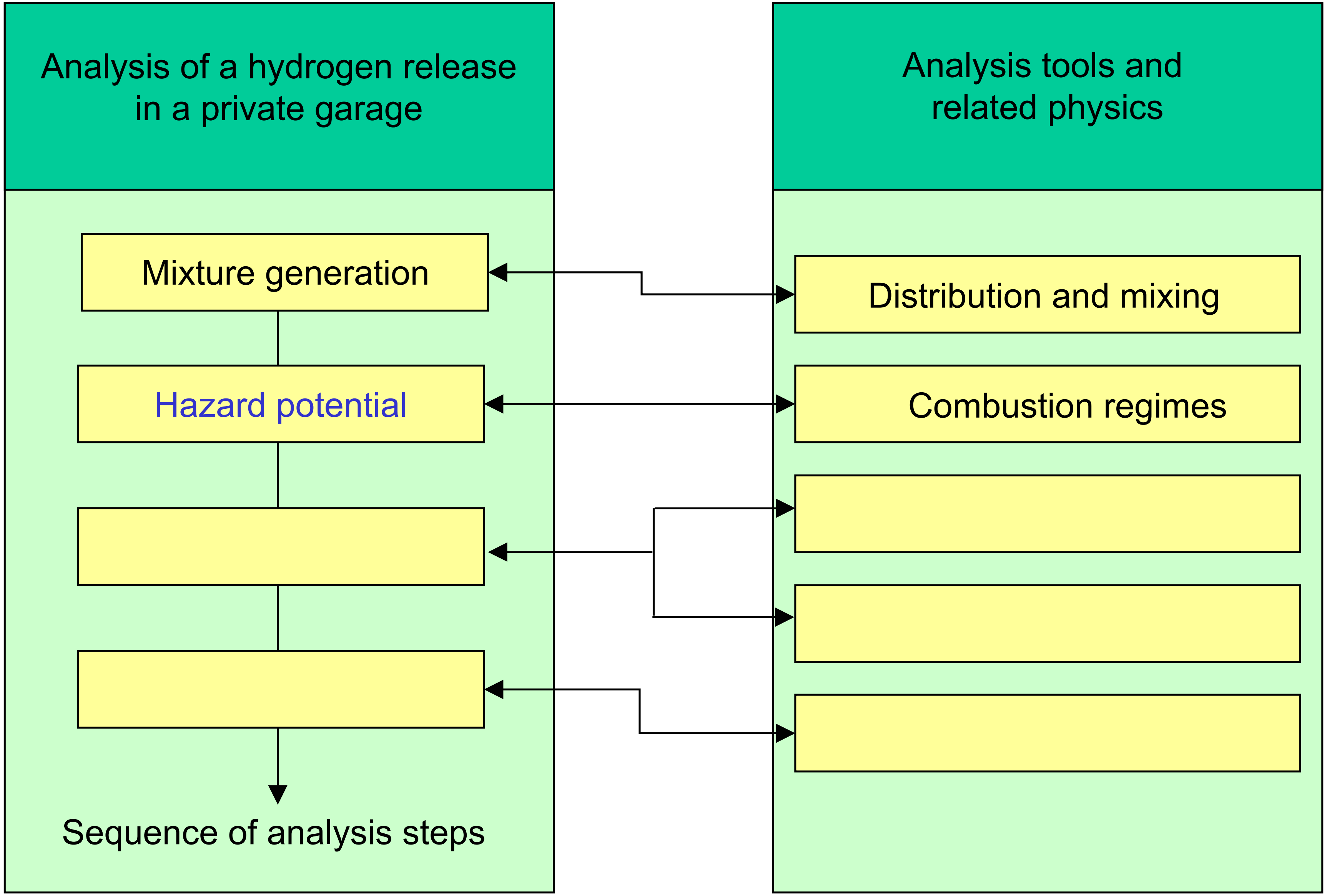


Detonation transition

$$\frac{D}{7\lambda} = \frac{(\text{Cloud volume})^{1/3}}{7\lambda\ (\text{average mixture})}\ \sigma_{index} > 1$$

$$= \begin{cases} < 1 \text{ exluded} \\ > 1 \text{ possible} \end{cases}$$

- 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



Analysis of a hydrogen release in a private garage

Analysis tools and related physics

Mixture generation

Hazard potential

Distribution and mixing

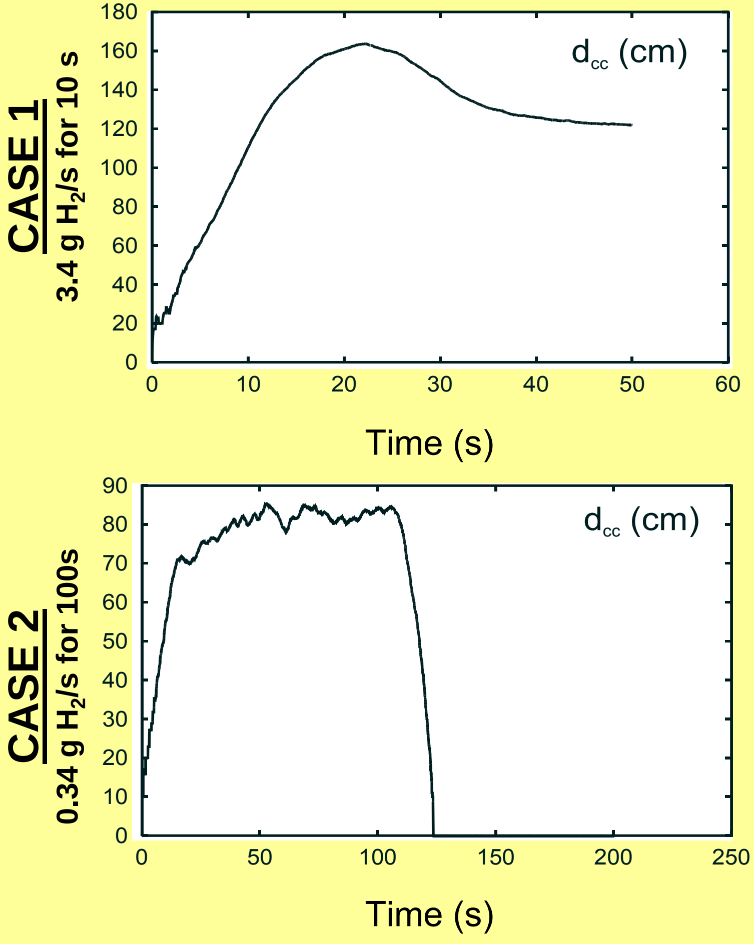
Combustion regimes

Sequence of analysis steps

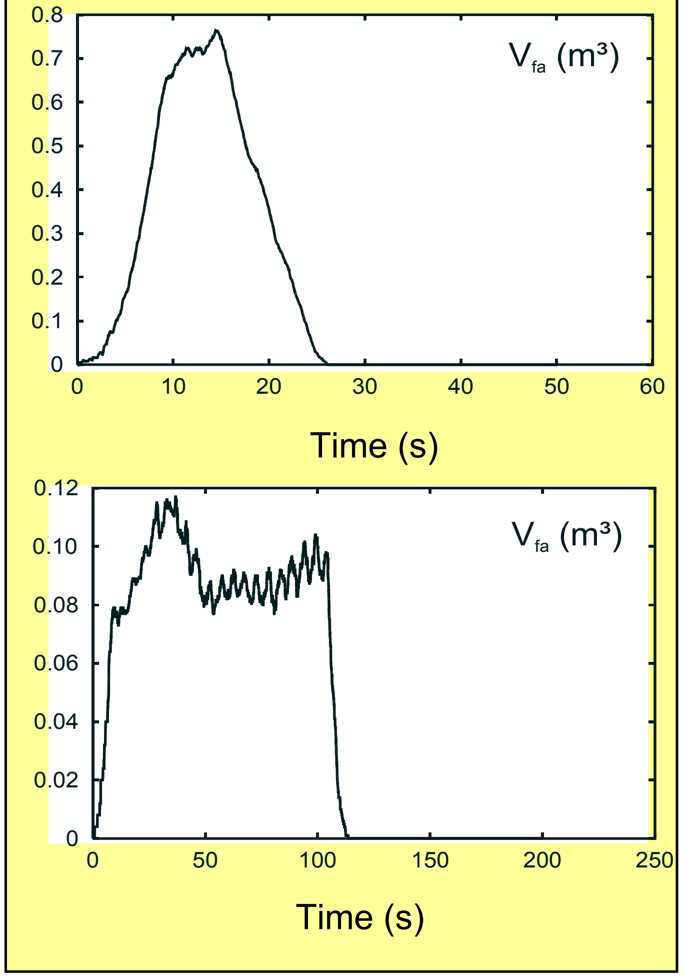
COMPUTED HAZARD PARAMETERS FOR GARAGE SCENARIOS

- Dimension of combustible cloud, 4 to 75 % H_2,

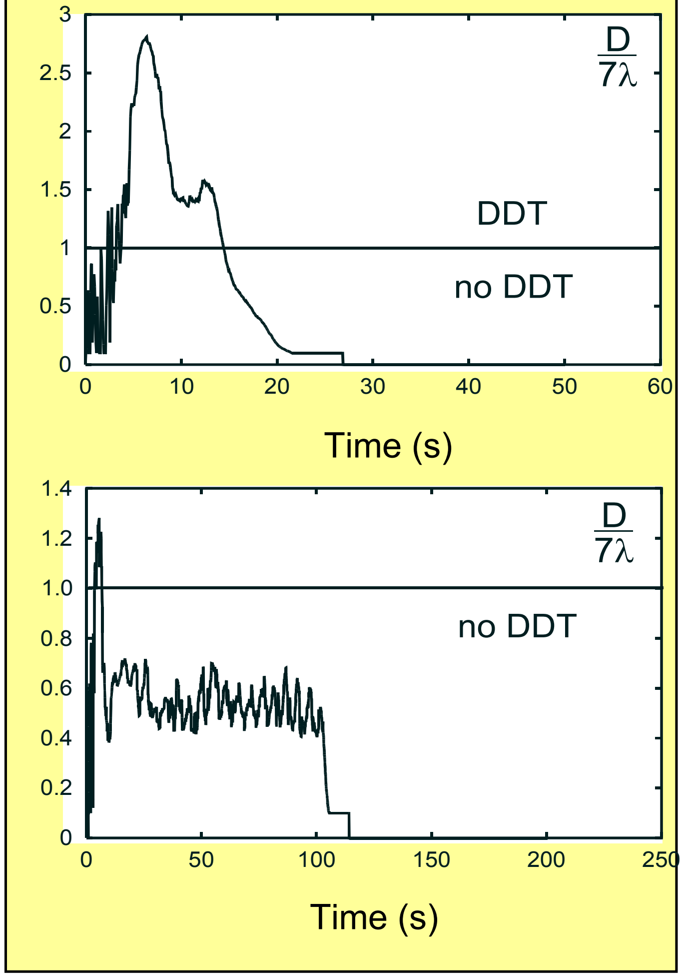
  $d_{cc} = (V_{cc})^{1/3}$



- 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)



HAZARD POTENTIAL FOR GARAGE SCENARIOS

- Risk parameters show strong dependence on H_2 release rate

- Case 1:
(3.4 g H_2/s)

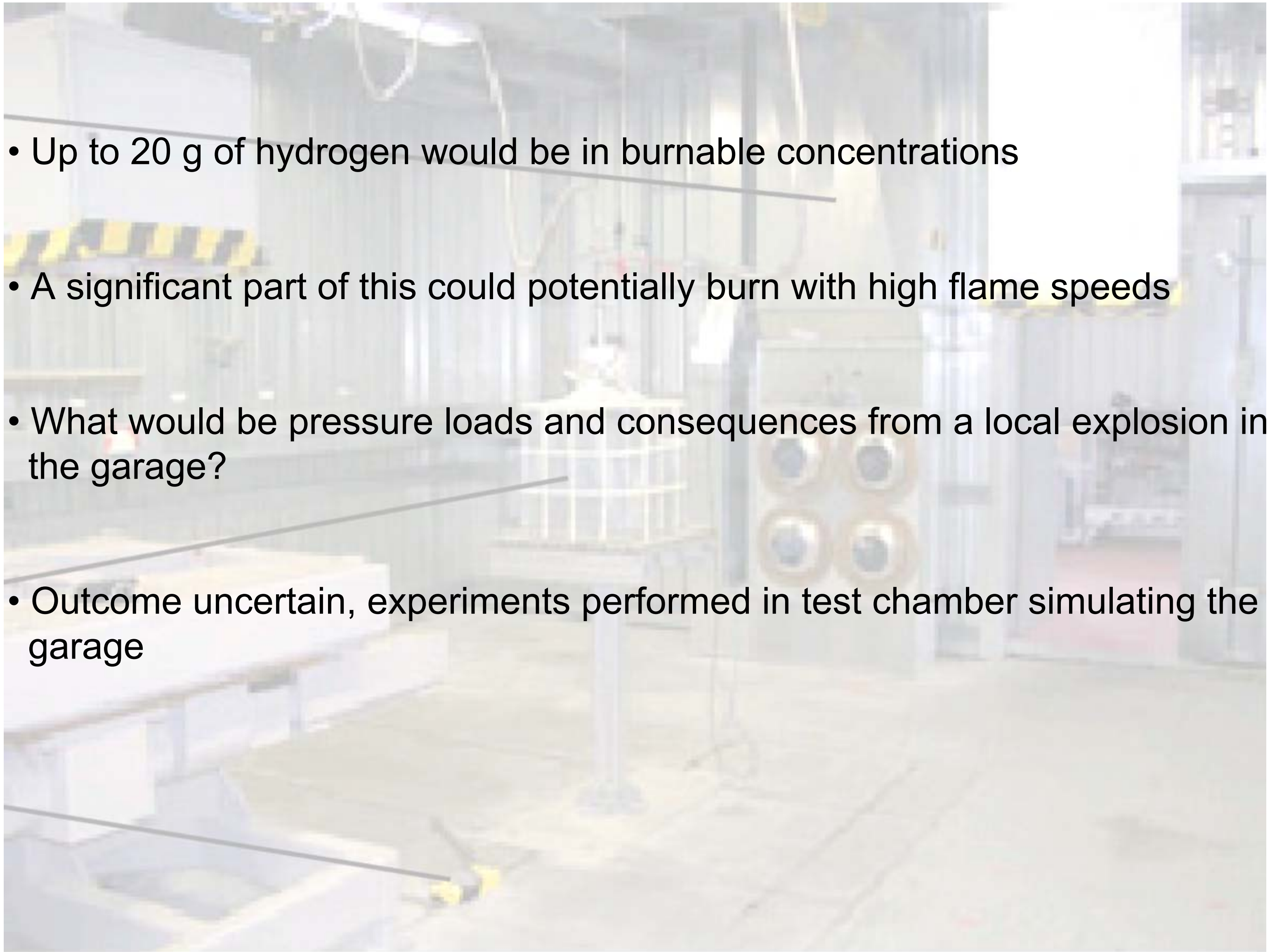
- Continuous potential for slow deflagration (≈ 20 g of 34 g)
- potential for supersonic combustion regimes (and ignition) during the release period
- high release rate not tolerable without mitigation measures

- Case 2:
(0.34 g H_2/s)

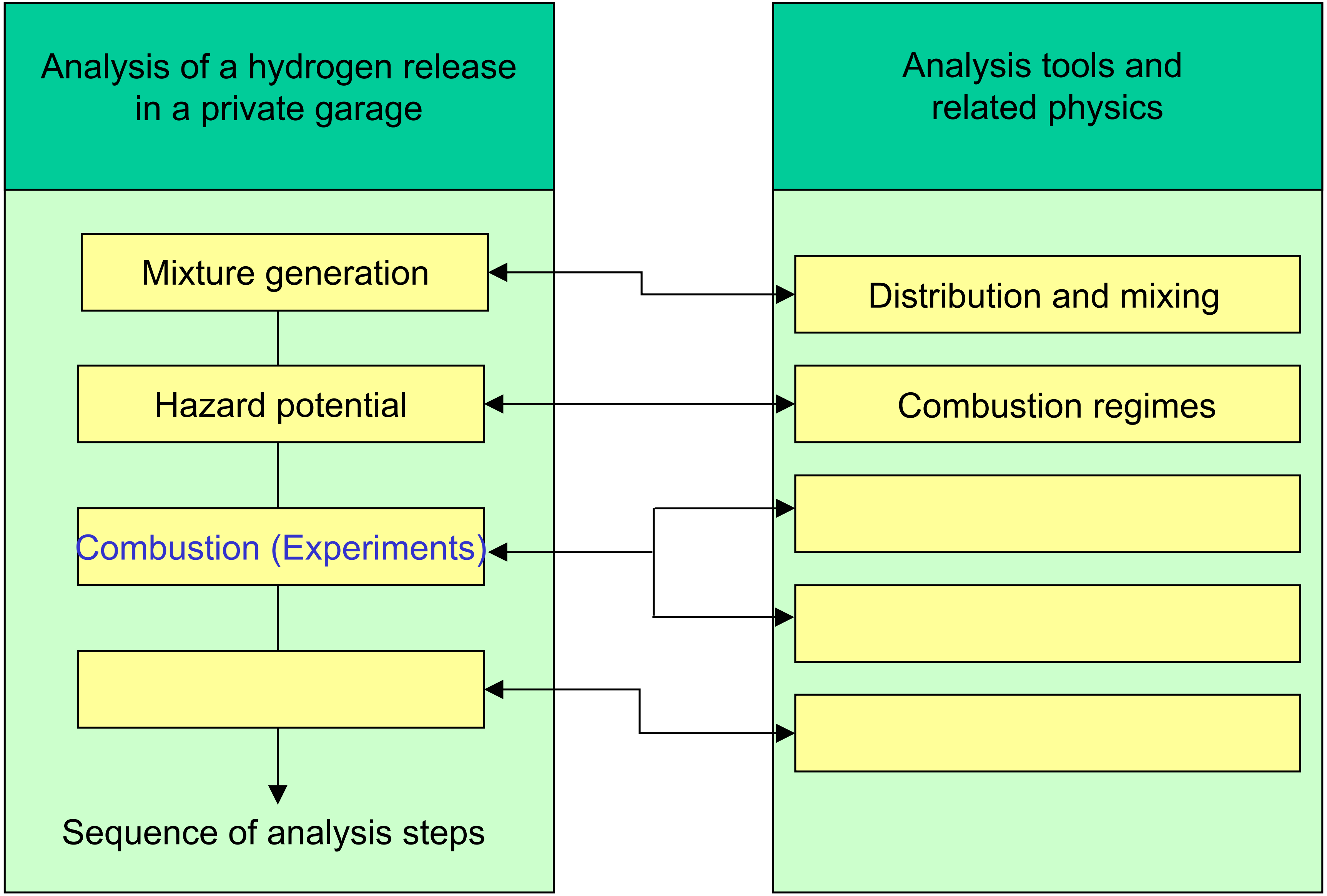
- only small potential for slow deflagrations, natural mixing processes sufficient
- release rate (and mass) seems tolerable for present garage design

- Only **Case 1** followed in further safety analysis

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



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Combustion (Experiments)

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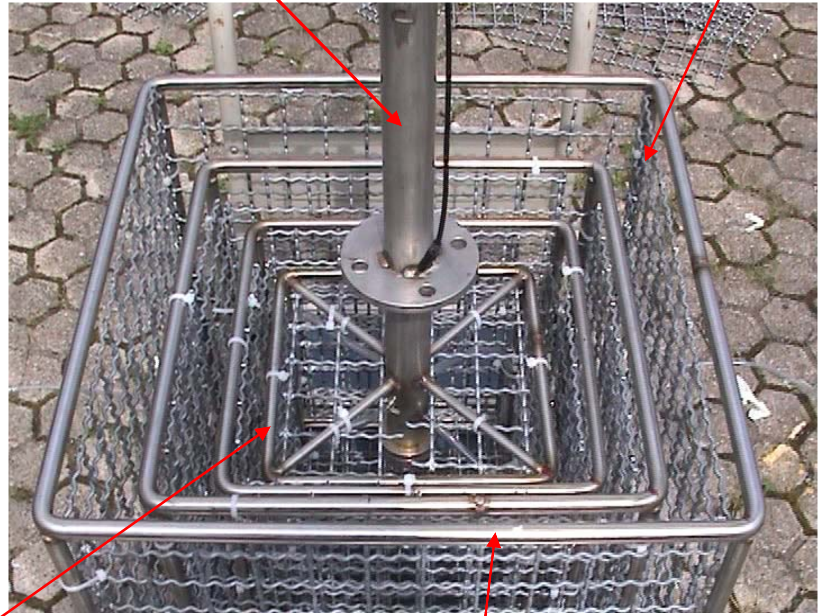
COMBUSTION UNITS

- To obtain conservative pressure loads, combustion units were developed providing the fastest possible flame speed for a given H_2 mass
- Cubes were made for 0.5, 1, 2, 4, 8 and 16 g of H_2, which can be inserted into each other
- Wire grids 6.5 x 0.65 mm, 12 layers between cubes

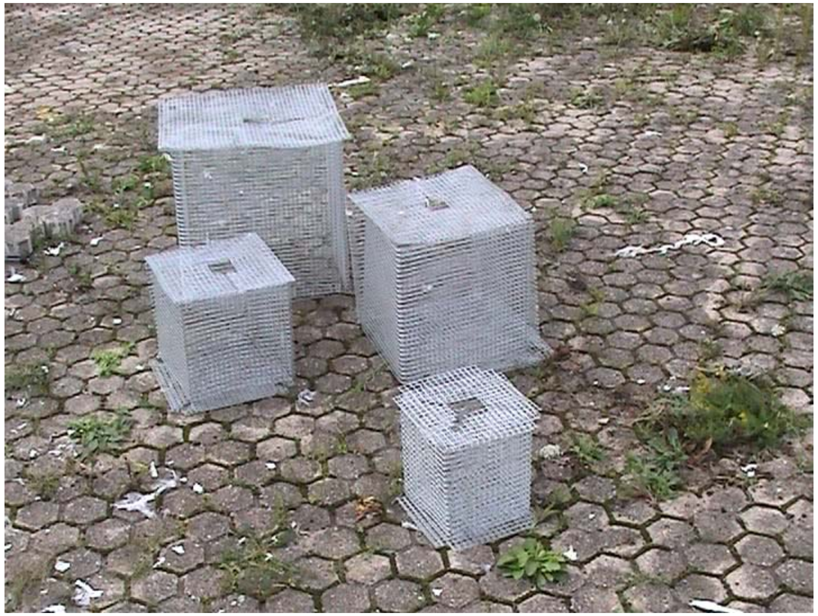


Hydrogen injection device

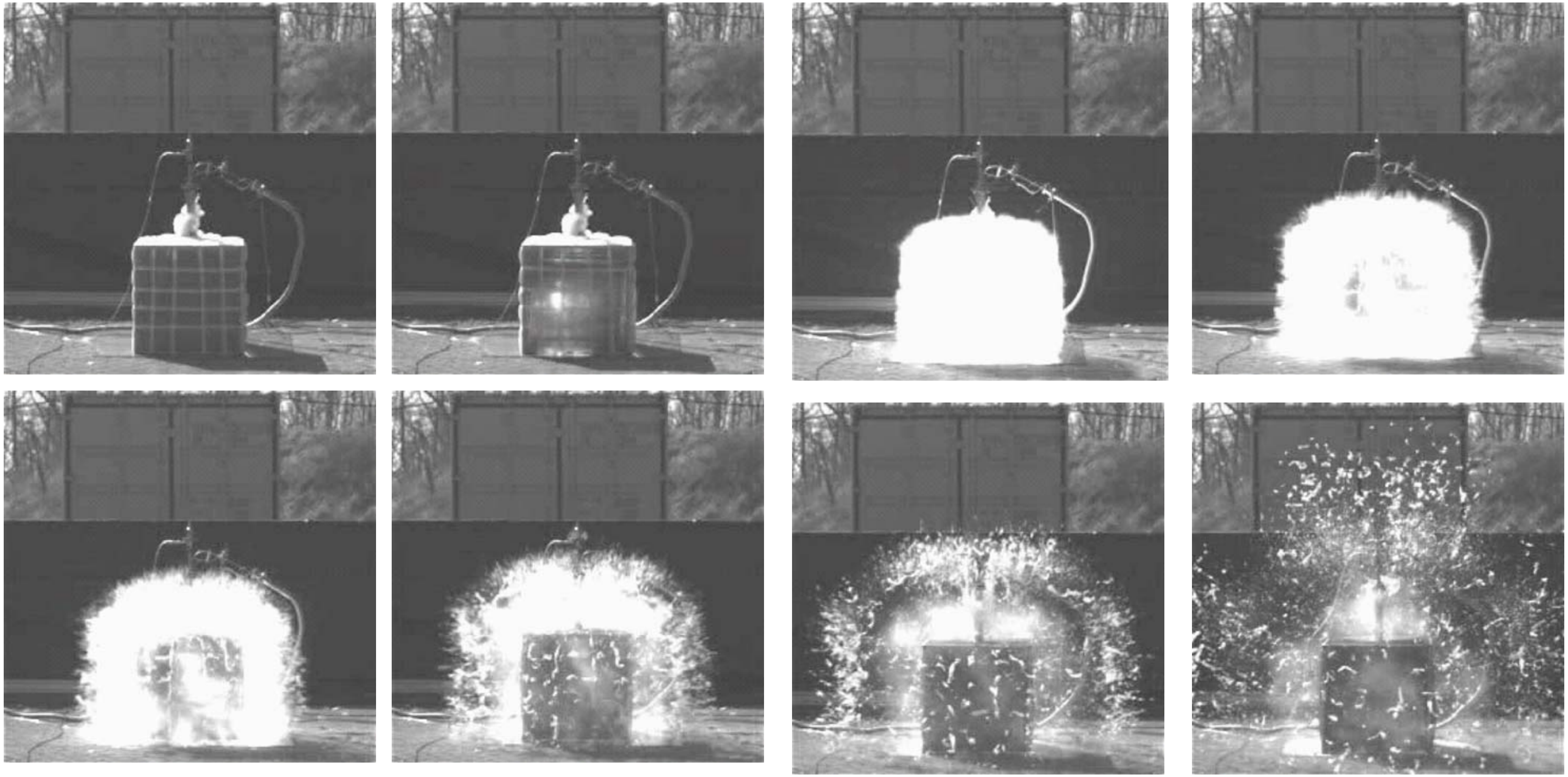
cubes covered with plastic,
filled with stoichiometric H_2 - air mixture

0.5 g

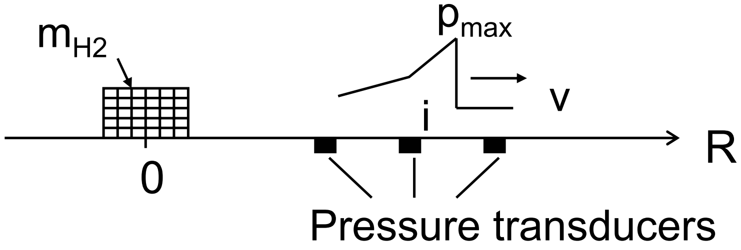
4 g



UNCONFINED TEST OF COMBUSTION UNIT



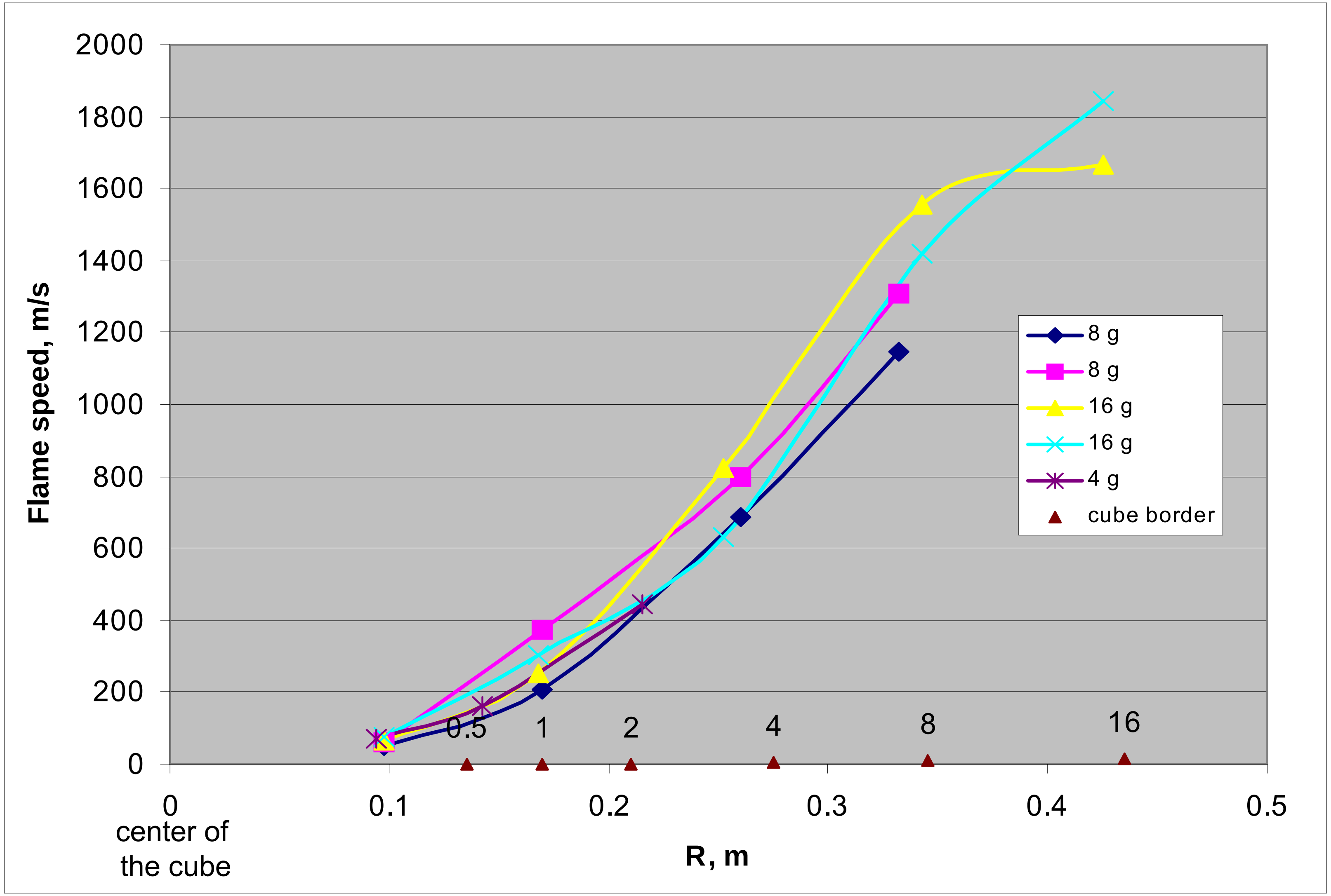
- Peak overpressure and impulse measured as function of distance to characterize blast effects from combustion unit



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

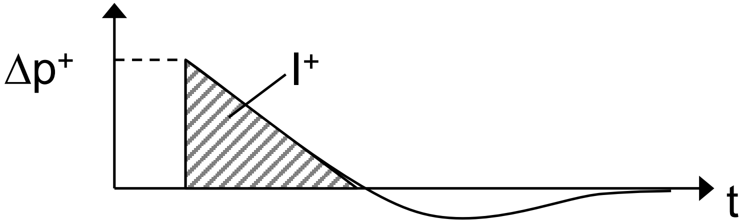
FLAME SPEEDS IN COMBUSTION UNITS

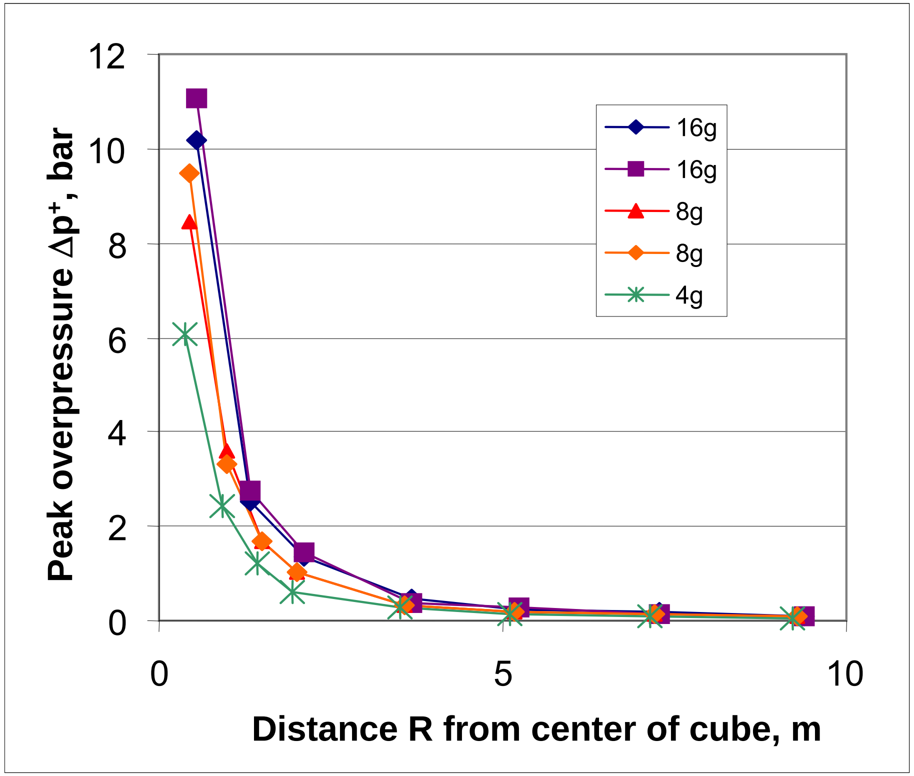
- The flame acceleration inside the combustion units was measured with photodiodes
- For 8 and 16 g H_2 detonation speeds are obtained at the outer edge of the cube

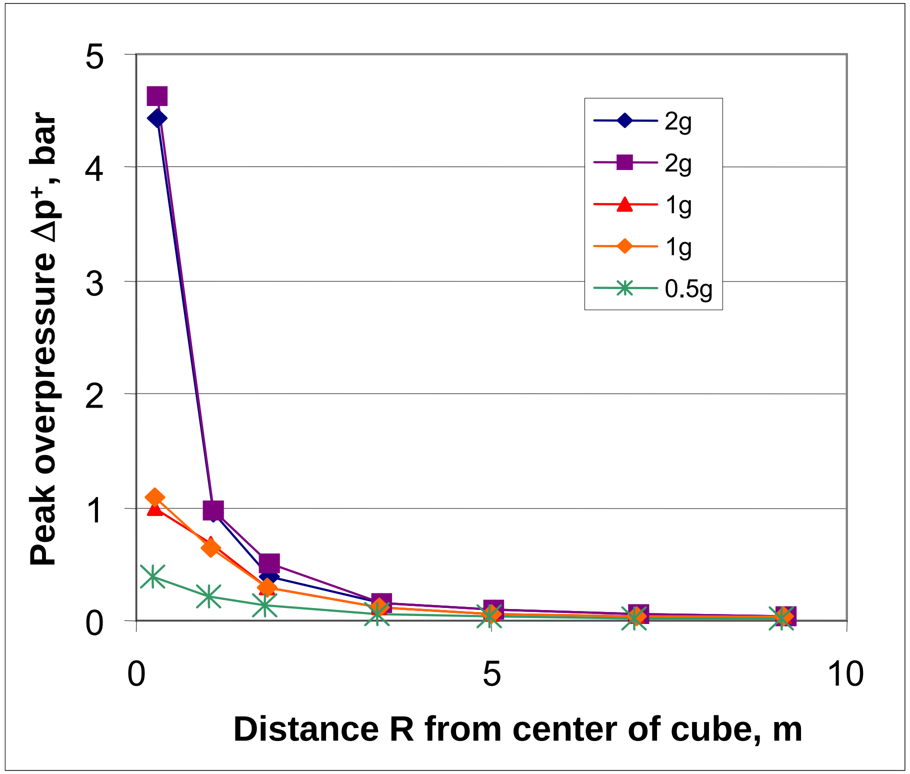


MAXIMUM OVERPRESSURE VS DISTANCE

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

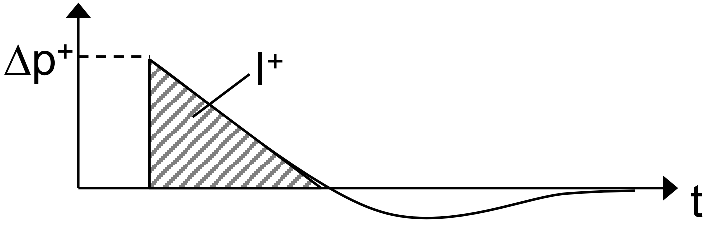


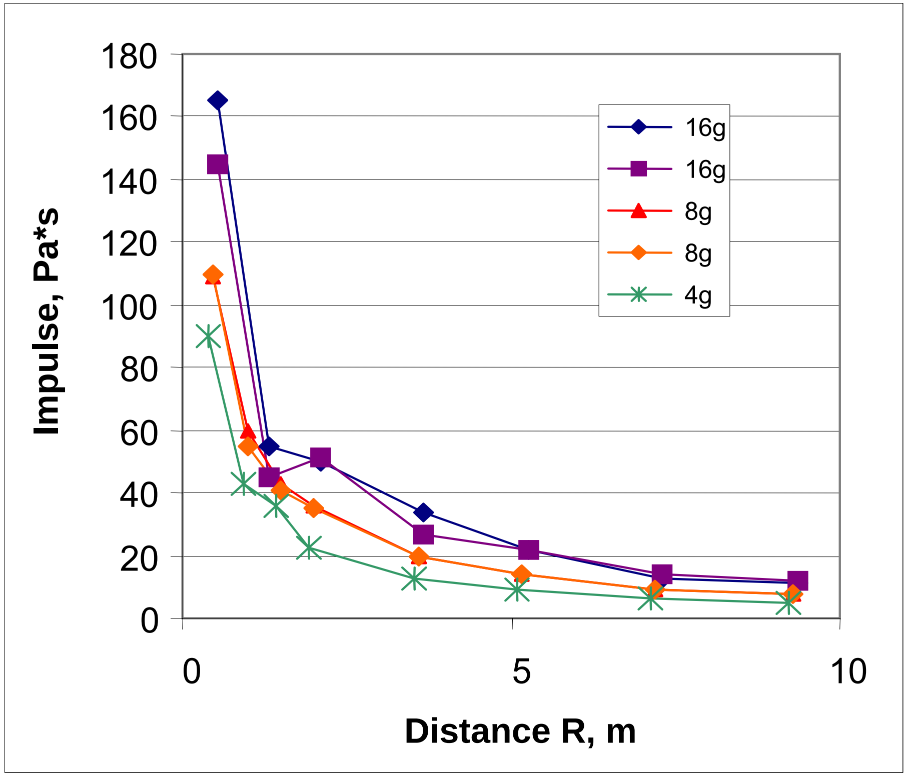


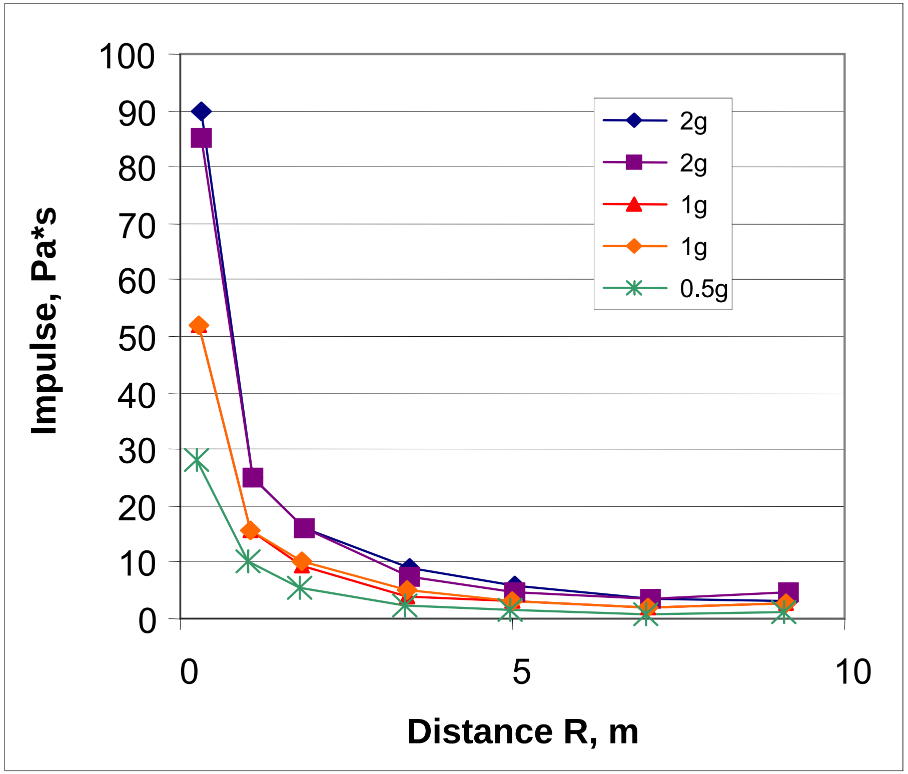


IMPULSE VS DISTANCE

- Measured positive impulse I^+ values from unconfined combustion units

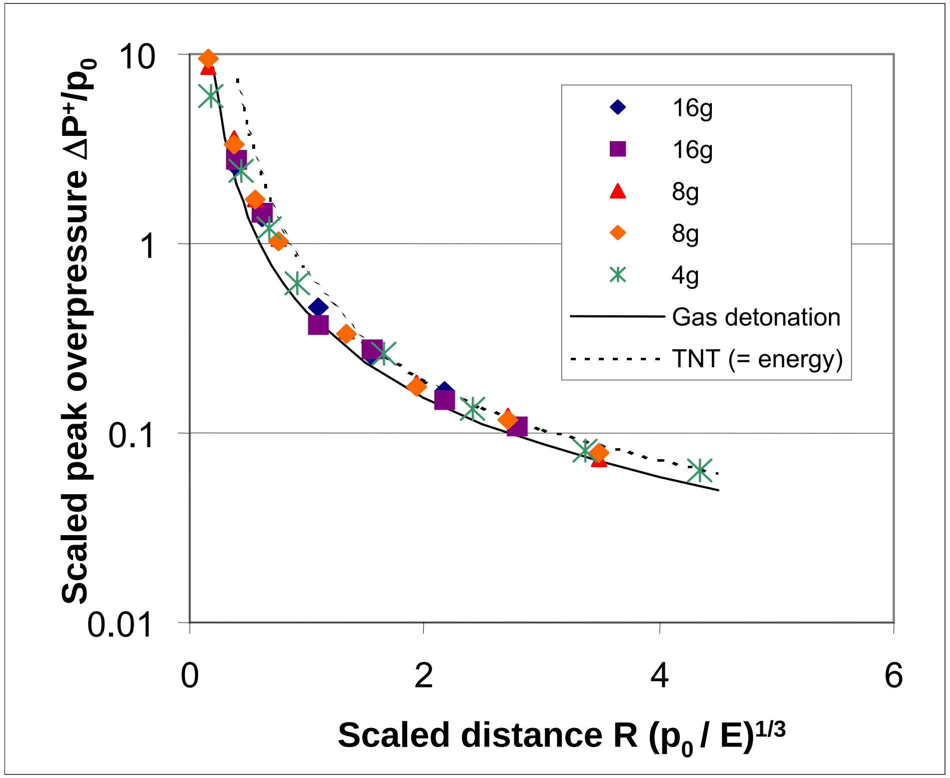


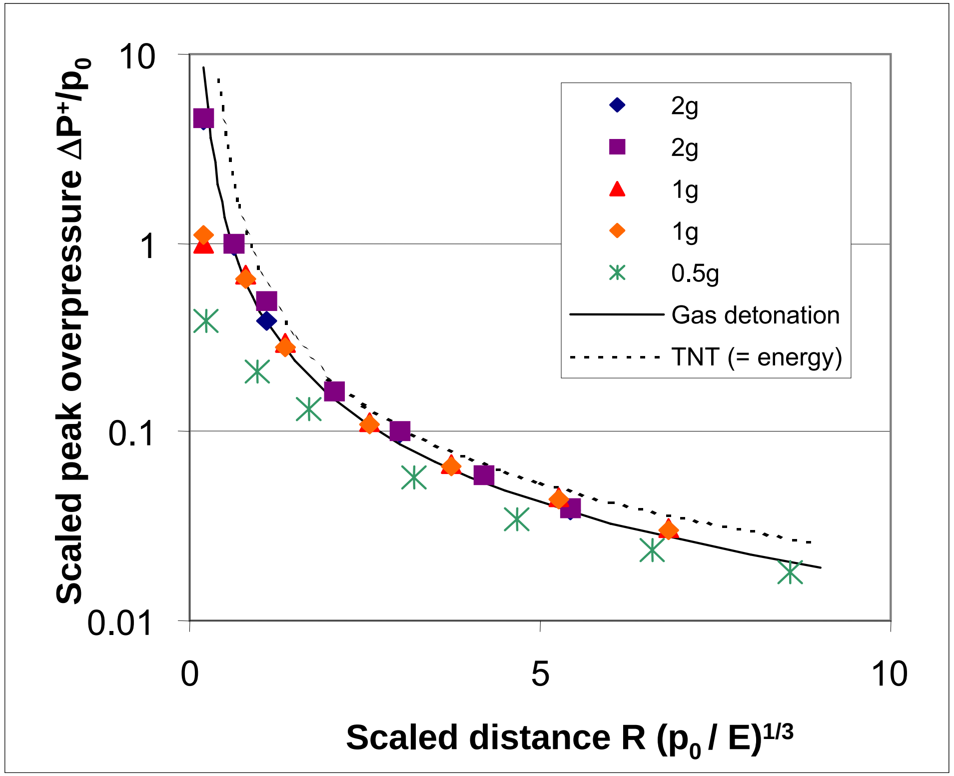




SCALED PEAK OVERPRESSURES VS DISTANCE

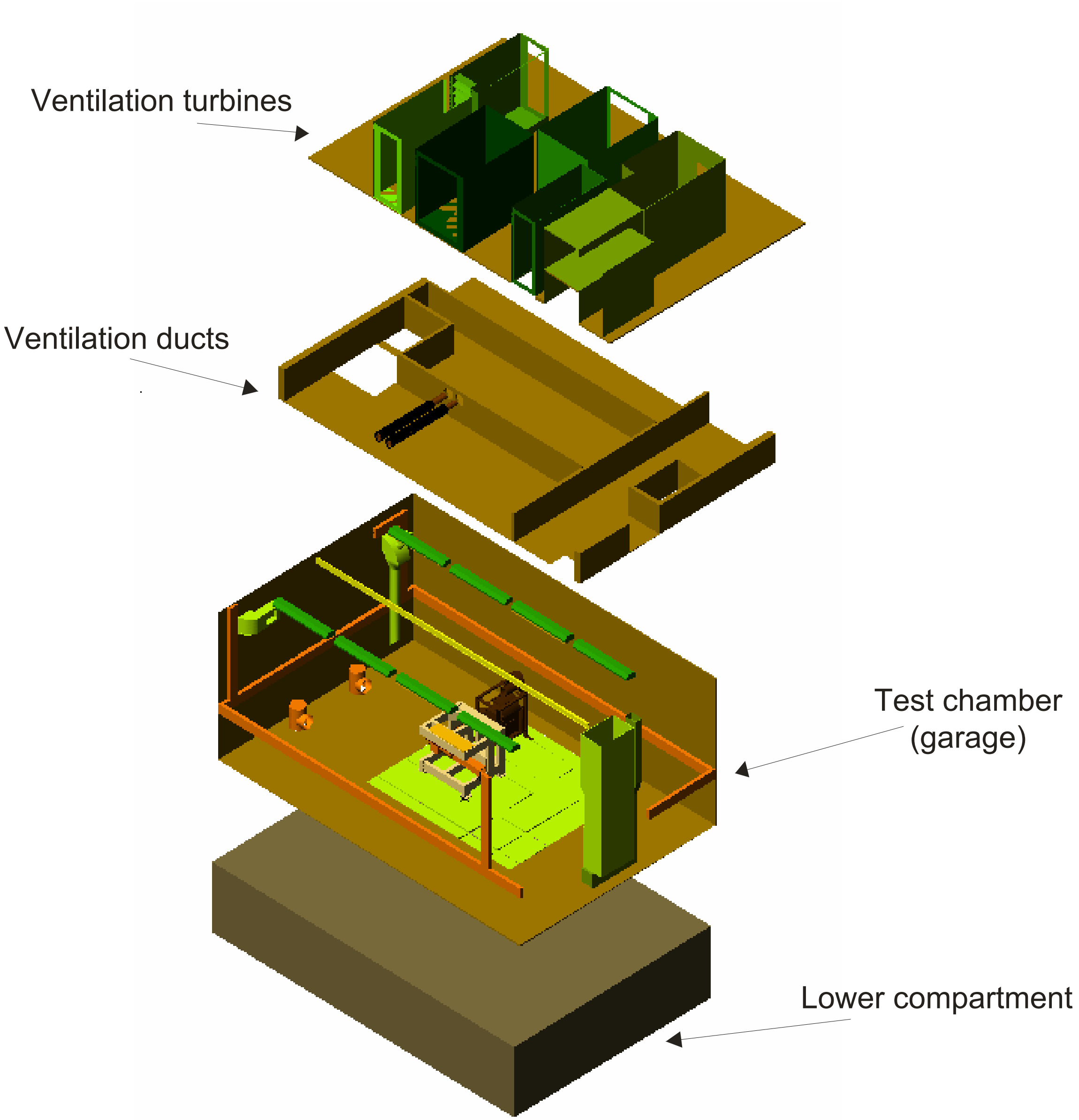
- Use of Sachs scaling collapses measured peak overpressures to universal correlation for ≥ 1 g H_2, E = total energy of explosive charge
- Combustion units provide conservative and well defined overpressures





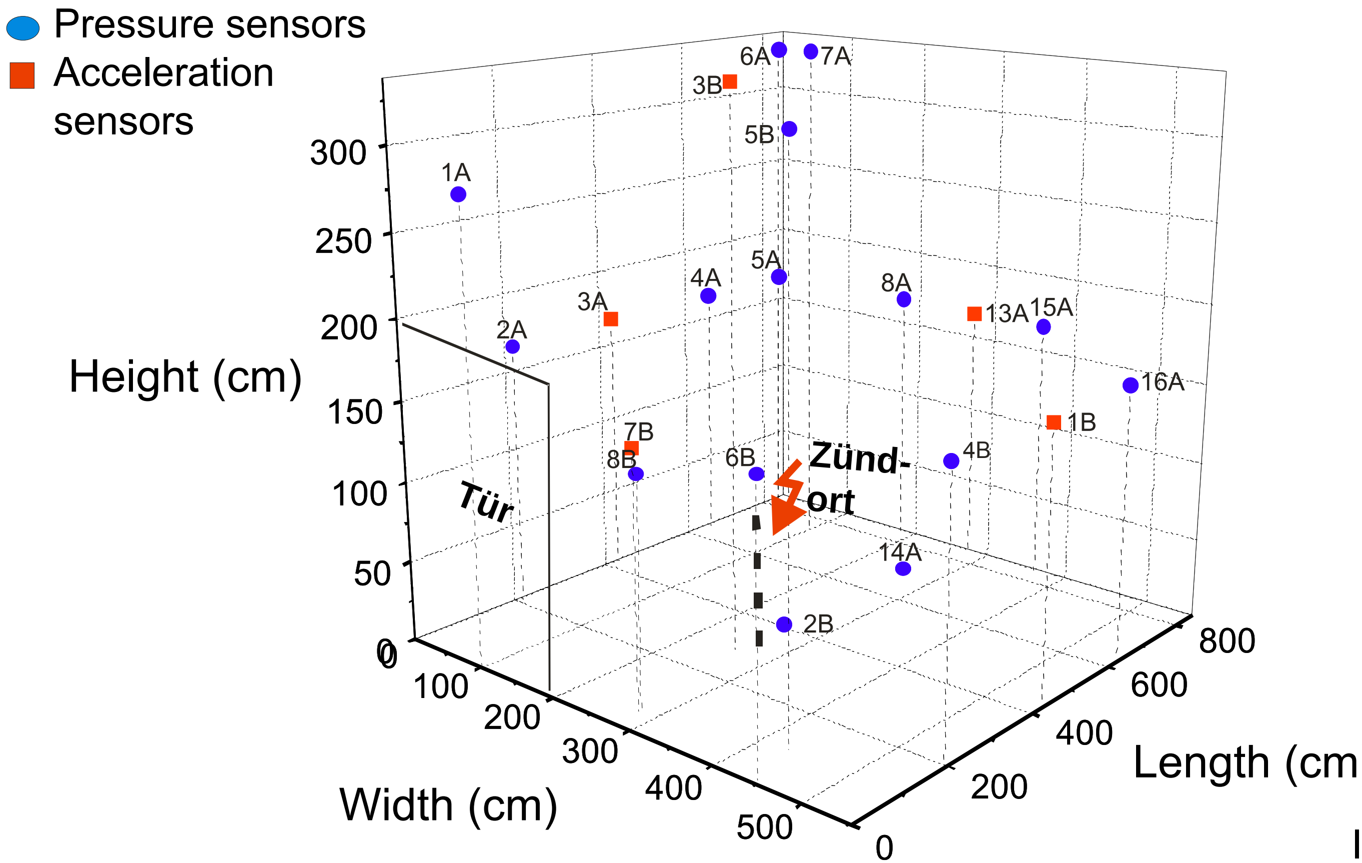
TEST CELL FOR GARAGE SIMULATION

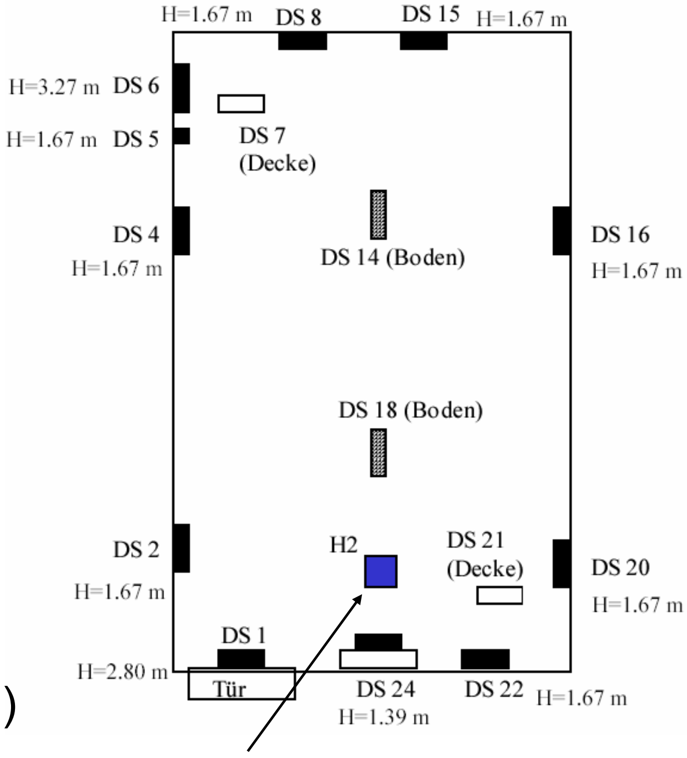
- Dimensions 5.5 x 8.5 x 3.4 m, about 160 m^3
- Air flow ≤ 24.000 m^3/h, up to 1 air exchange in 24s
- Controlled air flows in chamber possible
- All ventilation systems explosion protected
- Test cell used for simulation of garage /confined volume



INSTRUMENTATION OF GARAGE

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



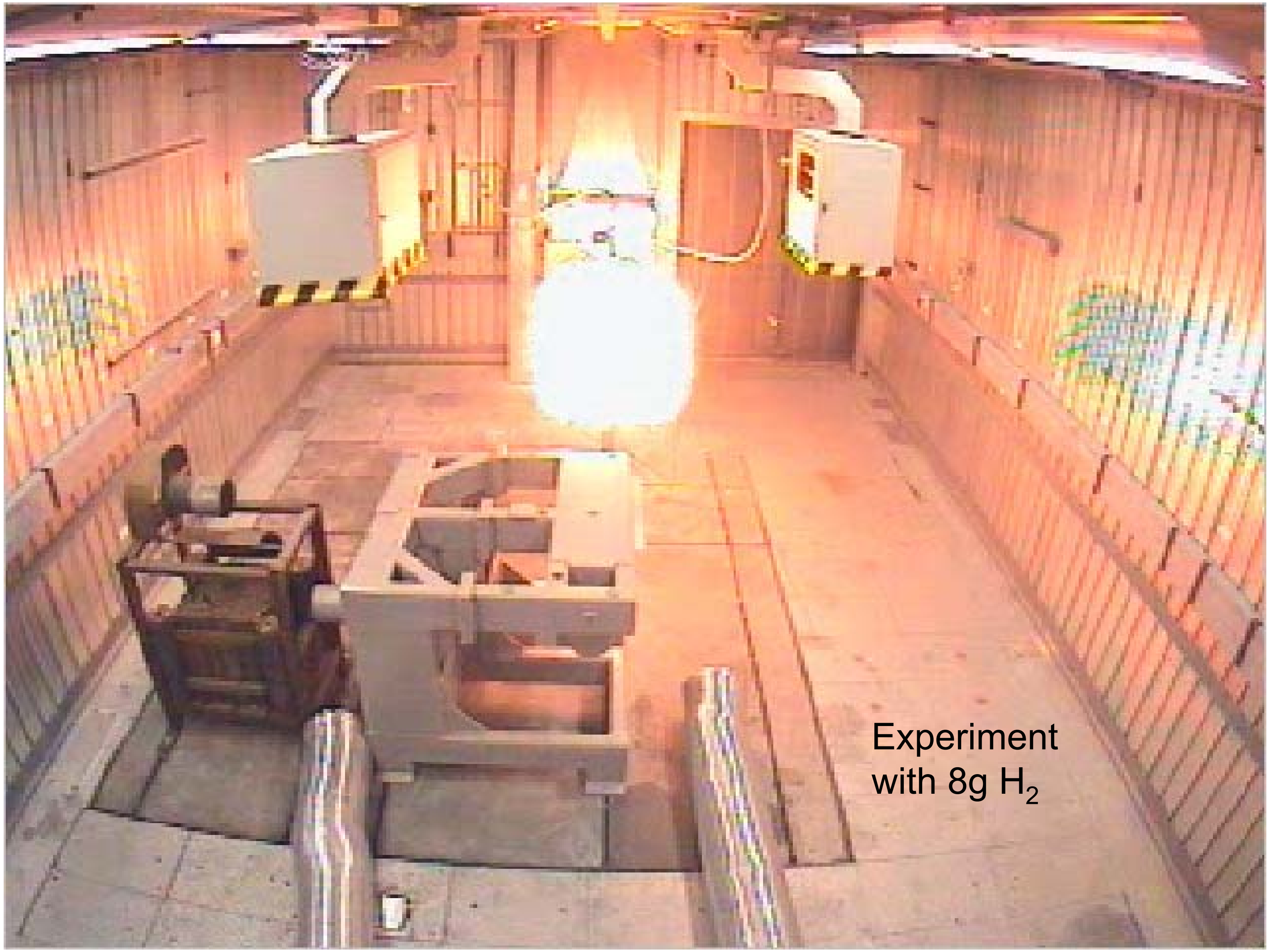


location of combustion unit

LOCAL HYDROGEN EXPLOSIONS IN A GARAGE

H_2 - mass:

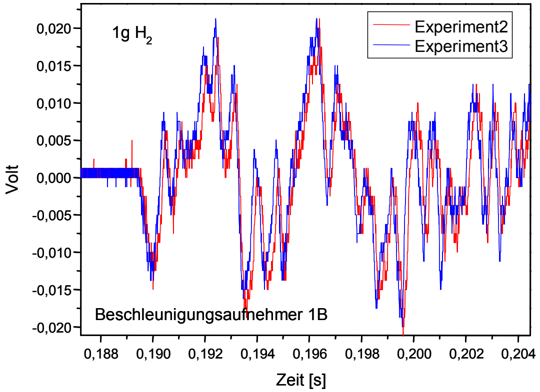
- 1g
- 2g
- 4g
- 8g
- 16g

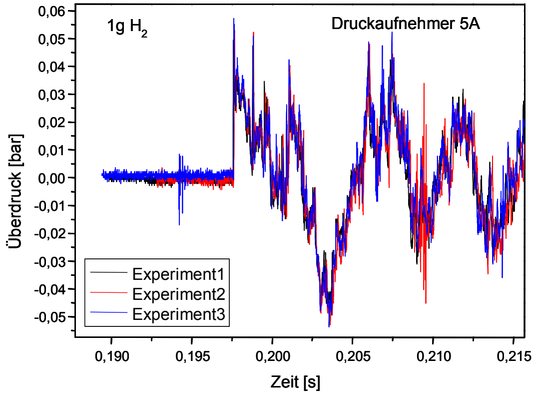


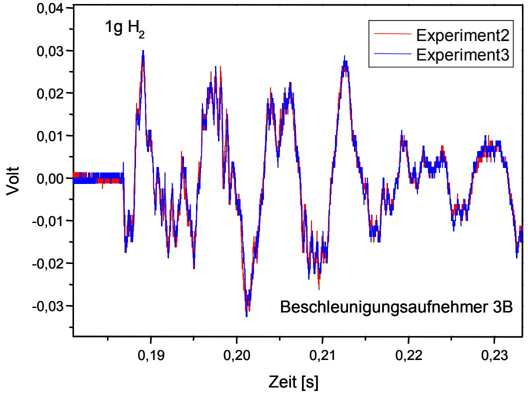
Experiment with 8g H_2

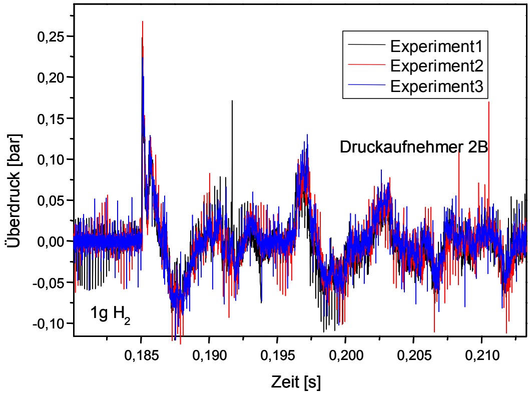
REPRODUCIBILITY OF MEASURED DATA

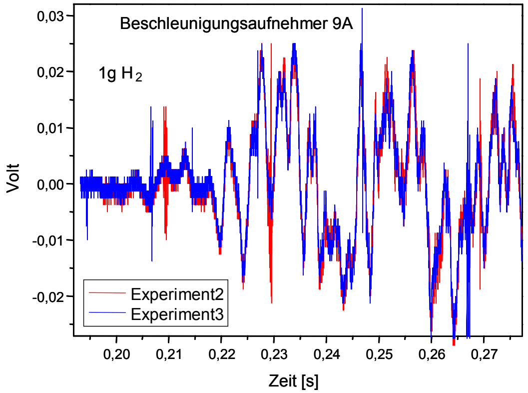
- The experiment with 1 g H_2 was performed three times
- Acceleration and pressure sensors show very good reproducibility of measured signals
- Complex, but reproducible pressure waves are created in confined local explosions of H_2-air mixtures

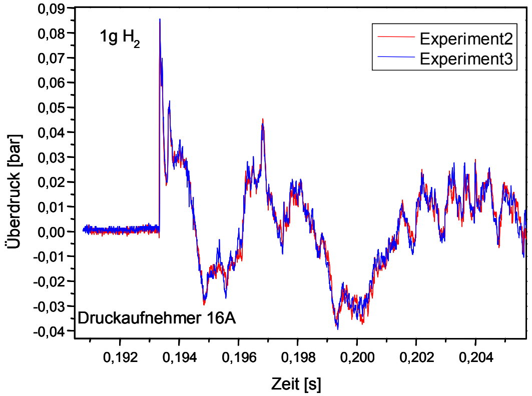




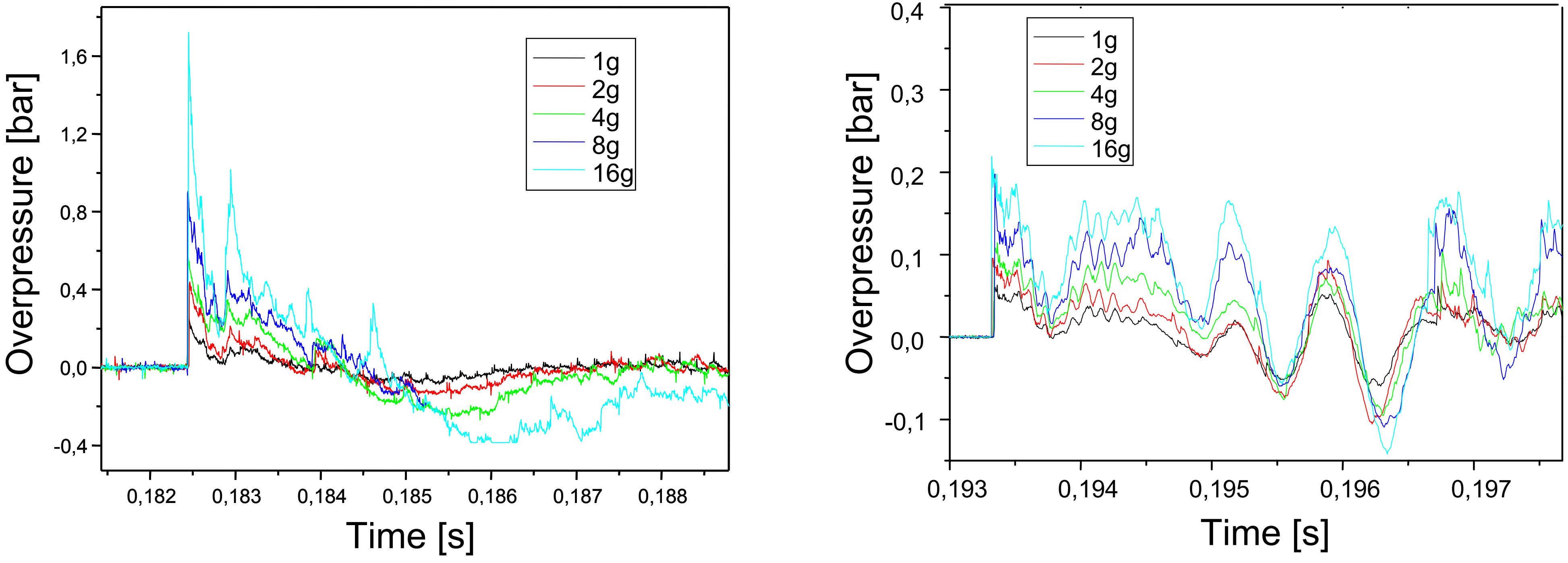




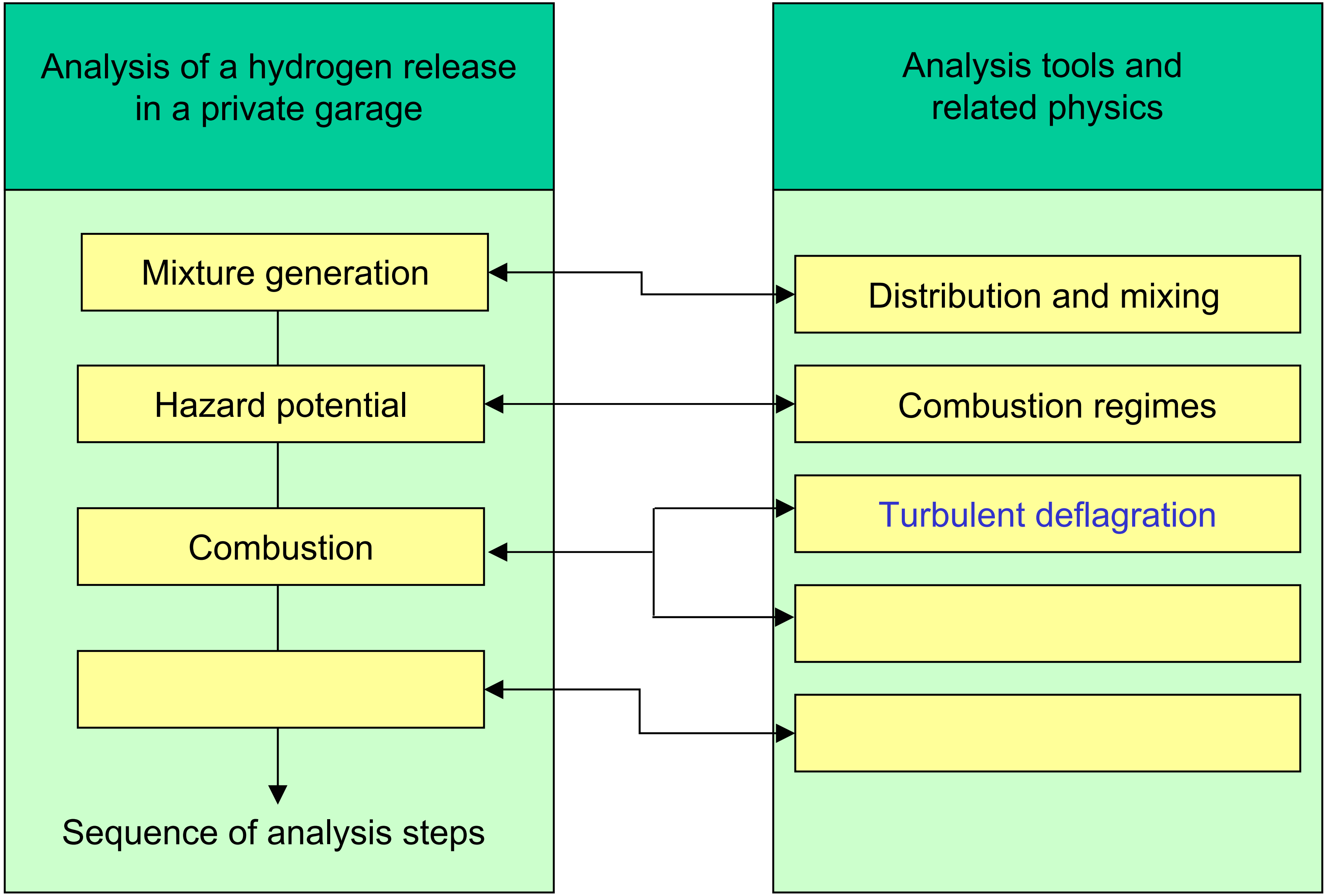




COMPARISON OF OVERPRESSURES



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



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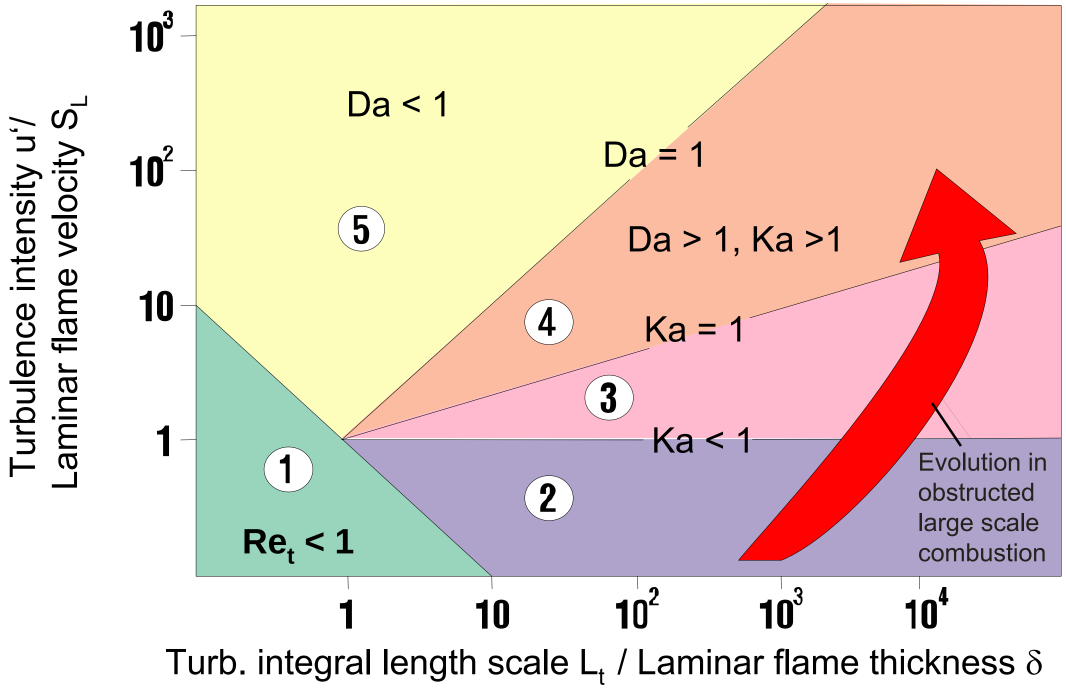
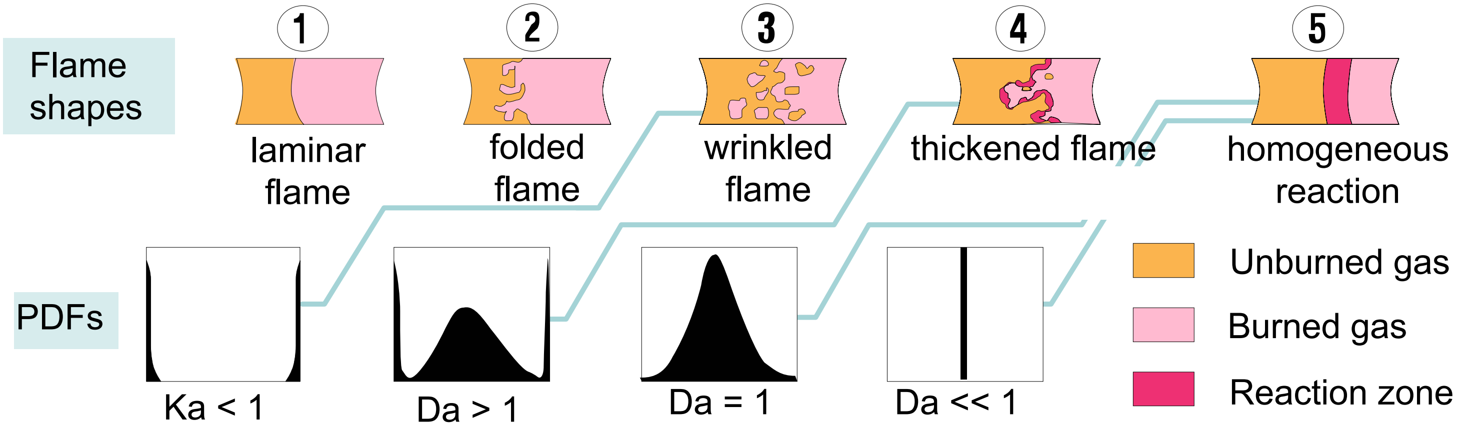
TURBULENT DEFLAGRATION REGIMES



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

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

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



COM3D EQUATIONS

- COM3D under development at FZK for simulation of turbulent deflagration

Hydrodynamic equations

The set of conservation laws for mass, momentum, energy and species reads as

$$(\rho)_t + (\rho u_j)_{x_j} = 0,$$
$$(\rho u_j)_t + (\rho u_i u_j)_{x_j} = \rho g_i - p_{x_i} + M_{ij,x_j}, \quad i = 1, 2, 3$$
$$(\rho e)_t + ((\rho e + p) u_j)_{x_j} =$$
$$\rho g_j u_j + u_i M_{ij,x_j} + (\frac{\mu_{tur}}{C_h}(e - \frac{1}{2} u_i u_i + \frac{p}{\rho})_{x_j})_{x_j} + B + \rho\epsilon,$$
$$(\rho f_\alpha)_t + (\rho f_\alpha u_j)_{x_j} = \overline{\dot{w}}_\alpha + (\frac{\mu_{tur}}{C_{f\alpha}} f_{\alpha,x_j})_{x_j},$$

here

$$e = \sum_{\alpha=1}^{N} \frac{f_\alpha}{\mu_\alpha} \left(h_\alpha + \Delta h_\alpha^0 - RT \right) + \frac{1}{2} u_j u_j, \quad f_\alpha = \frac{\rho_\alpha}{\rho},$$

$$M_{ij} = -\frac{2}{3}\delta_{ij}(\rho k + \mu_{tur} u_{r,x_r}) + \mu_{tur}(u_{i,x_j} + u_{j,x_i}).$$

Closure of the equation depends on the knowledge of the following variables: μ_{tur}, k, ϵ (theory of turbulence) and $\overline{\dot{w}}_\alpha$ (combustion model).

RNG k-ϵ model

$$(\rho k)_t + (\rho u_j k)_{x_j} = S - \rho\epsilon + (\frac{\mu_{tur}}{C_k} k_{x_j})_{x_j},$$
$$(\rho\epsilon)_t + (\rho u_j \epsilon)_{x_j} = \frac{\epsilon}{k}[(C_1 - C_\eta)S - C_2 \rho\epsilon] + (\frac{\mu_{tur}}{C_\epsilon}\epsilon_{x_j})_{x_j} +$$
$$+[C_3 - \frac{2}{3} C_\eta (C_\mu \frac{k}{\epsilon} u_{j,x_j} + 1)]\rho u_{j,x_j}\epsilon.$$

Here C_η is defined by

$$C_\eta = \frac{\eta(1 - \eta/\eta_0)}{1 + \beta\eta^3}, \qquad \eta_0 = 4.38$$

$$\eta = \frac{k}{\epsilon}\left(\frac{1}{2}(u_{i,x_j} + u_{j,x_i})(u_{i,x_j} + u_{j,x_i})\right)^{1/2},$$

and

$$C_3 = \frac{-1 + 2C_1 - 3m(\gamma - 1) + (-1)^\delta \sqrt{6} C_\mu C_\eta \eta}{3}.$$

Turbulence model constants

	C_μ	C_1	C_2	C_k	C_ϵ	β
RNG k-ϵ	0.0845	1.42	1.68	0.719	0.719	0.012
Standard k-ϵ	0.09	1.44	1.92	1.0	1.3	-

Turbulence and reaction model

The standard k-ϵ model (semi-empirical character: the constants C_α are calibrated against turbulent tube experiments)

$$(\rho k)_t + (\rho k u_j)_{x_j} = S - \rho\epsilon + (\frac{\mu_{tur}}{C_k} k_{x_j})_{x_j},$$
$$(\rho\epsilon)_t + (\rho\epsilon u_j)_{x_j} = \frac{\epsilon}{k}(C_1 S - C_2 \rho\epsilon) + (\frac{\mu_{tur}}{C_k}\epsilon_{x_j})_{x_j}.$$

Where

$$S = u_{i,x_j} M_{ij} - B; \;\; B = \frac{\mu_{tur}}{C_\rho}\frac{1}{\rho^2}\rho_{x_r} p_{x_r}; \;\; \mu_{tur} = \mu + C_\mu \rho \frac{k^2}{\epsilon}.$$

Limiting regimes of turbulent combustion $D_a = \tau_{turb}/\tau_{chem}$:
- low turbulence intensities / fast chemical reaction
- high turbulence intensities / slow chemical reactions

$$\dot{\omega} = \begin{cases} -C_f' \frac{\epsilon}{k}\omega(1 - \omega); & D_a > 1 \\ -K_{chem}\,\omega\, \exp(-E_a/T); & D_a < 1 \end{cases}$$

$$\tau_{turb} = \frac{k}{\epsilon}; \quad \tau_{chem} = \frac{1}{K_{chem}\,\omega\,\exp(-E_a/T)}$$

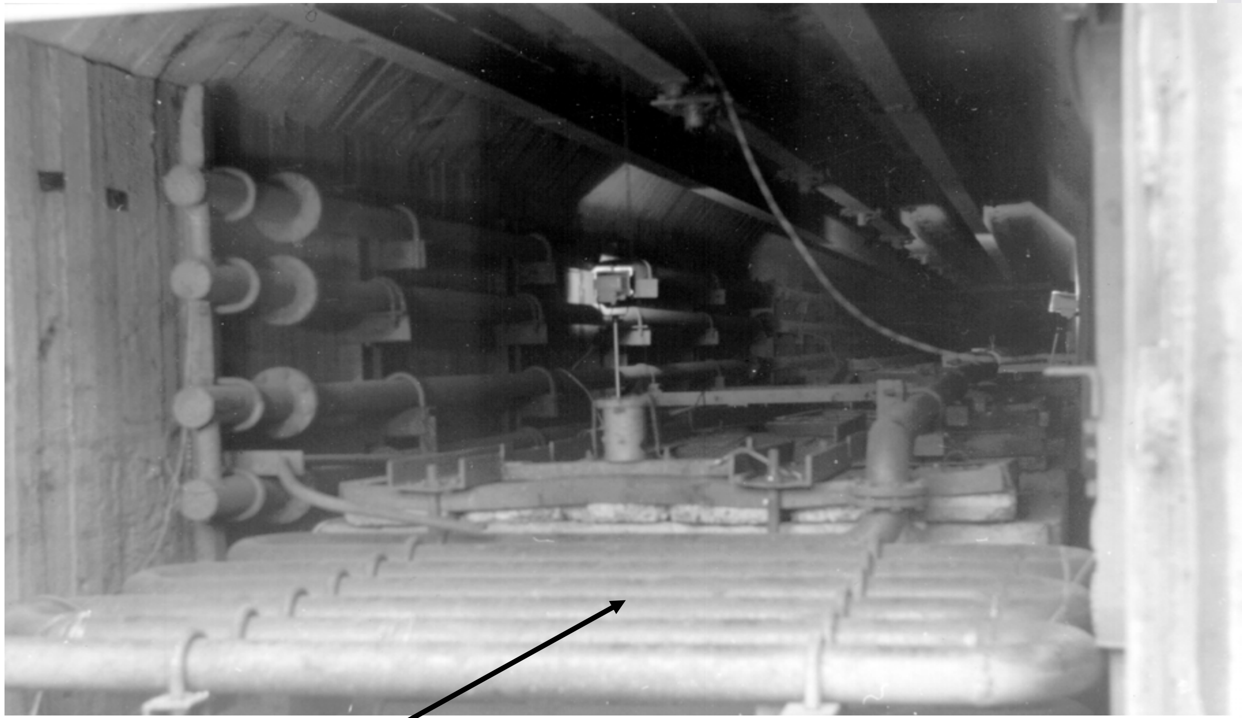
and (Said & Borghi)

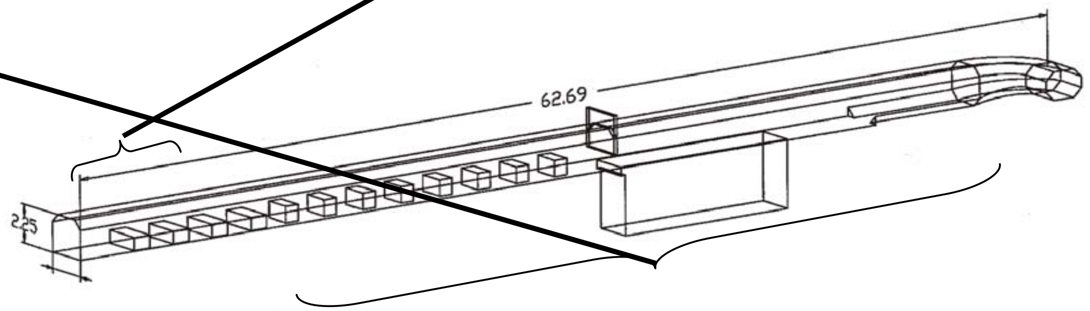
$$C_f' = C_f\left(1 + \frac{4.4}{1 + 3.2\frac{k^{1/2}}{S_L}}\right)$$

A. Kotchourko, IKET

COM3D VERIFICATION (1)

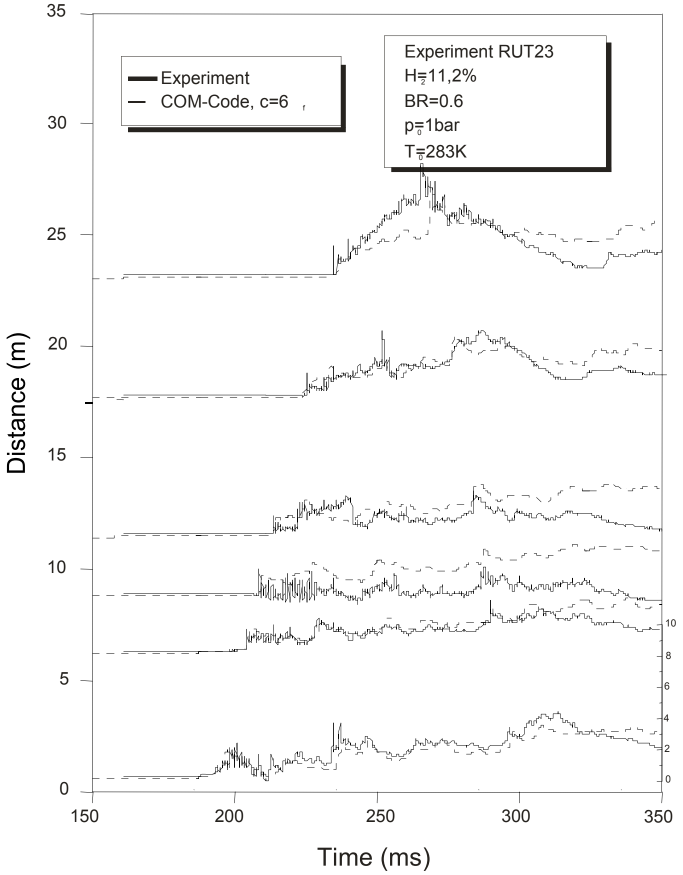
- Large scale experiments performed in RUT facility near Moscow (FZK, CEA, partly NRC), H_2-air, H_2-air-steam
  - Total length 62 m
  - Total volume 480 m^3
  - First channel with obstacles
  - Second part without obstacles

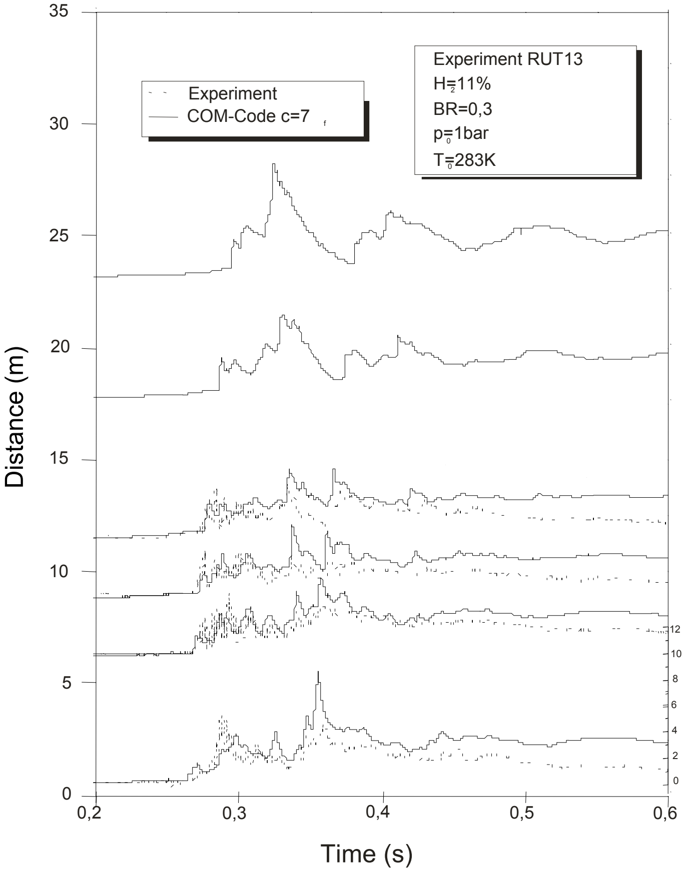


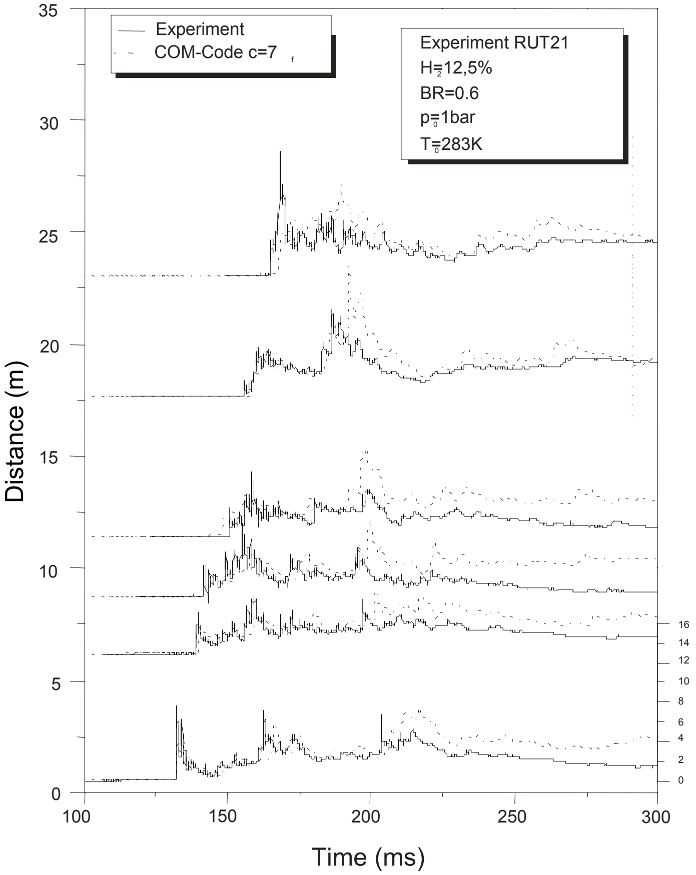


COM3D VERIFICATION (2)

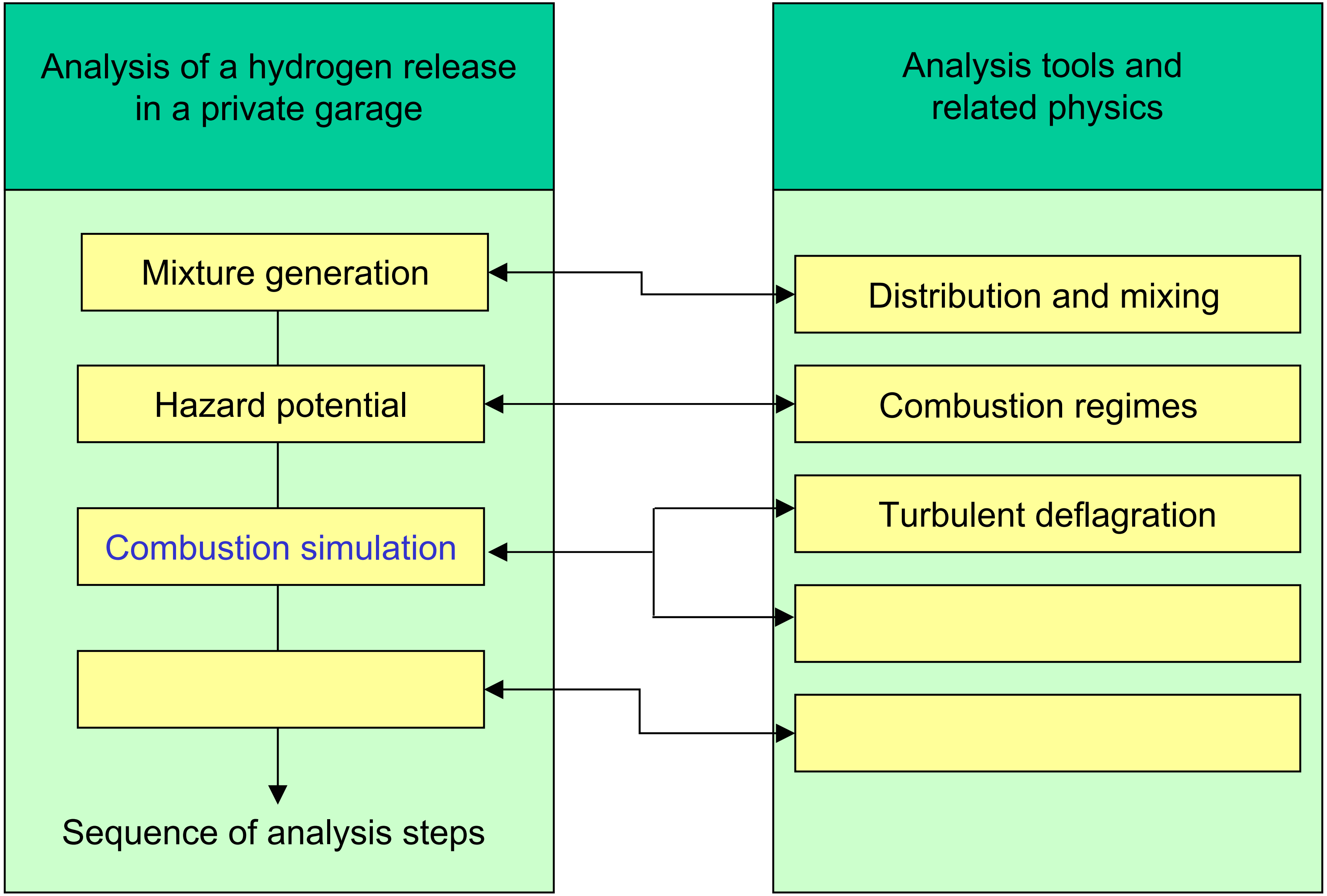
- Numerical simulation of large scale RUT experiments with hydrogen-air and hydrogen-air steam mixtures. Standard k-ε and Eddy-Break-up model.
- Venting in experiments, no venting in simulation







A. Kotchourko, IKET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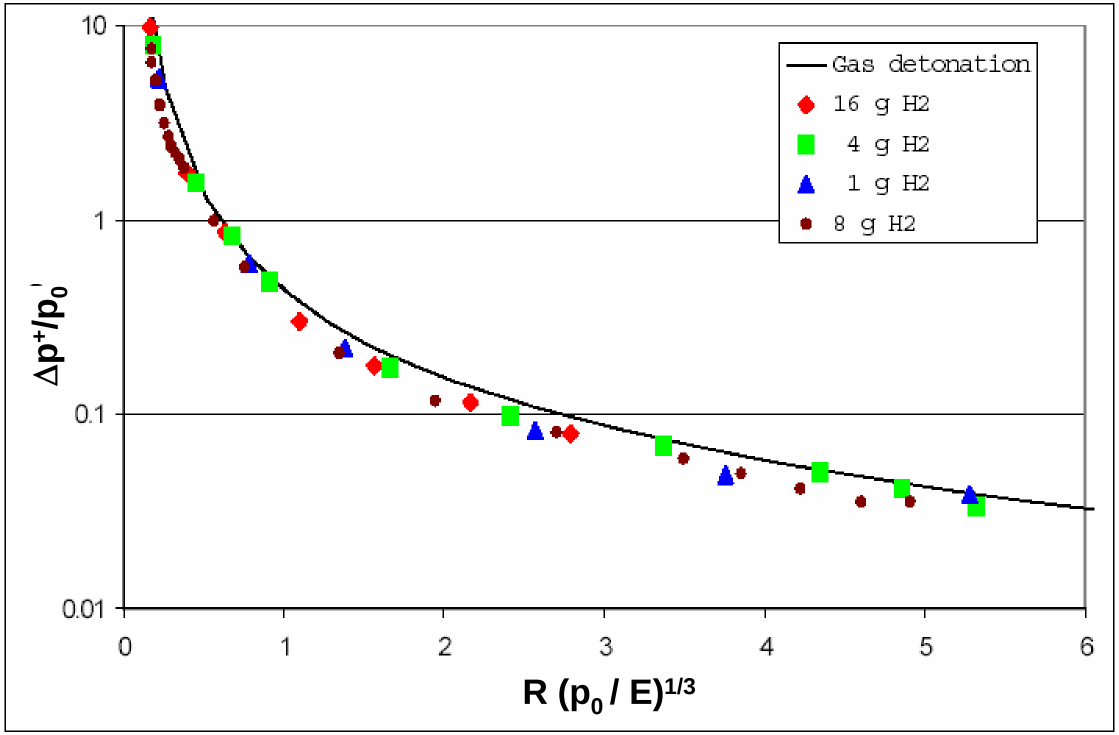
SIMULATION OF UNCONFINED TESTS

- The unconfined tests with different combustion units were simulated with COM3D

- The COM3D combustion model was fitted to the measured flame speed in the combustion units

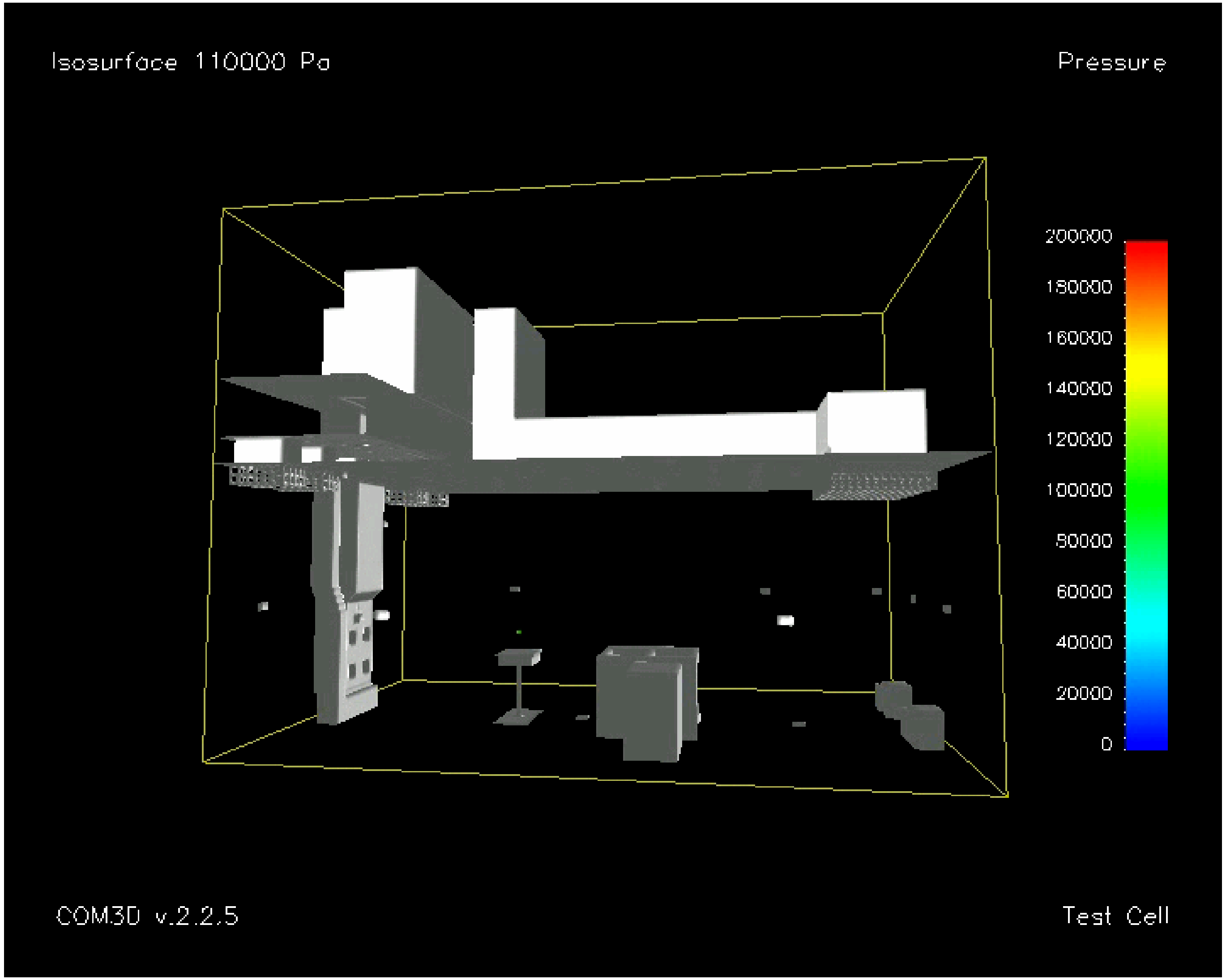


- The calculated peak overpressures agree with the experimental values and follow Sachs scaling

COM3D COMBUSTION SIMULATION

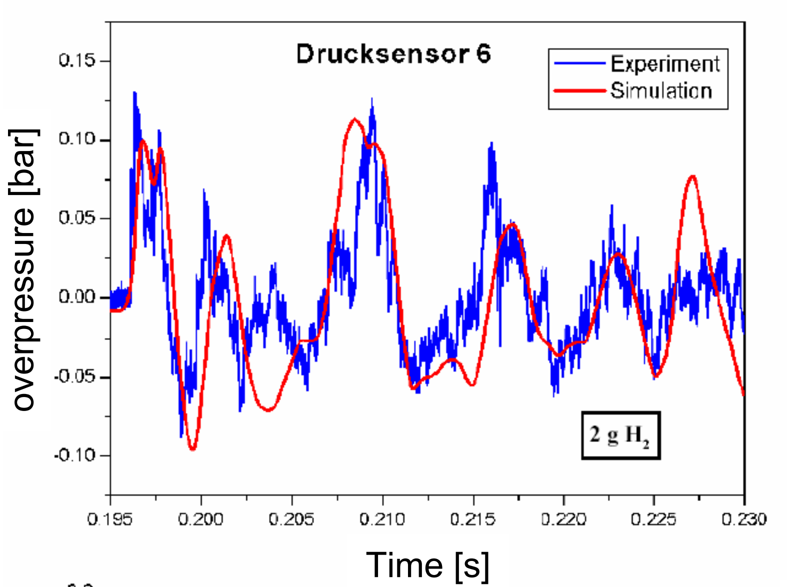
- 3d pressure field, calculated isosurface for 1.1 bar

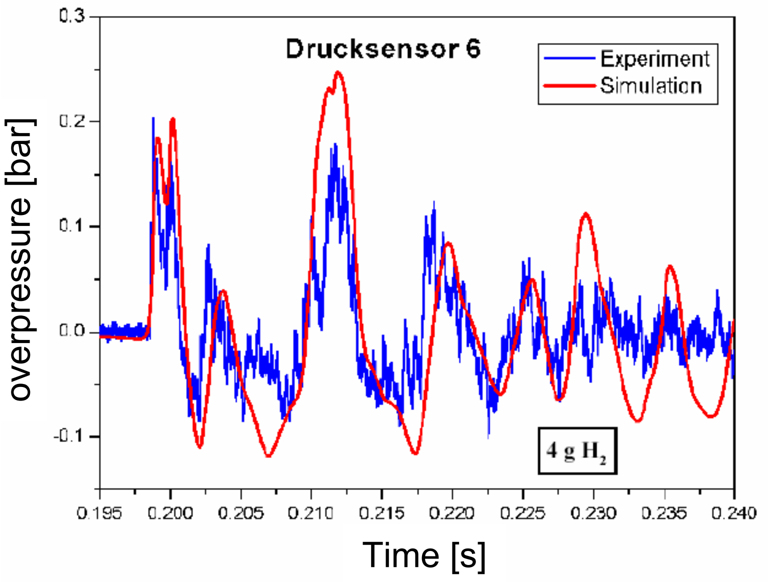
- Test with 8g H_2

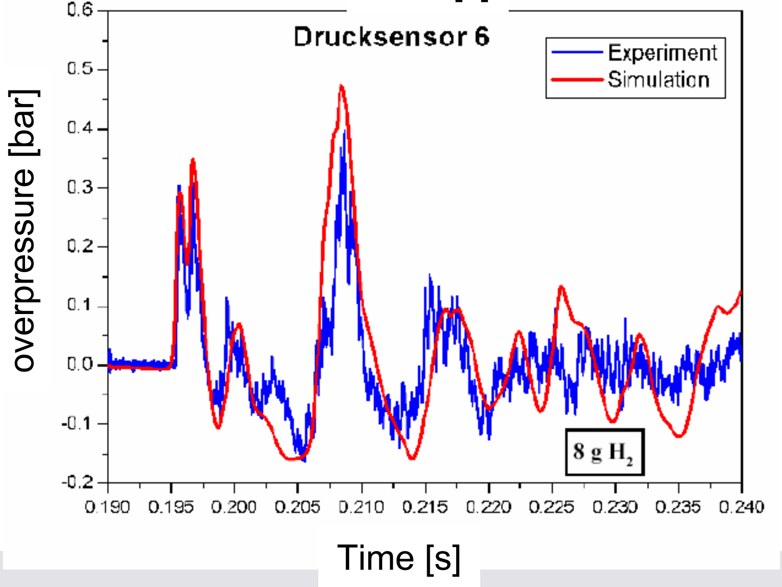


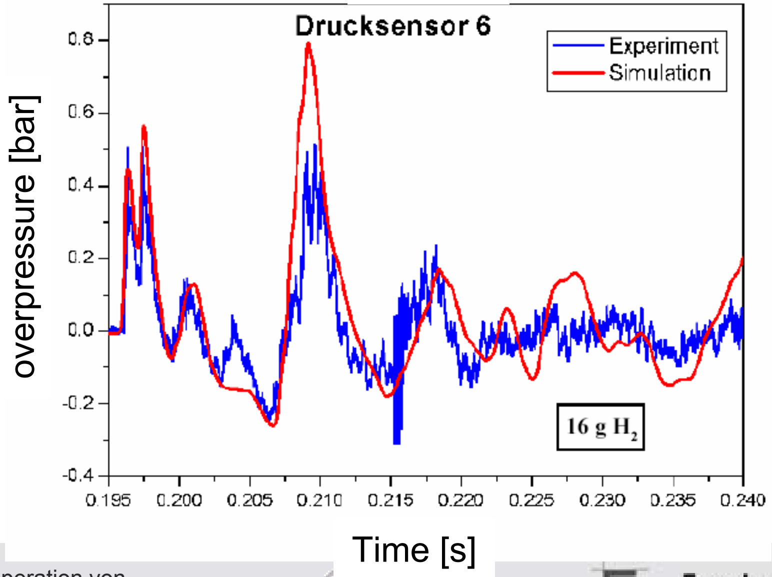
COMPARISON OF OVERPRESSURES

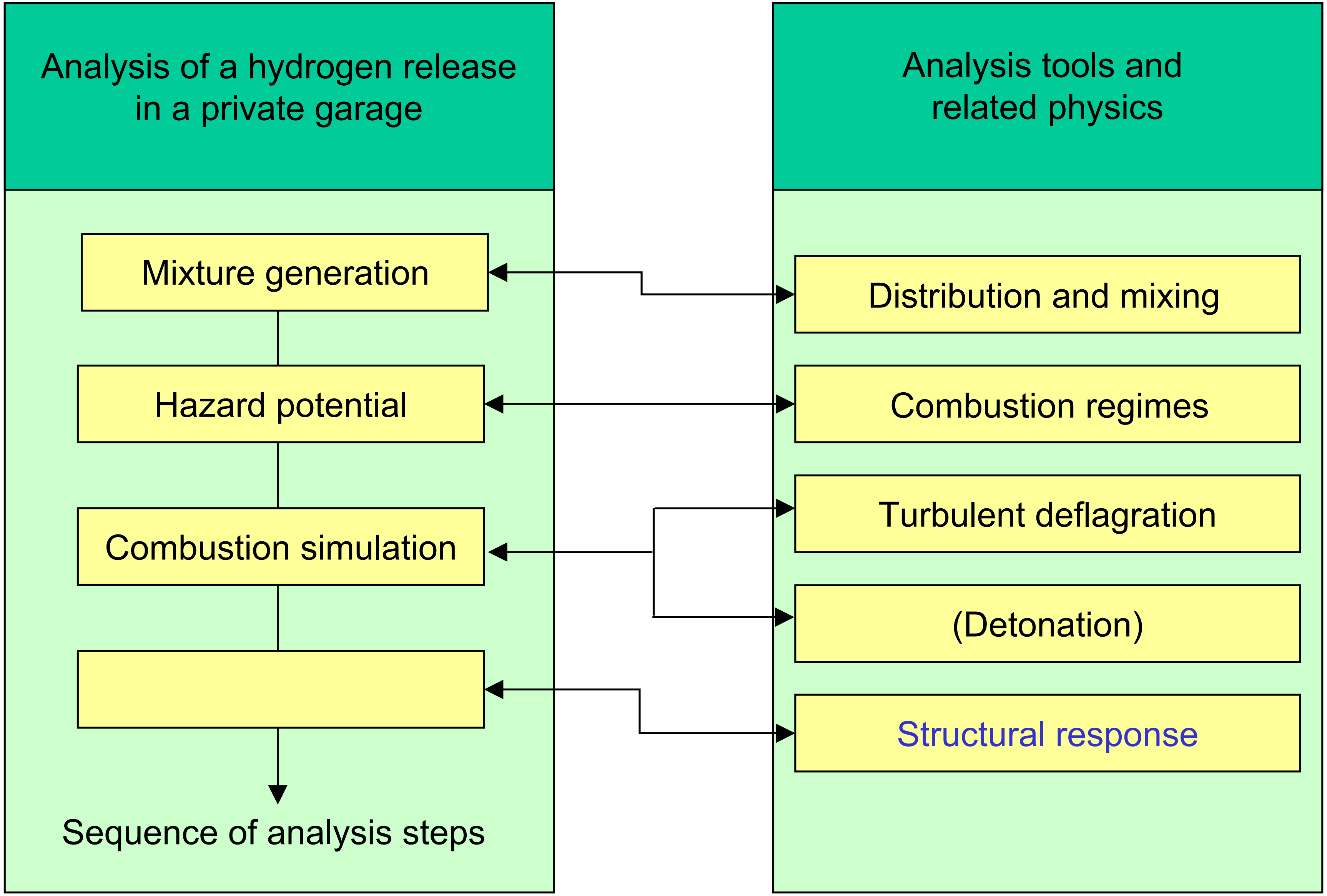
- Good agreement, remaining differences are due to geometry simplification and rigid wall model in simulation











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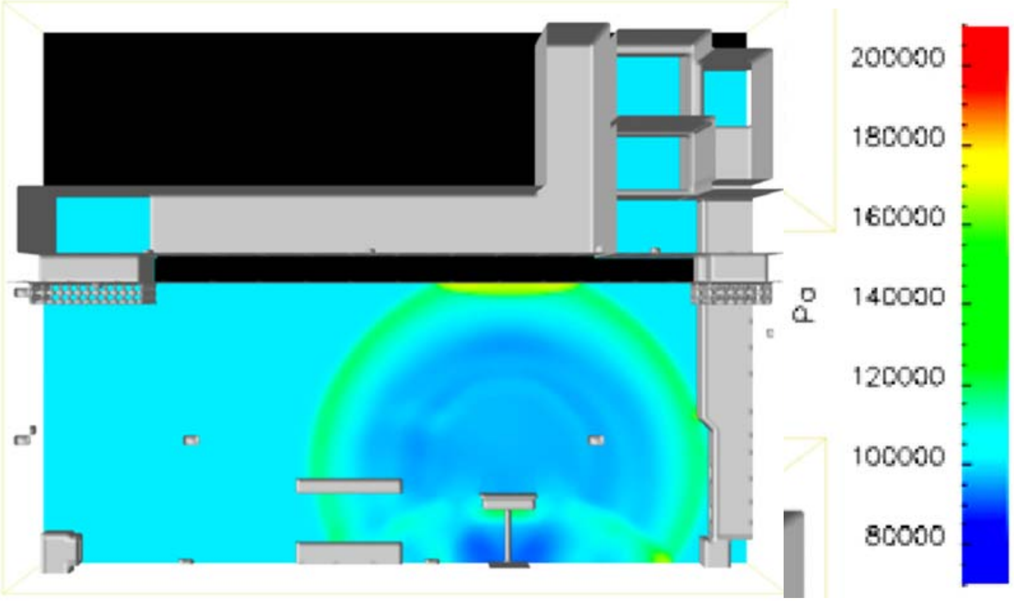
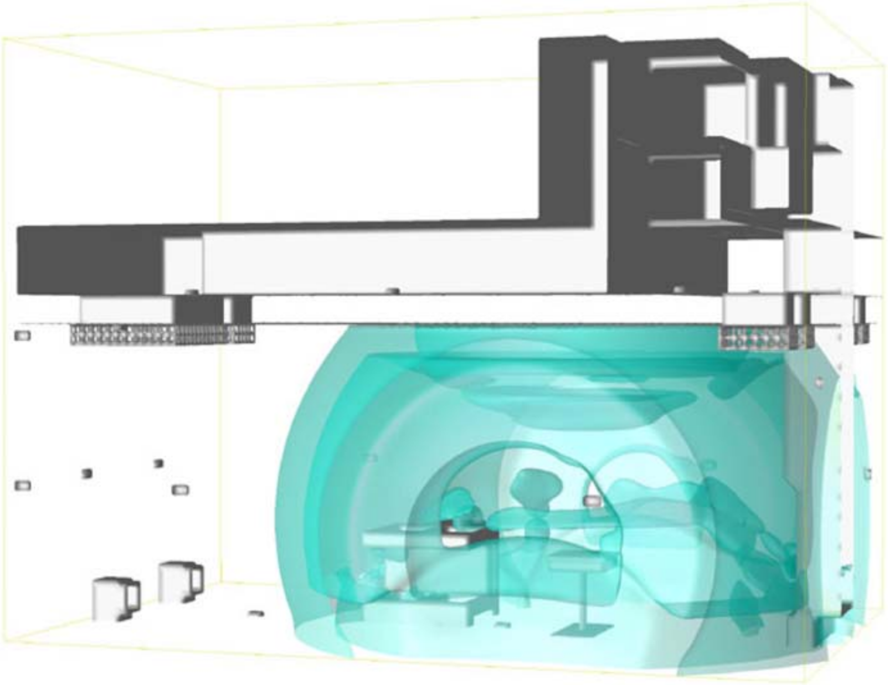
(Detonation)

Structural response

STRUCTURAL RESPONSE

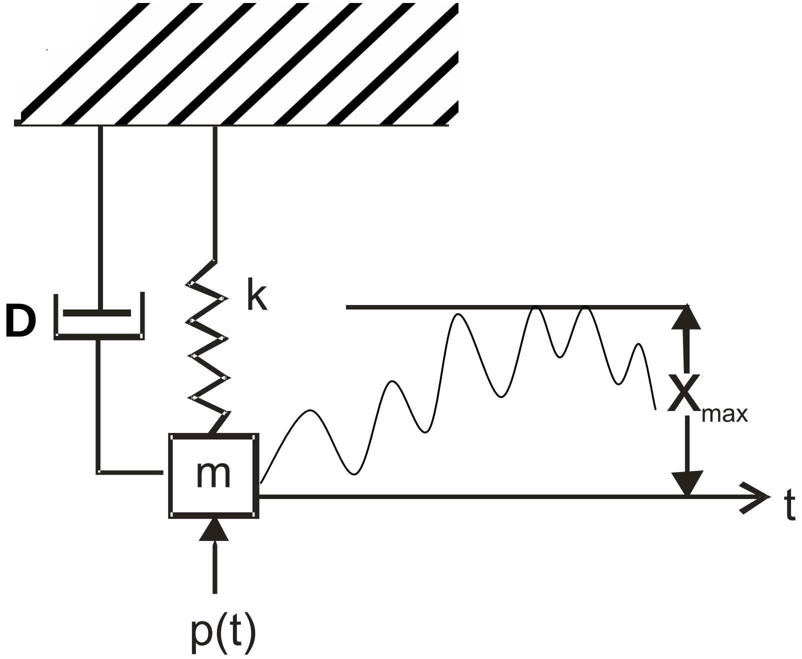
- What are effects of blast loads on the structure?





SINGLE-DEGREE-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



BLAST LOADED ELASTIC OSCILLATOR (1)

- Equation of Motion

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

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

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

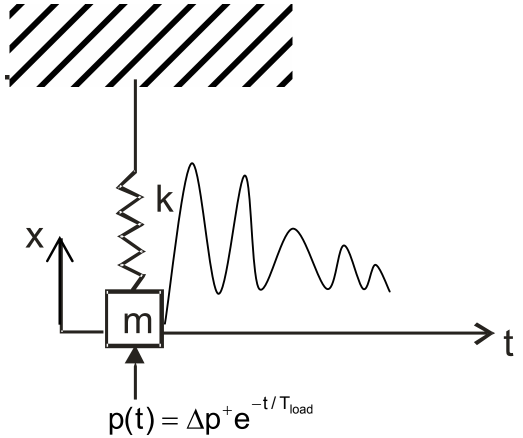
$$\text{with } x(t=0) = 0$$

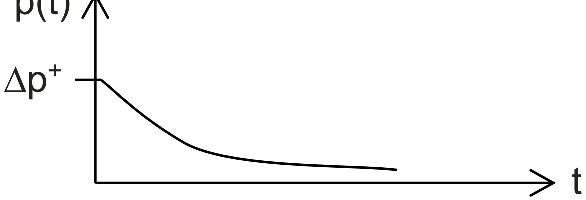
$$\dot{x}(t=0) = 0$$

Static maximum deflection

$$\ddot{x} = 0$$

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





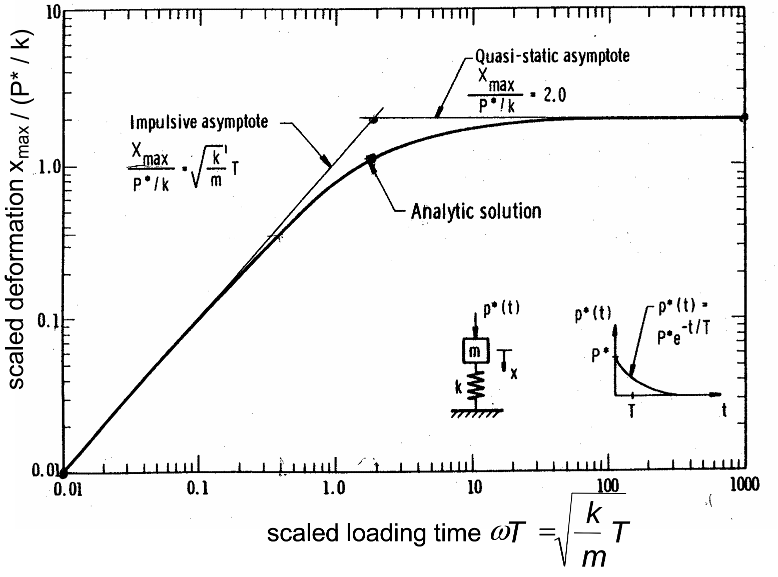
- Solution

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

$$\text{where} \quad \omega = \left(k/m^{1/2}\right) = \text{oscillator period} = \frac{2\pi}{T_{osc}}$$

- 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 realm ($T_{load} >> T_{osc}$)
  - strain energy = work on structure

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

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

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

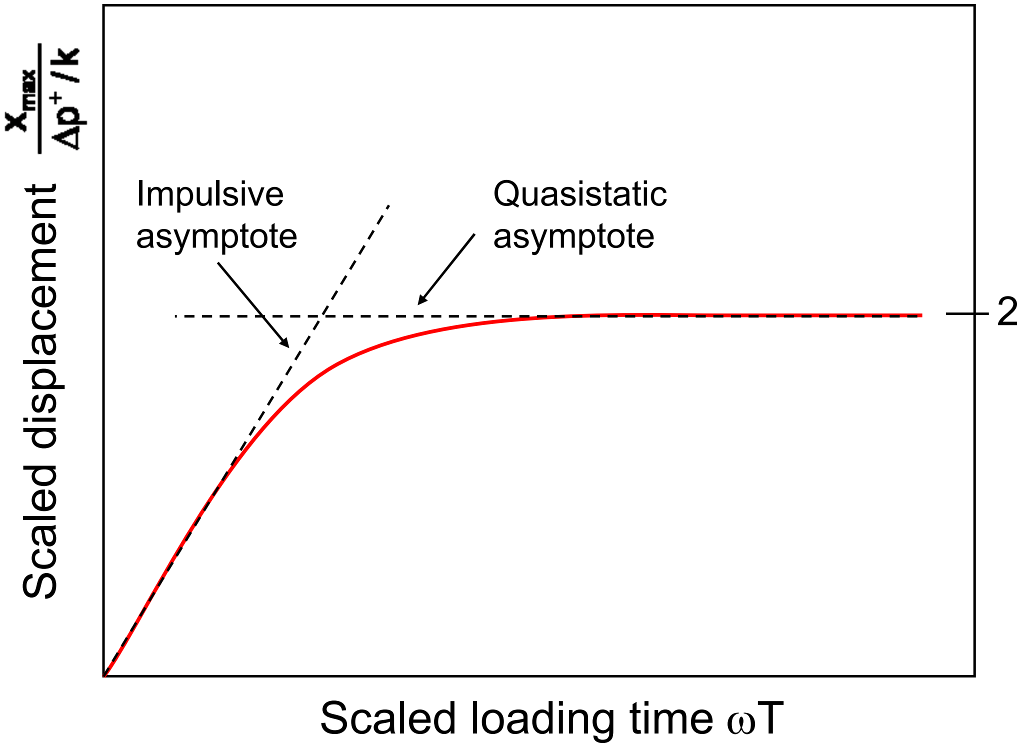
- Impulsive loading realm ($T_{load} << T_{osc}$)
  - initial kinetic energy = strain energy

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

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

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

maximum deformation is proportional to blast wave impulse I



W.E. Baker, P.A. Cox, P.S. Westine, J.J. Kulesz, R.A. Strehlow; Explosion Hazards And Evaluation; Fundamental Studies in Engineerings, 5; Elsevier

OSCILLATOR RESPONSE: ANOTHER VIEW

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

- Quasistatic asymptote

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

$$\boxed{\Delta p^+ = \frac{kx_{max}}{2}}$$

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

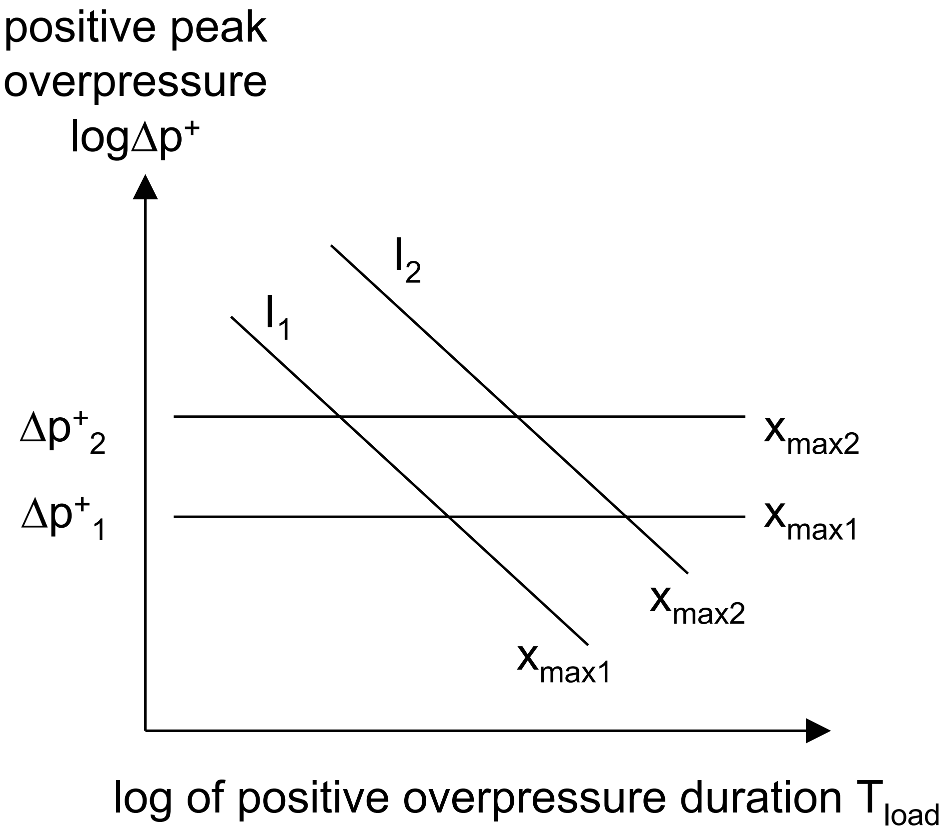
- Impulsive asymptote

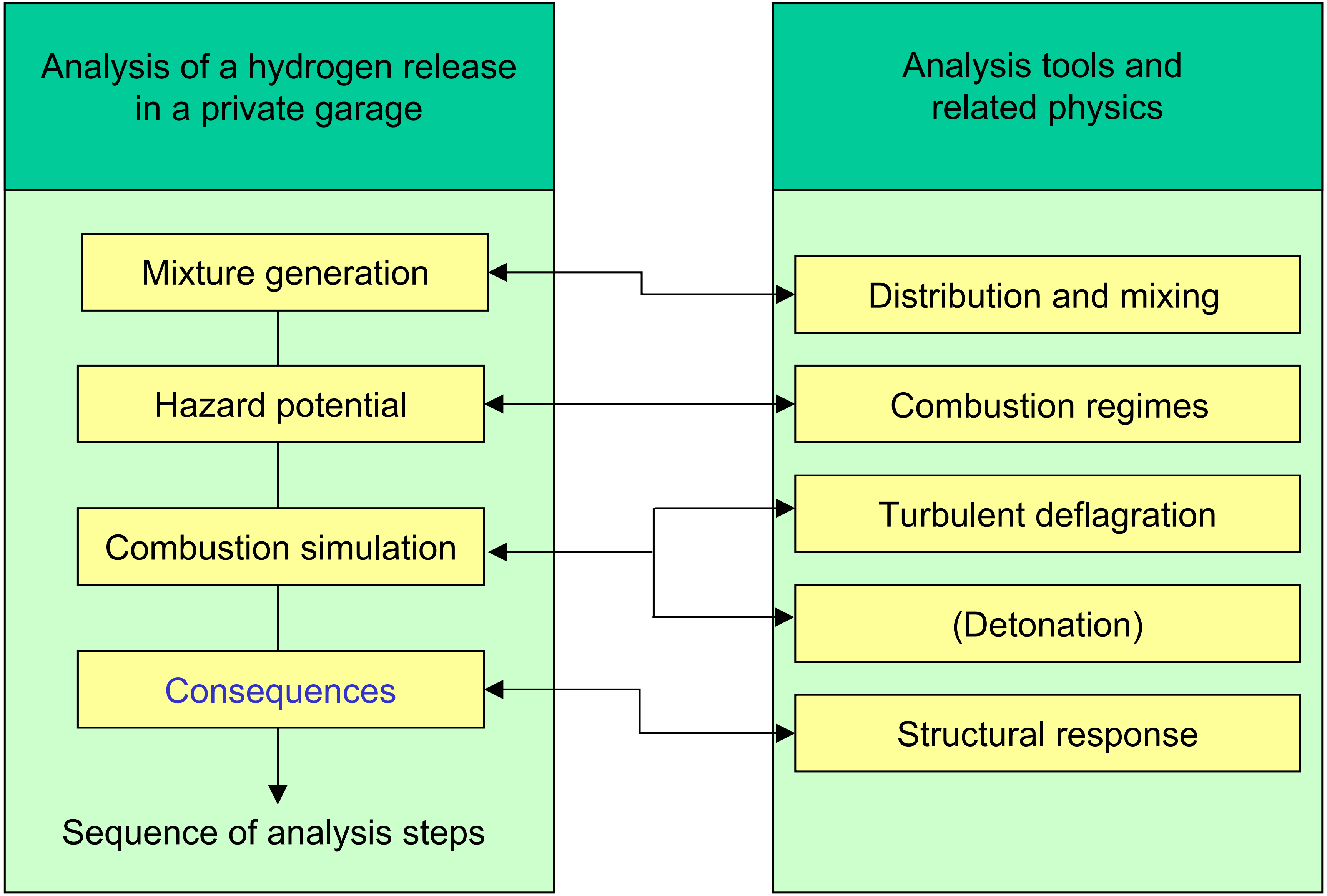
$$\frac{\Delta p^+}{kx_{max}} = \frac{1}{\omega T_{load}}$$

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

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

Maximum deflection x_{max} is proportional to applied impulse





Analysis of a hydrogen release in a private garage

Mixture generation

Hazard potential

Combustion simulation

Consequences

Sequence of analysis steps

Analysis tools and related physics

Distribution and mixing

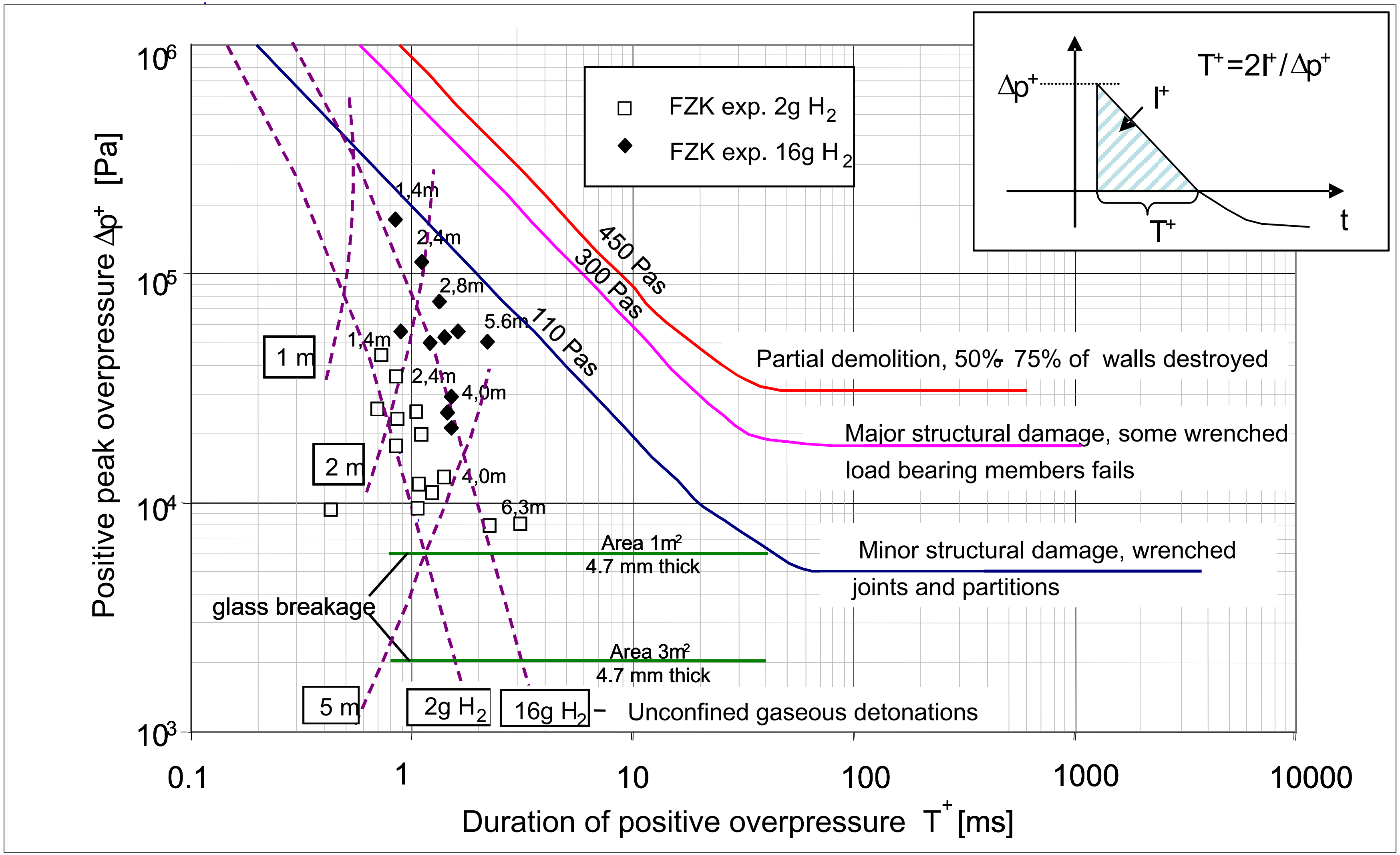
Combustion regimes

Turbulent deflagration

(Detonation)

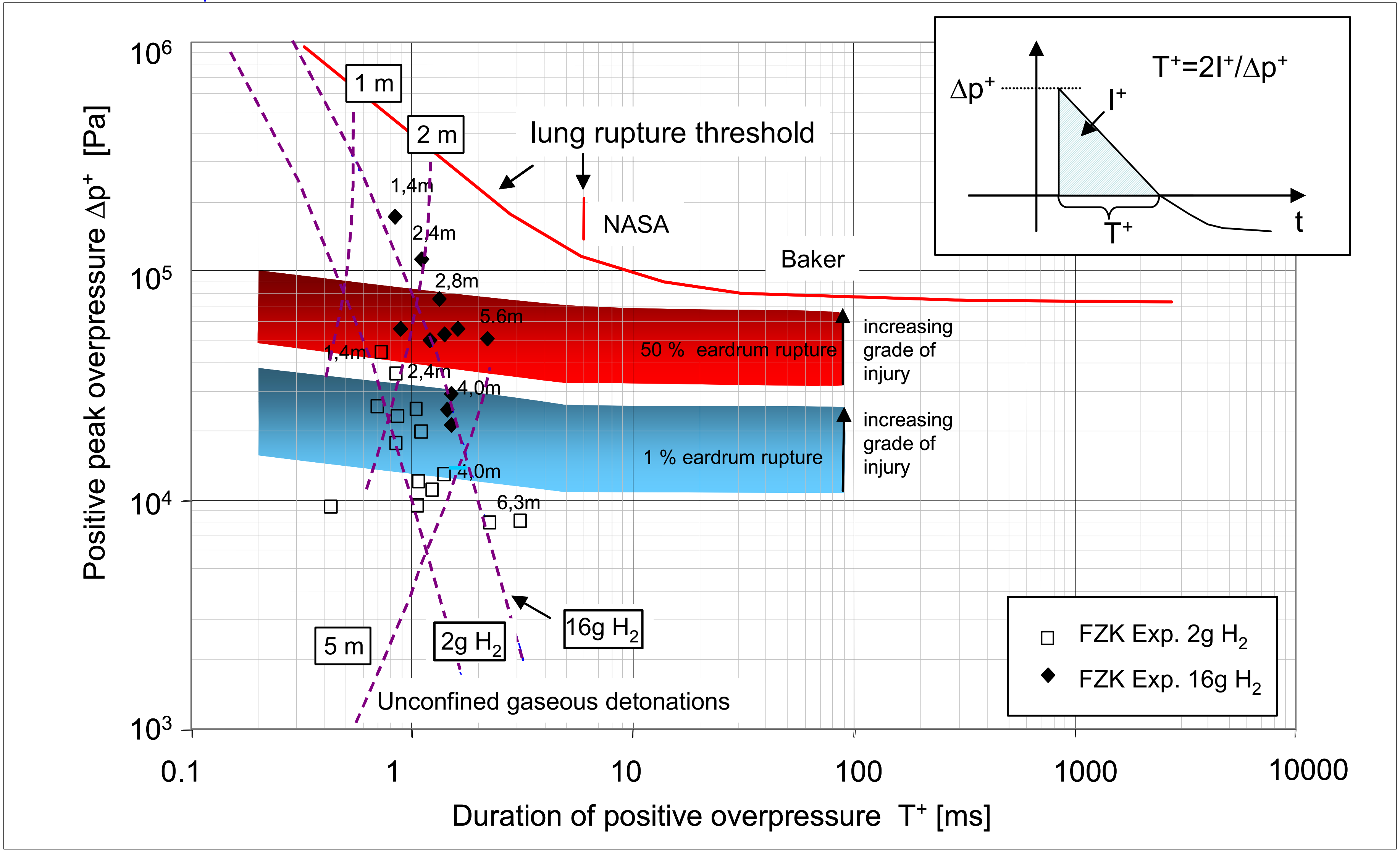
Structural response

STRUCTURAL DAMAGE FROM CONFINED LOCAL H_2 EXPLOSIONS IN GARAGE



Results: - windows and light garage components (door) wold break
- damage to masonary walls only from nearly explosion of 16 g H_2
- wooden framework construction would be destroyed

HUMAN EFFECTS FROM CONFINED LOCAL H_2 – EXPLOSIONS IN GARAGE

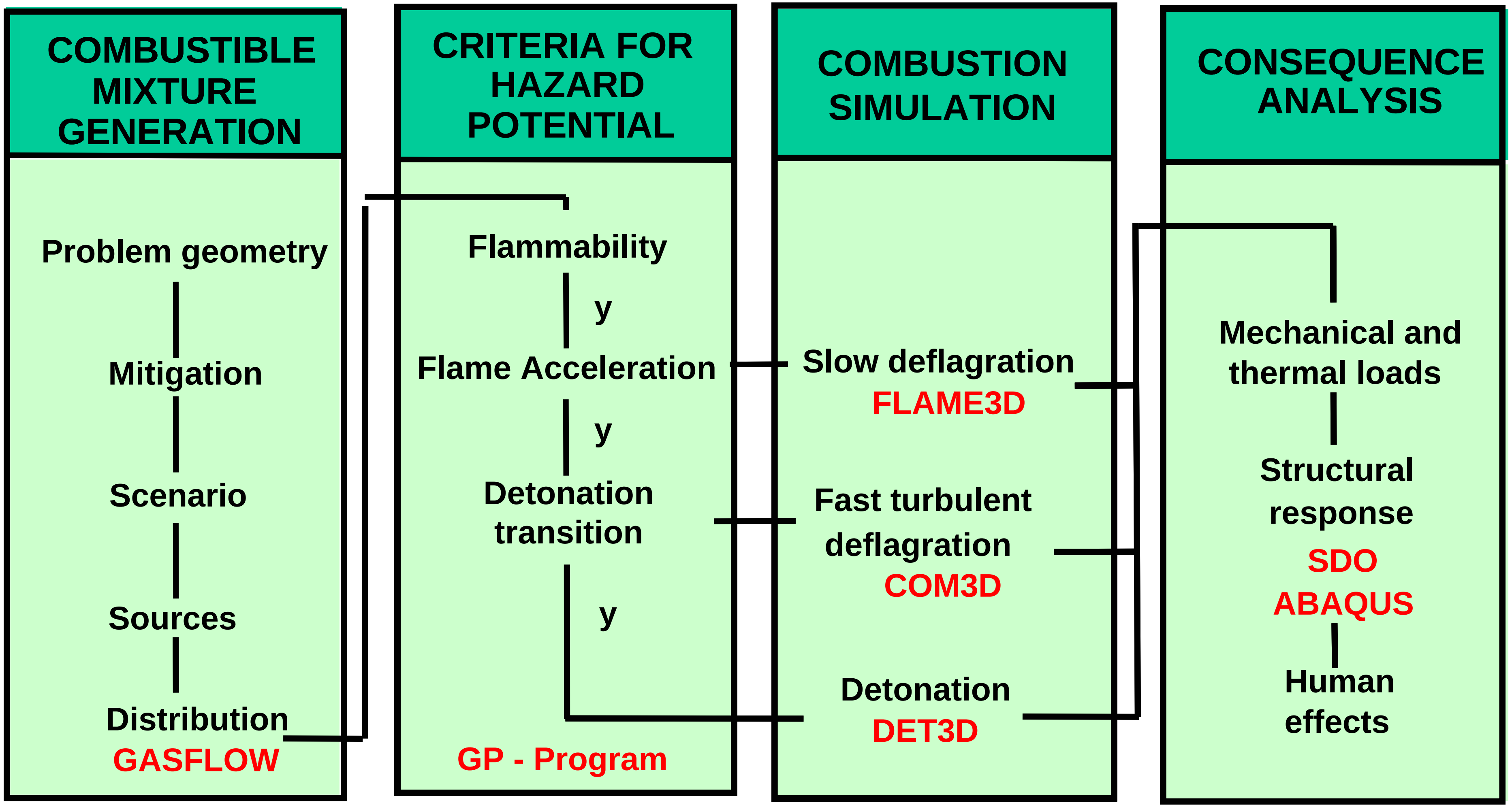


Results: - high probability of ear drum rupture
- no long damage

SUMMARY OF MECHANISTIC SAFETY ANALYSIS OF HYDROGEN BASED ENERGY SYSTEMS

PROCEDURE FOR HYDROGEN SAFETY ANALYSIS

- A complete, self-consistent and mechanistic analysis procedure has been developed which addresses all important physical phenomena of hydrogen behaviour in accidental release scenarios



COMBUSTIBLE MIXTURE GENERATION

Problem geometry

Mitigation

Scenario

Sources

Distribution

GASFLOW

CRITERIA FOR HAZARD POTENTIAL

Flammability

y

Flame Acceleration

y

Detonation transition

y

GP - Program

COMBUSTION SIMULATION

Slow deflagration

FLAME3D

Fast turbulent deflagration

COM3D

Detonation

DET3D

CONSEQUENCE ANALYSIS

Mechanical and thermal loads

Structural response

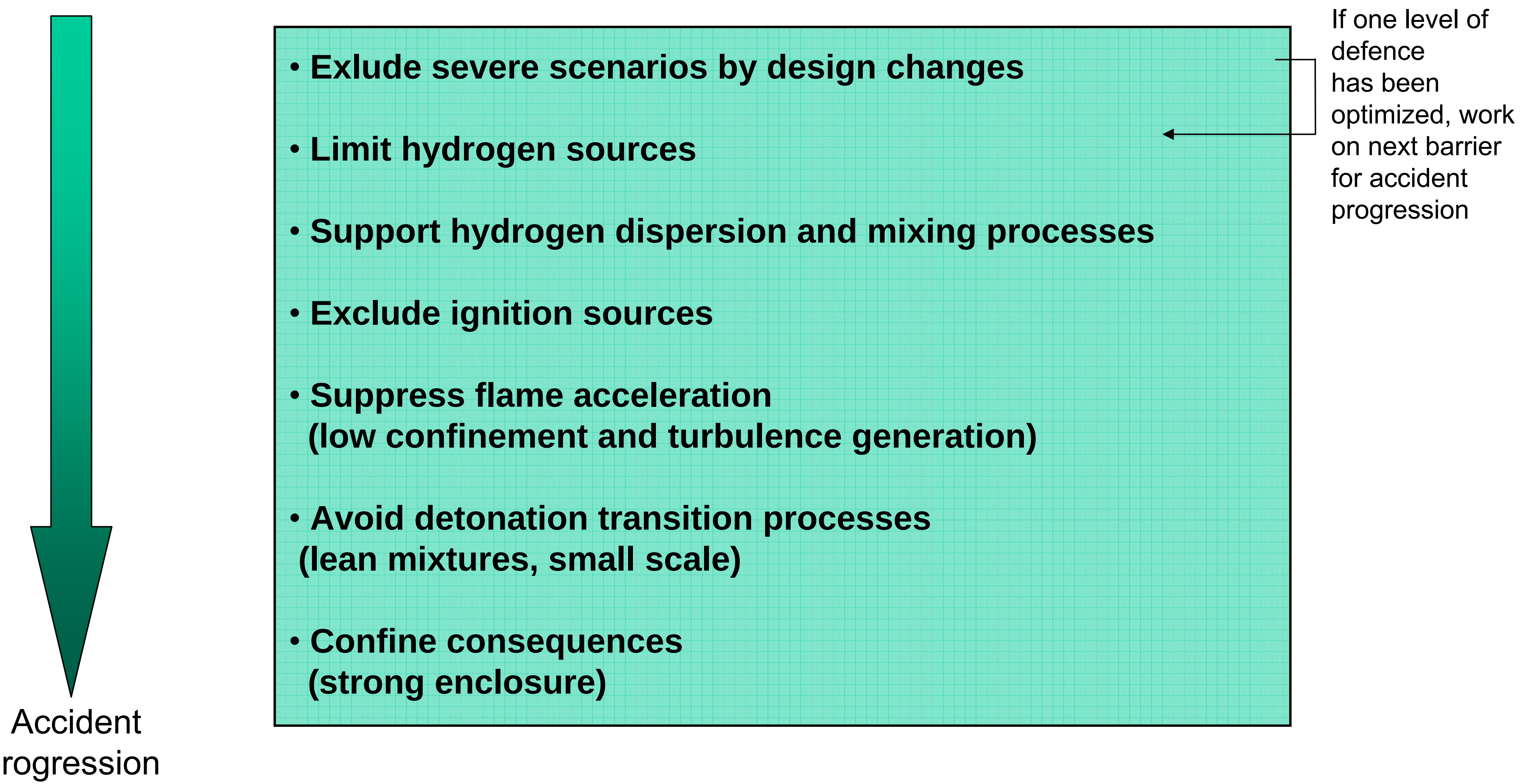
SDO

ABAQUS

Human effects

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

Accident progression