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BASICS OF HYDROGEN SAFETY FOR FIRST RESPONDERS

Lecture. Hazards of hydrogen use indoors

FCH

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

Content

- Objectives of the lecture
- Hazards of hydrogen use indoors
- Passive and forced ventilation
- Regimes of indoor jet fires:
  - Well ventilated
  - Under ventilated
    - Self-extinction
    - External flame
- Pressure peaking phenomenon

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Objectives of the lecture

- Identify the main hazards of hydrogen use indoors
- Distinguish between passive and forced ventilation
- Describe the main regimes on hydrogen indoor fires
- Understand the effect of deflagration venting
- Explain pressure peaking phenomenon
- Use nomograms to evaluate the possibility of pressure peaking phenomenon

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Hazards of hydrogen use indoors

- Oxygen depletion and asphyxiation
- Effects of high temperature and heat flux from jet fires
- Overpressure effects
- Structural collapse
- “Domino” effects
- Damage to environment
- Injury and loss of life

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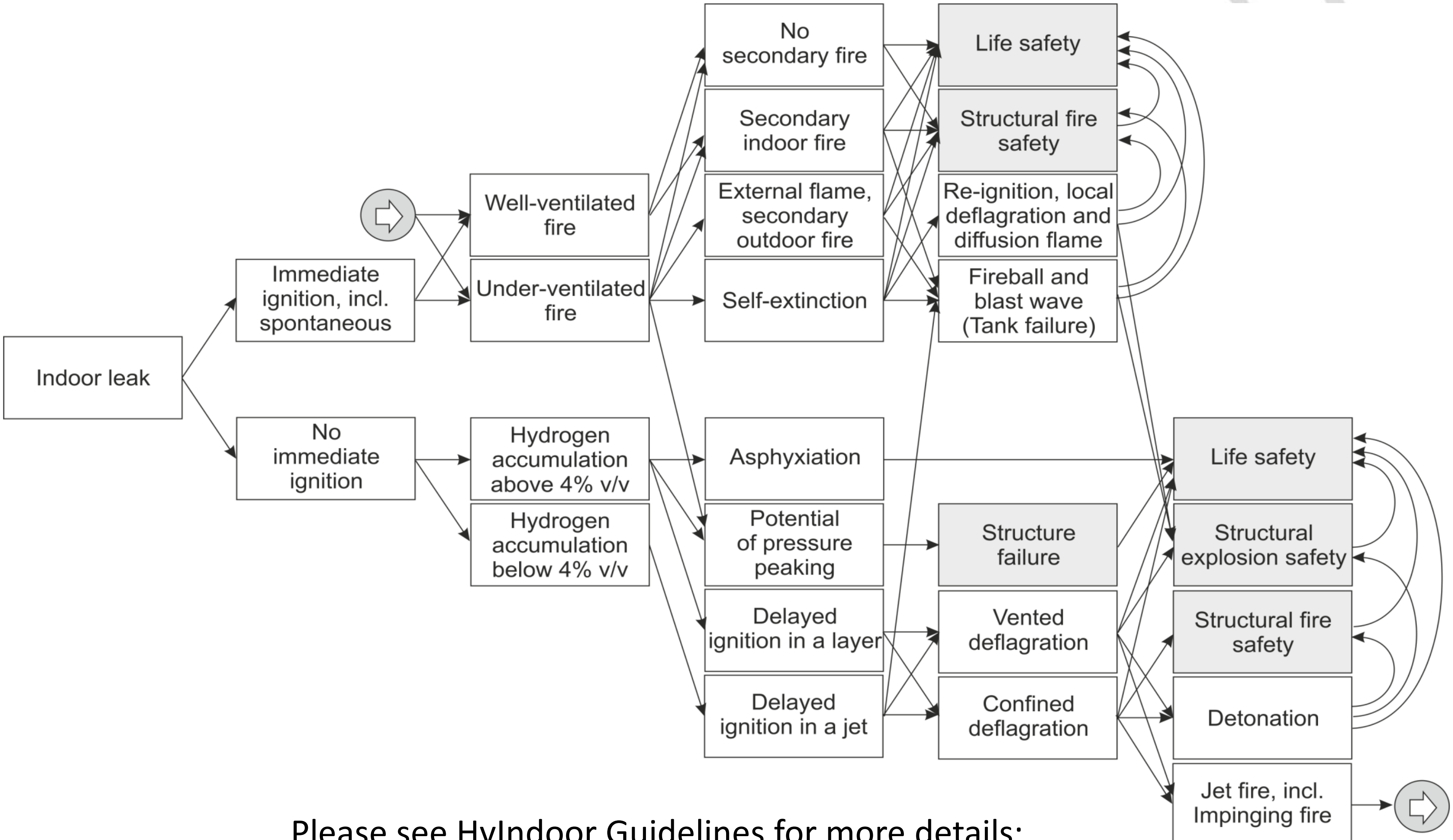
Hydrogen phenomena and consequences



Please see HyIndoor Guidelines for more details:
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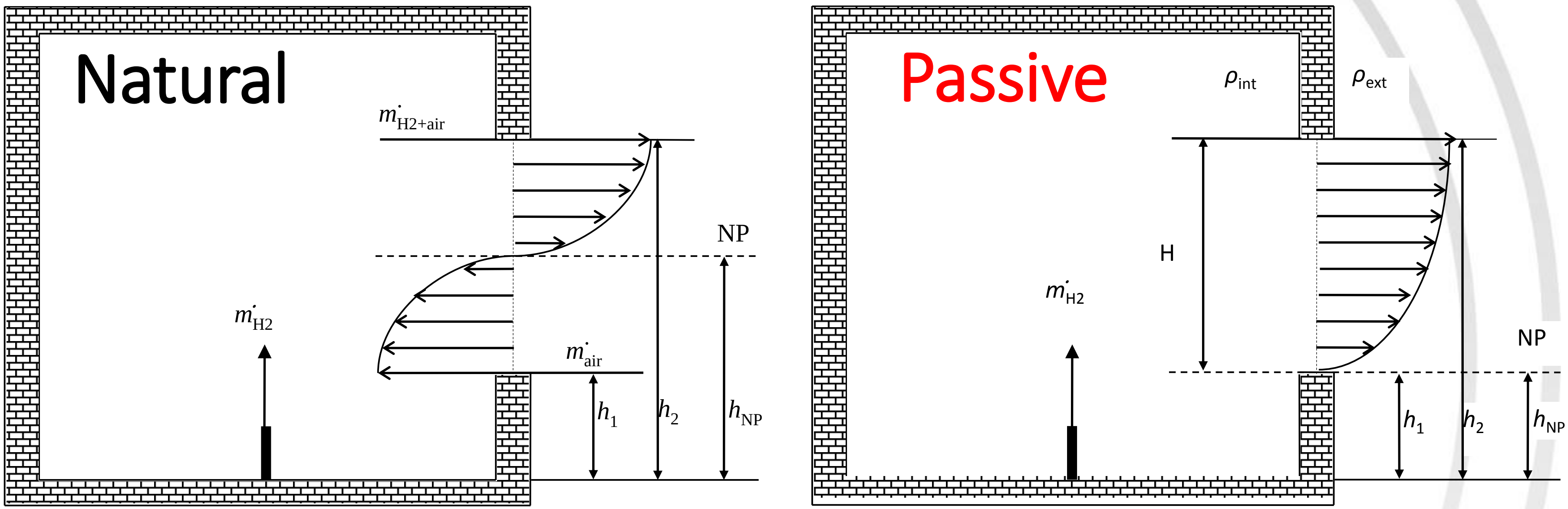
Natural *vs.* passive ventilation



Natural ventilation equations for air ventilation are derived in the assumption of **equality** of flow in and out (**neutral plane is at half vent height**).

Passive ventilation: neutral plane for lighter than air gases can be **anywhere below half of vent height**.

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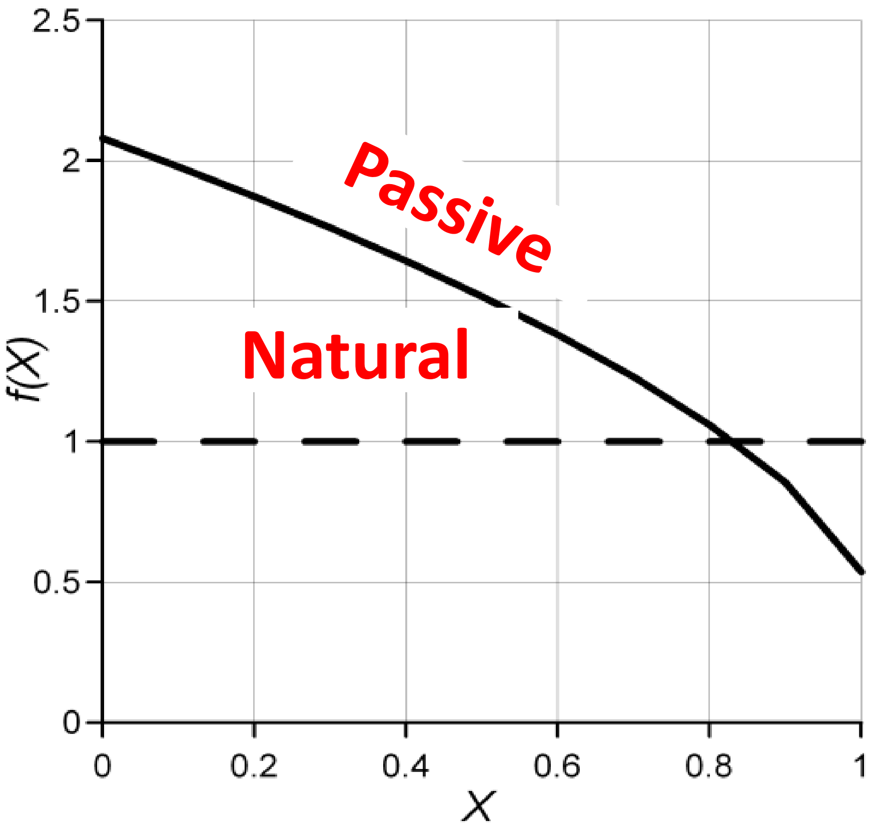
Safety implications

$$X = f(X) \cdot \left[\frac{Q_0}{C_D A (g' H)^{1/2}} \right]^{2/3}$$

Difference:

$$f(X) = \left(\frac{9}{8} \right)^{1/3} \cdot \left\{ \left[1 - X \left(1 - \frac{\rho_{H_2}}{\rho_{air}} \right) \right]^{1/3} + (1 - X)^{2/3} \right\}$$



Natural ventilation equation should not be used:

- Underestimate by **x2 (lean)**
- Overestimate by **x2 (rich)**

Ventilation nomogram

- The nomogram is developed by UU to calculate the maximum concentration for sustained hydrogen leak in an enclosure with one vent. Allows to calculate:
  - Steady-state hydrogen uniform concentration for the given release rate (Q) and vent size (HxW).
  - Parameters of the vent to get desired concentration for the given release rate.
  - The release rate to get desired concentration for the given vent sizes.

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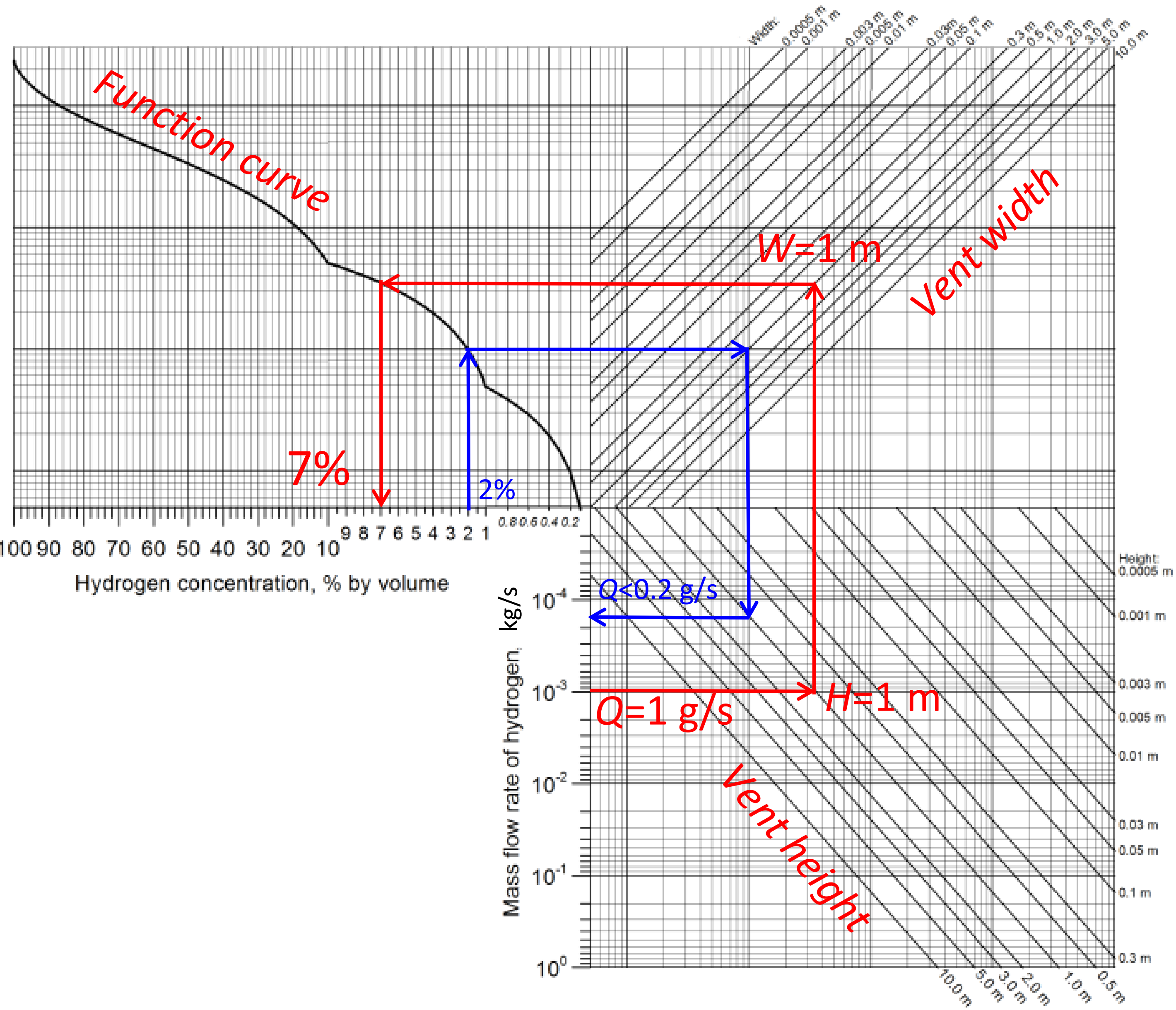
Nomogram (C_{max} steady-state)



Calculation examples:

- Release rate (1 g/s)
- Vent Height (1 m)
- Vent width (1 m)
- Function curve
- Concentration (7%)

1. RCS require no more than 2% v/v (50% LFL)
2. For the same 1x1 m vent release rate Q<0.2 g/s

Hydrogen jet fire indoor

- Important to understand for practical applications.
- Behaviour of fire depends on the release conditions and geometry of an enclosure/ventilation.
- Well-ventilated and under-ventilated fires.

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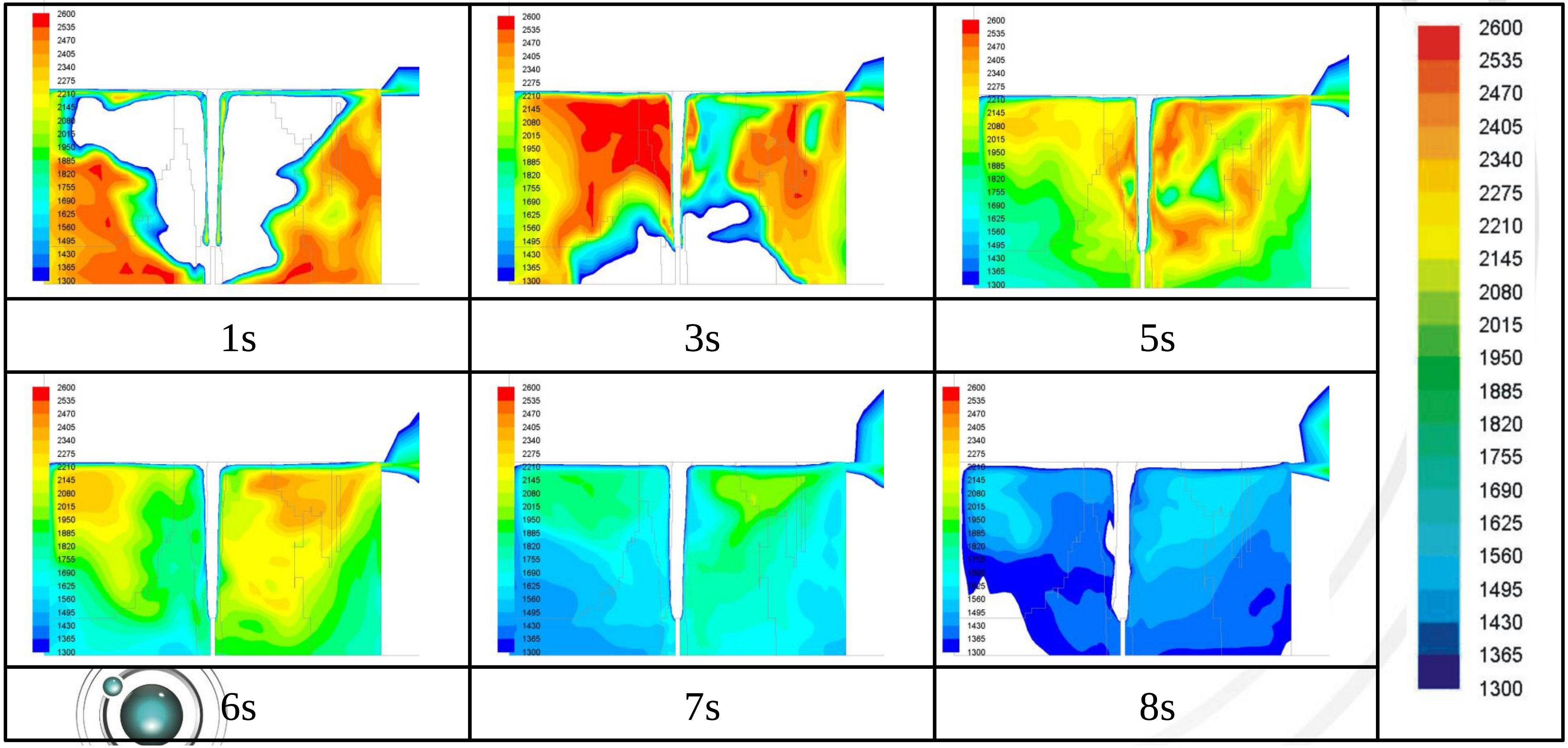
Jet fire from a TPRD of a FC car in a garage

Size of a small garage LxWxH=4.5x2.6x2.6 m (with a “brick”-sized vent).

Mass flow rate: **390 g/s (350 bar, *D*=5.08 mm, today cars)**



Indoor hydrogen fires

Two regimes of indoor fires:

- Well-ventilated: sufficient amount of oxygen (from the air) for complete combustion of hydrogen inside an enclosure
- Under-ventilated: insufficient amount of oxygen (from the air) to burn hydrogen completely

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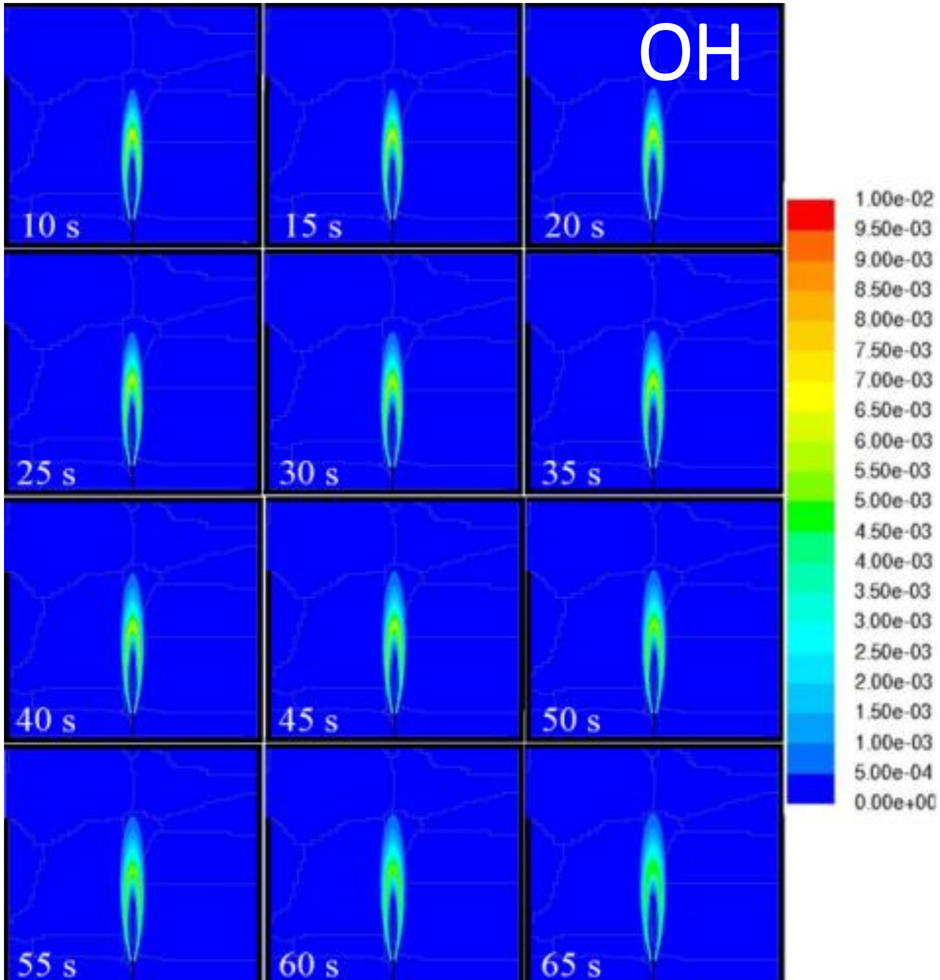
Jet fires: numerical experiments

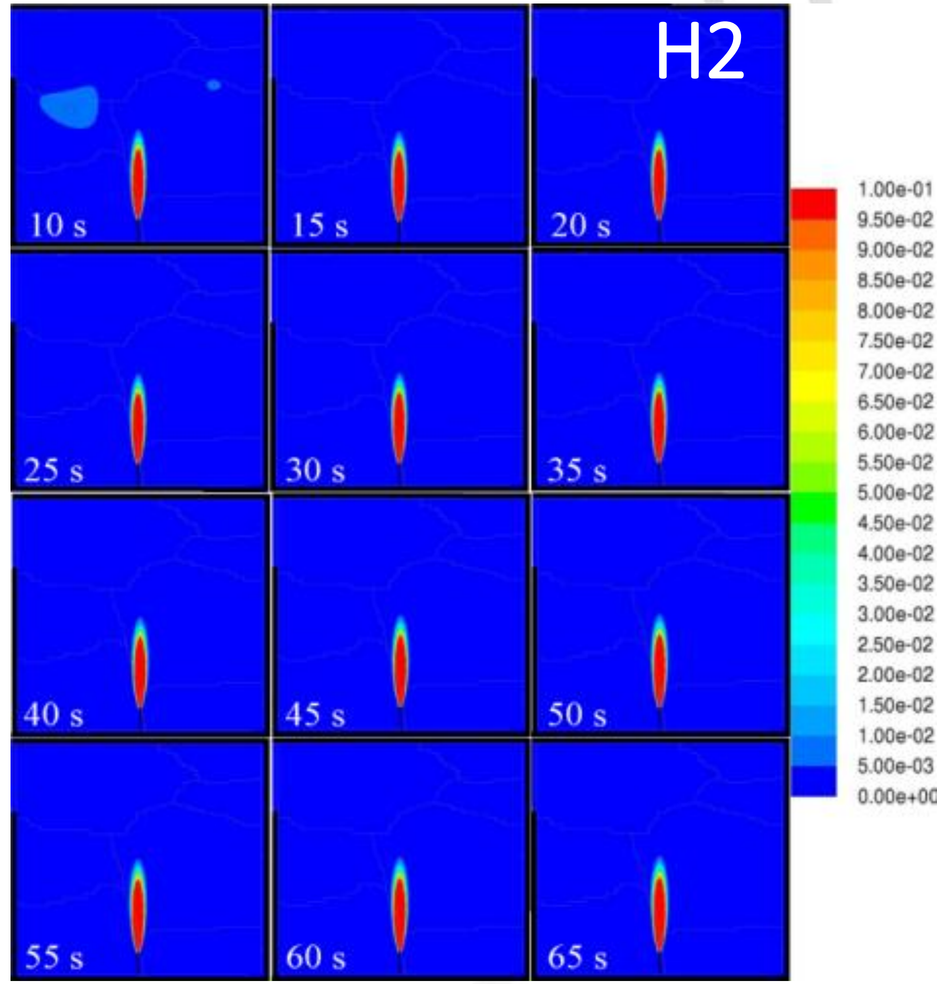
Seven numerical experiments with a single vent were performed (a FC-like enclosure LxWxH=1x1x1 m; vertical upward release of hydrogen from 5 mm pipe with exit 10 cm above the floor centre; a single vent located centrally at the top of one wall):

No.	Vent size, HxW	Velocity, m/s	Flow rate, g/s	Result
1	Horizontal 3x30 cm	600 m/s	1.0857	**Self-extinction**
2	Horizontal 3x30 cm	300 m/s	0.5486	**Self-extinction**
3	Horizontal 3x30 cm	150 m/s	0.2714	**External flame**
4	Vertical 30x3 cm	600 m/s	1.0857	**External flame**
5	Vertical 30x3 cm	60 m/s	0.1086	**Well ventilated**
6	Vertical 13.9x3 cm	600 m/s	1.0857	**Self-extinction**
7	Vertical 13.9x3 cm	300 m/s	0.5486	**External flame**

Well-ventilated fire (1/2)

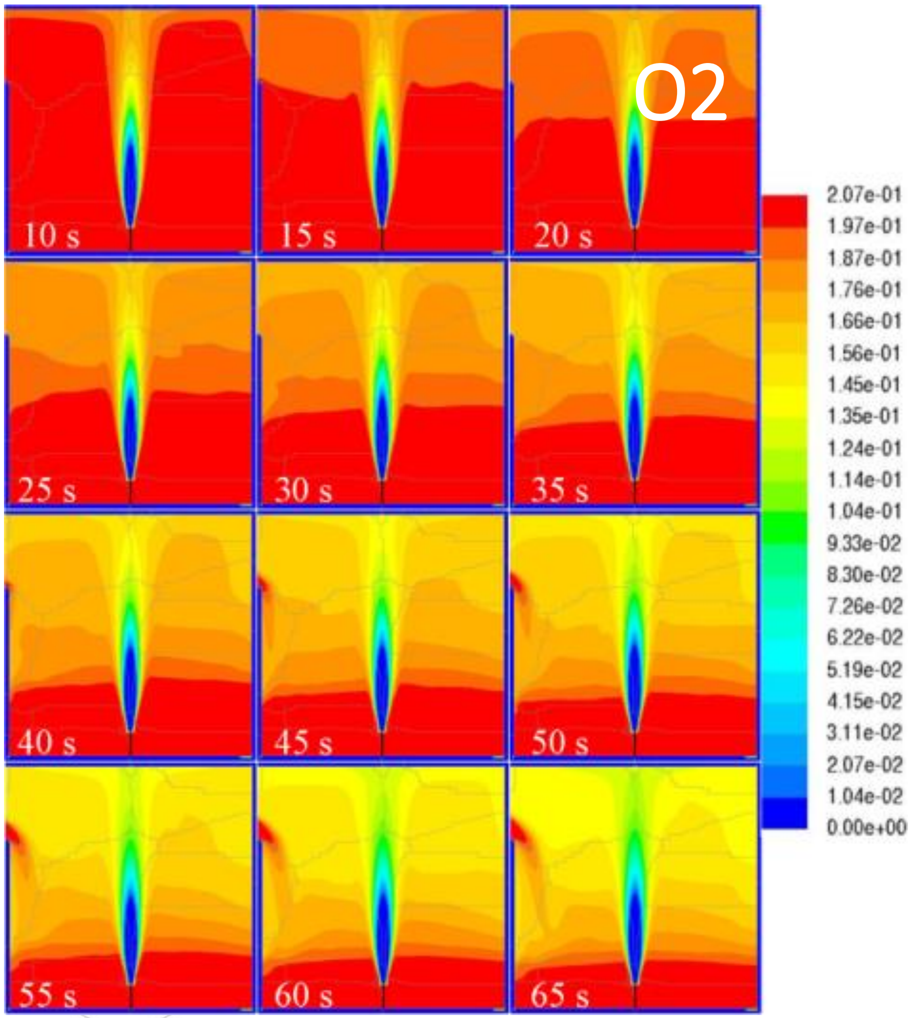
No.5: vertical vent 30x3 cm; release 60 m/s - 0.11 g/s.

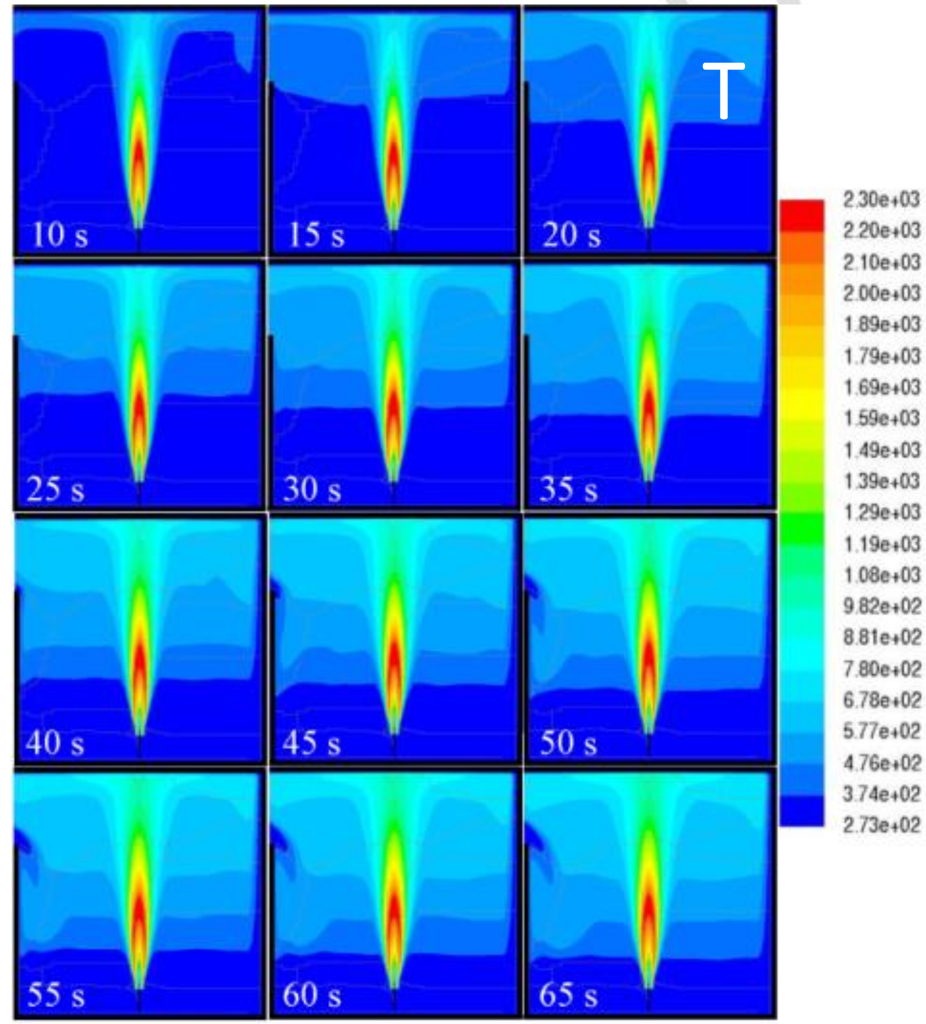




Well-ventilated fire (2/2)

No.5: vertical vent 30x3 cm; release 60 m/s - 0.11 g/s.





Simulation videos

Well-ventilated fire:

No.5 (vertical vent 30x3 cm; release 60 m/s, 0.11 g/s) - OH

No.5 – Temperature (70 C – “no harm” temperature)

Under-ventilated fire (two modes):

Self-extinction mode:

No.6 (vertical vent 13.9x3 cm, 600 m/s) – Temperature

No.6 – OH

External flame mode:

No.7 (vertical vent 13.9x3 cm, 300 m/s) – OH

No.4 (vertical vent 30x3 cm, 600 m/s) – Temperature

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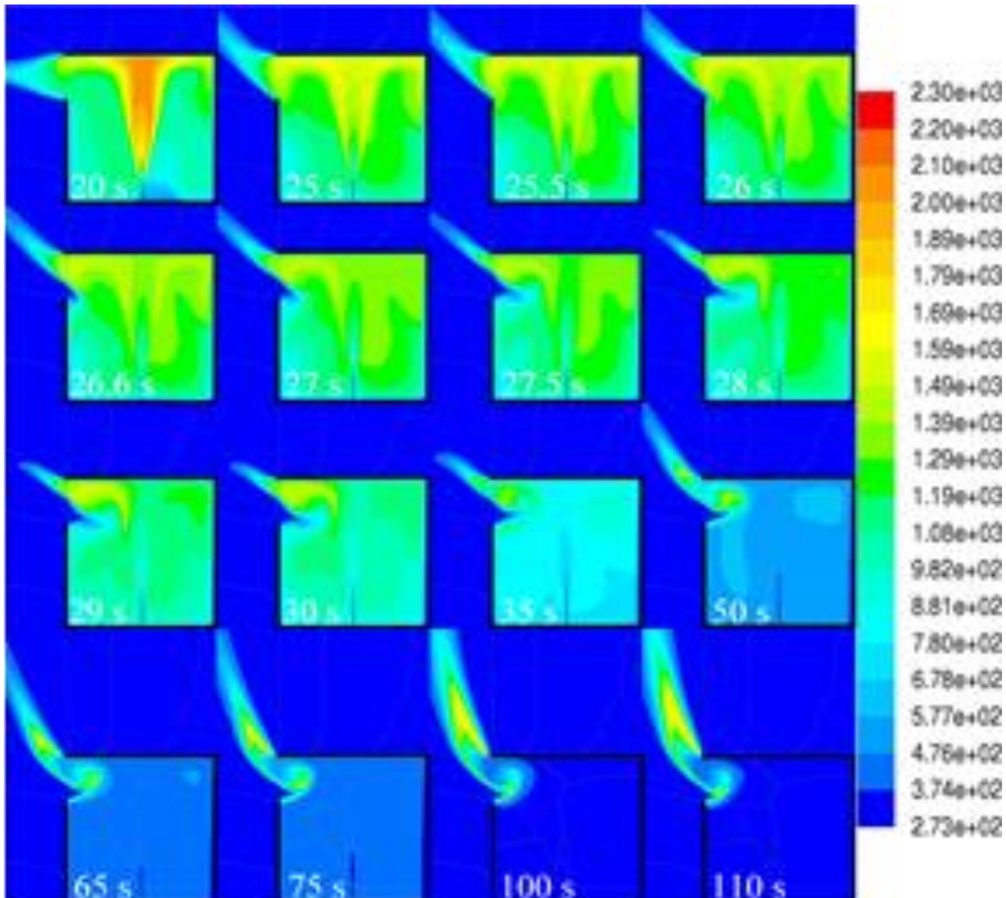
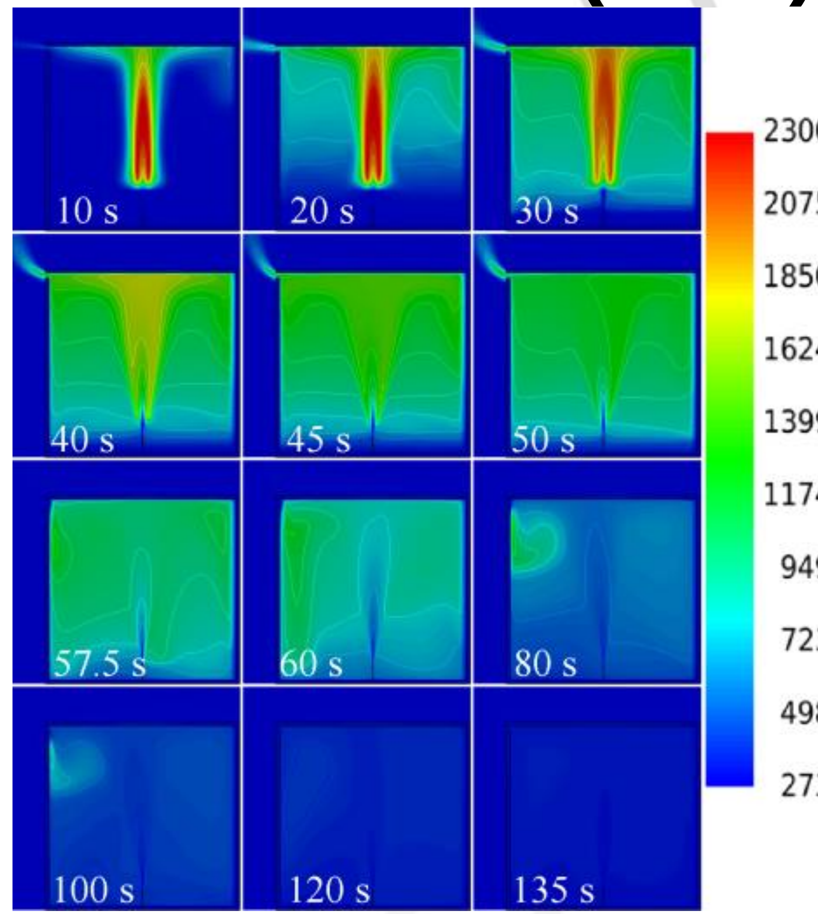
Why two modes?

External flame (No.4)



Vertical 30x3 cm	600 m/s

Self-extinction (No.2)



Horizontal 3x30 cm	300 m/s

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Self-extinction of jet fire in a 1 m^3 box

- Calculation domain hexahedron; LxWxH=7x6x4 m.
- Cubical enclosure LxWxH=1x1x1m.
- One horizontal vent HxW=0.03x0.3 m under the ceiling (“tracer box”). The vent size is calculated to ensure no air ingress after self-extinction, and that pressure peaking (unignited) is below 1 kPa.
- Mass flow rate 1 g/s (50 kW fuel cell).
- Release from a pipe of 5.08 mm diameter located 10cm above the floor.
- Box has aluminium walls of thickness 20 mm

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Hydrogen indoor fire regimes

The general rule for indoor fire with one upper vent is as follows. The increase of hydrogen release flow rate changes fire regime from:

- well-ventilated fire (small leak rates), to
- under-ventilated fire with external flame (moderate flow rates), to
- under-ventilated fire with self-extinction of combustion (higher flow rates), and again to
- under-ventilated fire with external flame (very high flow rates)

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Vented deflagrations

- Vented deflagration is based on a limiting of pressure build-up within an enclosure through the release of burned and unburned mixtures through a vent.
- If no venting is provided, the maximum pressures developed during the deflagration are typically 6 to 10 times higher than the initial absolute pressure.
- This is the most effective mitigation techniques for deflagrations. It is discussed in more detail in the Lecture ‘Dealing with hydrogen explosions’.

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Overlooked safety issue

- **Problem**: Hydrogen-powered car is in a **closed garage** of 44 m^3 free volume. Release from an onboard storage through a PRD of 5.08 mm diameter at pressure 350 bar gives mass flow rate 390 g/s (volumetric flow rate is 390/2*0.0224=**4.4 m^3/s**).
- **Consequences**: Every second of non-reacting release, pressure in the garage will increase by (44+4.4)/44=1.1 times, i.e. on 10 kPa. Civil building structures can withstand 10-20 kPa.

Thus, in 1-2 s the garage "is gone".

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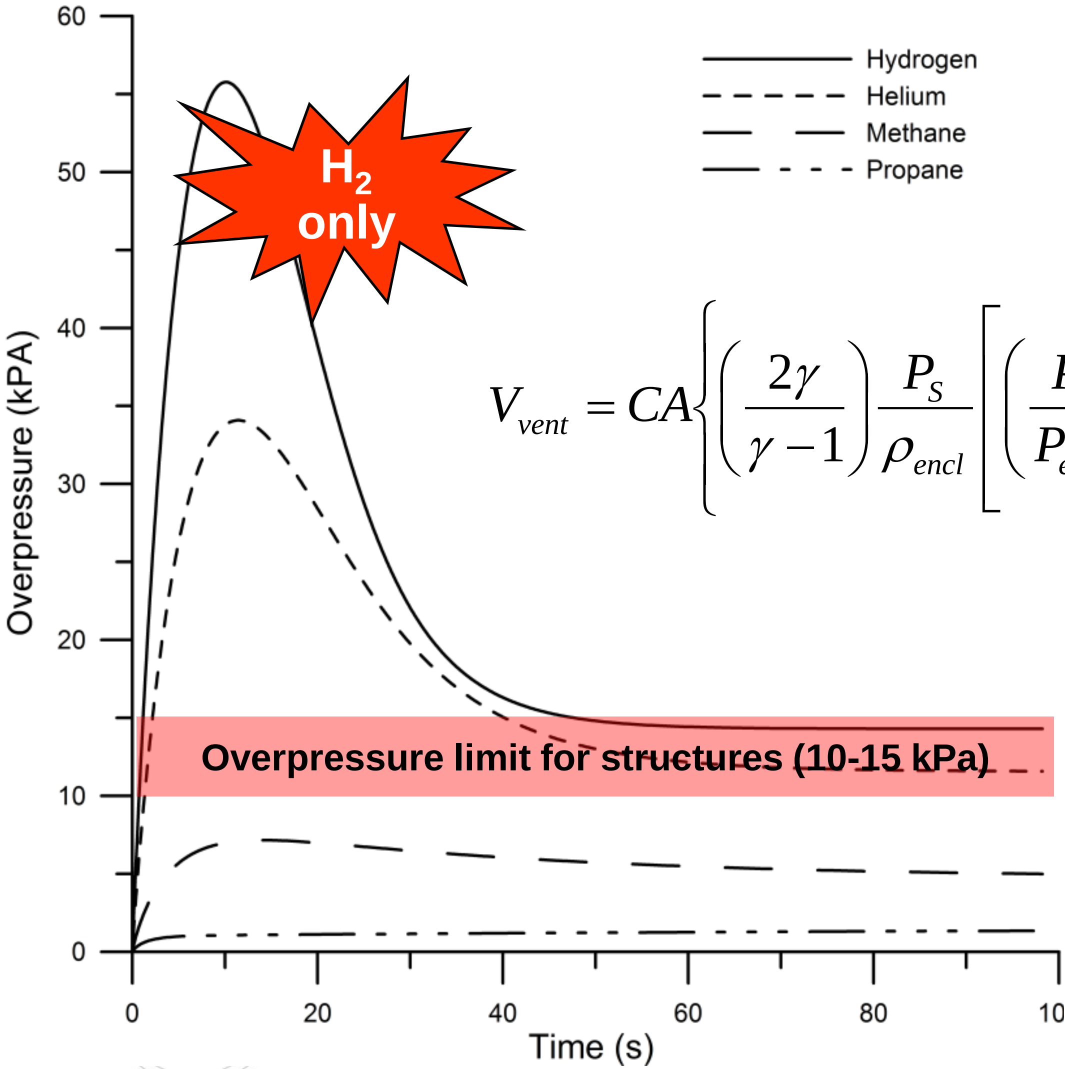
Pressure peaking phenomenon



Garage: 4.5x2.6x2.6 m with a "brick" vent.
Car: mass flow rate 390 g/s (H2: 350 bar, 5.08 mm orifice).

$$V_{vent} = CA\left\{\left(\frac{2\gamma}{\gamma-1}\right)\frac{P_S}{\rho_{encl}}\left[\left(\frac{P_S}{P_{encl}}\right)^{\frac{2}{\gamma}} - \left(\frac{P_S}{P_{encl}}\right)^{\frac{\gamma+1}{\gamma}}\right]\right\}^{\frac{1}{2}}$$

Definition: it is a transient peak in the pressure dynamics during hydrogen release in enclosures with vent(s) (Brennan and Molkov, 2013).

Solution: decrease TPRD diameter (increase fire resistance of tank).

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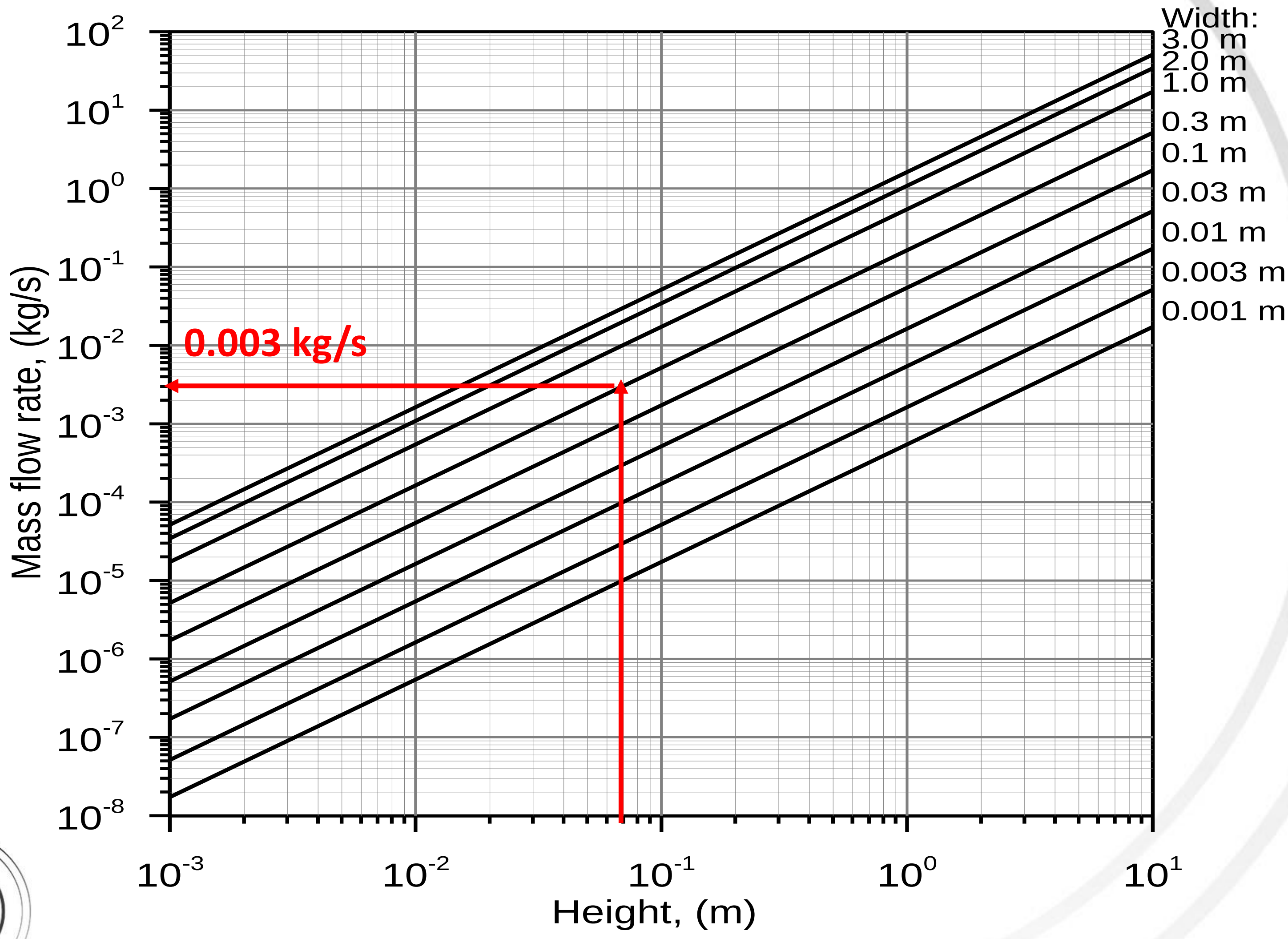
Pressure peaking phenomenon: step 1 of 2



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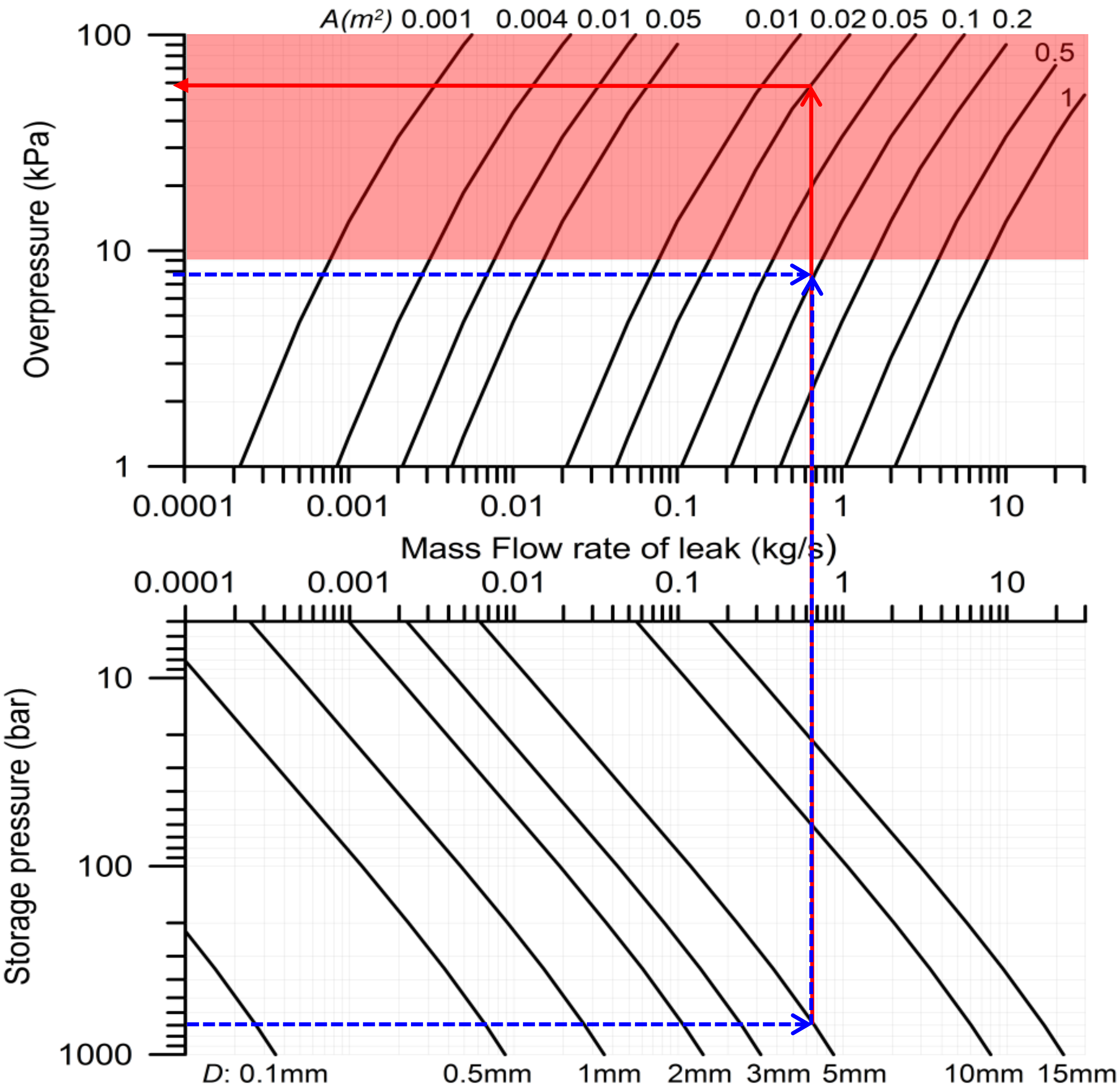
Pressure peaking phenomenon: step 2 of 2



The nomogram use:

1) Pressure p=700 bar; Orifice diameter D=5 mm Vent size area A 0.07mx0.3m=0.021 m^2 Overpressure 60 kPa

2) Overpressure 8 kPa below the limit for structures.

Then the venting area in a garage should be A=0.1 m^2, e.g. about 0.3mx0.32m (0.1mx1m).

Garages in cold climate zones would not have such large vent area (and thus would be destroyed).

Non-reacting releases.

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