Unignited hydrogen releases outdoors and their mitigation

Content

Objectives of the lecture (1/2)

1. Classify unignited hydrogen releases (leaks/jets) to distinguish between permeation leaks, sub-sonic, sonic and super-sonic jets; expanded and under-expanded jets, momentum- and buoyancy-controlled jets;
2. Evaluate hydrogen concentration decay in the momentum-controlled jets using a nomogram;
3. Predict the distance, at which hydrogen jet becomes buoyant;
4. Calculate the size of hydrogen flammable envelope, i.e. to determine the furthest point from the source of leak, at which a jet can be ignited;
5. Assess a safe size of a PRD with the view to avoid the formation of a flammable hydrogen layer under a ceiling in the enclosure;

Objectives of the lecture (2/2)

6. Calculate the blow-down time for compressed hydrogen tanks of different capacities;
7. Recognise the means of reducing hazard distances from the point of the release;
8. State the main prevention techniques for hydrogen jets;
9. Recognise the mitigation measures of hydrogen leaks consequences;
10. Point out the detection means of hydrogen releases.

Hydrogen releases

- FC vehicles have on-board hydrogen storage tanks at pressures up to 70 MPa, and a refuelling infrastructure operates at pressures up to 100 MPa.
- Due to the small size of its molecules hydrogen is prone to leak, e.g. permeation.
- The releases may originate from: valves, connections, pinholes in pipes, a full-bore pipe rupture (worst-case scenarios); cylinders, pumps, regulators, etc.
- A release of hydrogen either through a TPRD or from pipe rupture will result in a high-pressure jet.
- The releases can be unignited (non-reacting) or ignited (reacting).
- Catastrophic release of hydrogen during high-pressure tank rupture, e.g. in a fire.
- Hydrogen releases may occur both indoors and outdoors.

Typical flow rates of hydrogen releases

- **Permeation** of hydrogen, diffusion through the walls or interstices of a vessel, pipes or interface materials (SAE J2578, 2009).
- The **safe permeation rate** for FC vehicles at 20ºC is limited to 6 mL/hr per L of a storage tank capacity (The European Regulation for type approval of hydrogen-powered vehicles, 2010). For 170 L capacity – **25.3×10^{-6} g/s.**
- ISO/TS15869:2009 (JARI, 2004) – 2.0 (NmL/hr/L water capacity) @ 35 Mpa and 2.8 (NmL/hr/L water capacity) @ 70 Mpa.
- A leak from a broken pipe (150 kW FC): about **3 g/s.**
- A release via TPRD (diameter 5.08 mm) from a storage tank at 35 MPa: **390 g/s.**
- A release from an industrial pipeline (diameter 30 cm) at p=2.5 MPa: **100 kg/s.**

Permeation and dispersion (1/2)

- The **rate of hydrogen permeation** through a particular material depends on **temperature, internal pressure and the membrane thickness.** The higher is the storage pressure the higher is the permeation rate.
- Three main phenomena drive the dispersion of permeated hydrogen: **buoyancy, diffusion, and natural ventilation.**
- A permeation-induced release of hydrogen differs from plumes and jets: hydrogen releases slowly, in very small amounts, equally along the surface of a storage tank.
- Permeated hydrogen is distributed homogeneously in a garage-type enclosure.
- Maximum allowable permeation rate at 20ºC for a **passenger car** is **8 mL/hr/L** and for a **FC-bus 5 mL/hr/L** in a garage-type enclosure. **UU simulations demonstrated that with this level of permeation rate the hydrogen dispersion in a typical garage is not a problem.**

Permeation and dispersion (2/2)

Example:

Imagine you went on holidays and left your old Honda Clarity fuel cell vehicle alone in a garage for 2 weeks with the average temperature inside of 20 °C. Using maximum allowable permeation rate for Type 4 tanks according to calculate the average concentration and amount (kg) of hydrogen accumulated inside the garage due to permeation on return back, assuming it is fully sealed (ACH=0), if the tank volume is 171L and hydrogen density at 200 ° C is 0.0837535 kg/m3. The size of the garage is L x W x H =4.5 x 3 x 2.65 m^3. Show all workings (note you will need to use SI units) and conclude on safety aspects.

Using a maximum permeation rate of 8 Nml/h/L at 20 °C, the total volume of permeated hydrogen is given by:

VH_2 = permeation rate * time * volume = 8 Nml/h/L *(14*24h) *171L= 459,648 Nml = 0.459648 Nm^3

MH2 = density * volume = 0.0837535 * 0.459648 = 0.0385 kg.

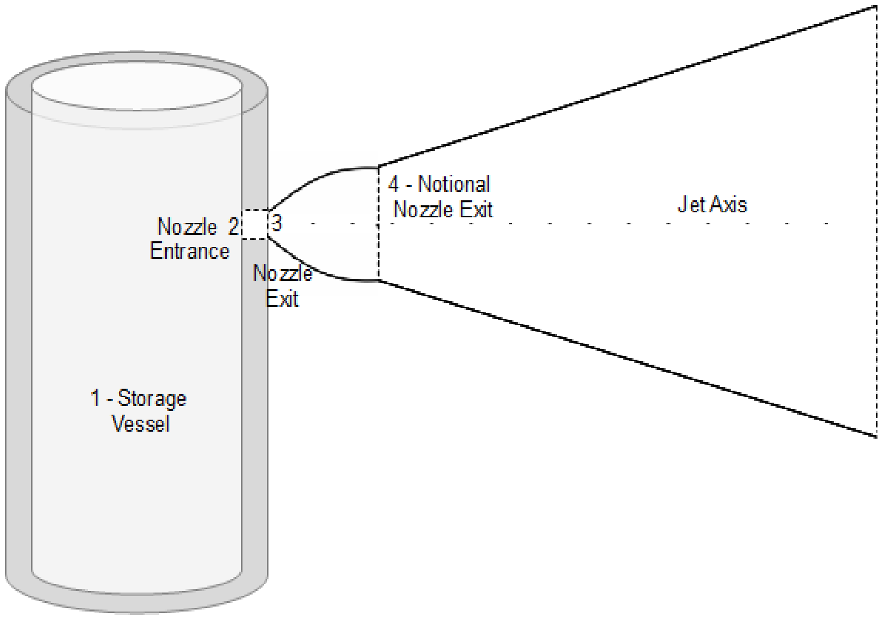
Average volume concentration is:

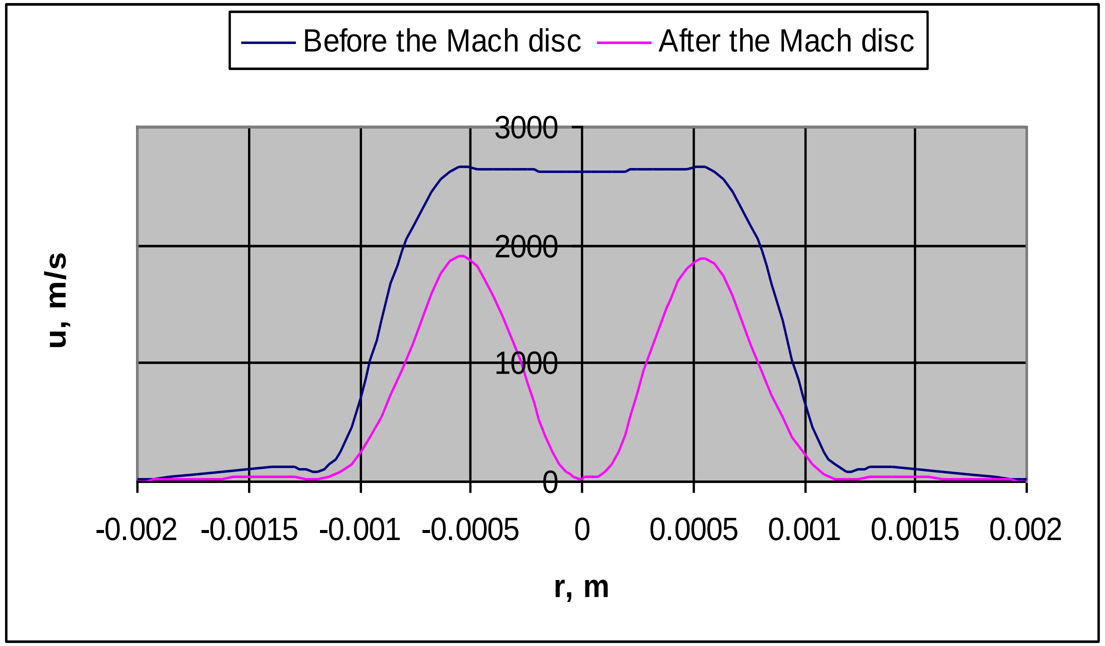
Cav= VH2 / Garage volume*100= 0.038497128768/35*100 = 1.377%

In condition of full sealed enclosure, the value of average concentration is around 35% of LFL

Expanded and under-expanded jets

- The critical ratio between storage and ambient pressures for sonic (choked) flow is about 1.9 at STP.
- The pressure ratios <1.9, the gas flow in an orifice is **expanded (subsonic)**.
- The pressure ratios >1.9, the releases are considered to be **under-expanded** (sonic “choked” flow).
- An unscheduled release from a high-pressure storage tank creates a **highly under-expanded jet.**





Unignited hydrogen releases outdoors and their mitigation

Sub-sonic, sonic and supersonic flows

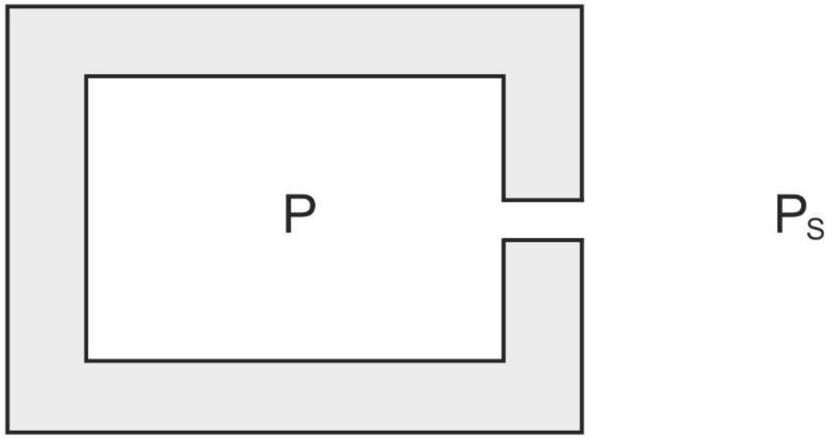
- Speed of sound: $$C = \sqrt{\gamma \frac{P}{\rho}} = \sqrt{\gamma \frac{RT}{M}}$$

γ is the ratio of the specific heats at constant pressure and constant volume.

The Mach number (M) of the jet is a dimensionless number equal to a ratio of local flow velocity to the local speed of sound. It is an important parameter in determining its behaviour.

- **Subsonic** flow: velocity *U<C, M<1*

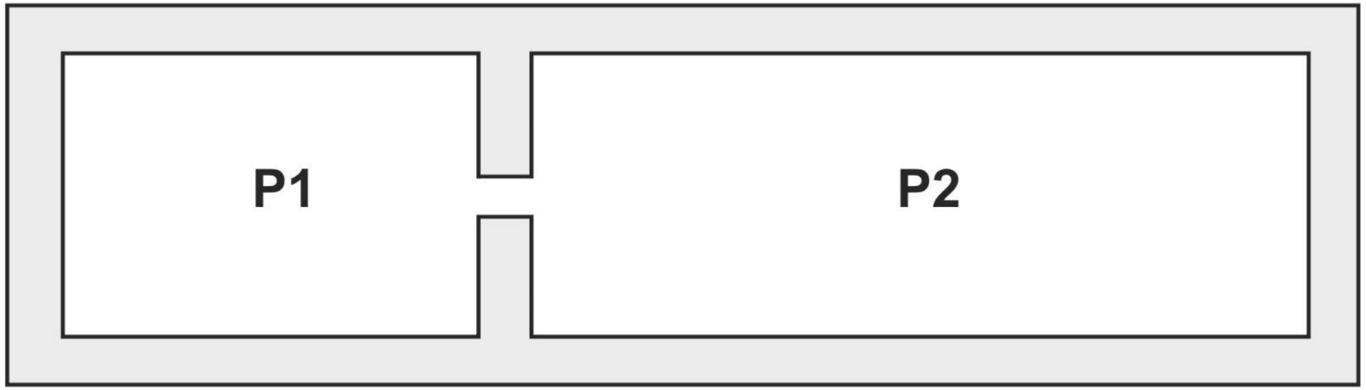
$$\frac{P_S}{P} \geq \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)} = \frac{1}{1.89}$$



- **Sonic** flow: velocity *U=C* (choked flow at the exit, *M=U/C*=1)
- **Super-sonic** flow: velocity is larger than the speed of sound (*U>C*)

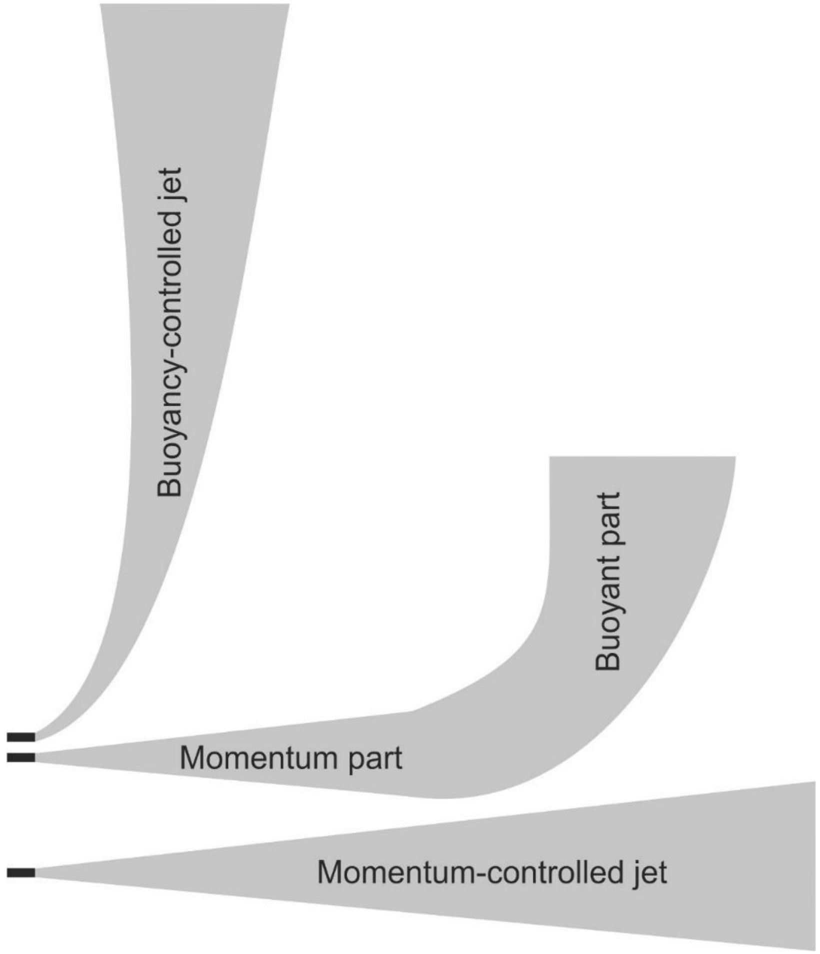
Sub-sonic, sonic and supersonic jets

- **Subsonic matched jets:** ratios of pressure in high-pressure and low-pressure chambers is P_1/P_2= **1- 4.1** (theoretical ratio P_1/P_2=1.89! ... P_1/P_N=2 and P_N/P_2=2 …)
- **Sonic under-expanded jets:** P_1/P_2 = **4.1- 41.2**
- **Supersonic under-expanded jets:** P_1/P_2 **> 41.2**



Sources: [1] Ishii et al., J. Fluid Mech., 1999, 392, pp.129-153. [2] Molkov, V (2012). Fundamentals of hydrogen safety engineering, Part I and Part II.

Momentum vs. buoyancy-controlled jets



- Fully momentum-dominated jet
- Fully buoyancy-controlled jet
- Momentum jet transits to buoyant

Hazard distance (horizontal) strongly depends on a type of jet (effect of buoyancy).

Buoyant jets decay faster than momentum jets (vertical).

The similarity law is a conservative approach

HyResponder

Unignited hydrogen releases outdoors and their mitigation

Effect of buoyancy on hazard distance – e-Laboratory

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

Login: HyResponderTrainer **Password**: safetyfirst

Effect of buoyancy on decrease of hazard distance for unignited releases

For horizontal release the distance and concentration at whichrelease becomes buoyant and hazard distance to 4% v/v along the jetcentral line

For vertical downward release the distance and concentration at which flow start to go up due to buoyancy

Units

p_1 (H2 pressure in reservoir)	Pa
T_1 (H2 temperature in reservoir)	K
d_3 (Orifice diameter)	m
p_4 (Ambient pressure)	Pa
X (Axial distance from nozzle to C_B% by vol. H_2 where release becomes buoyant.)	m
$X_{4\%}$ (Axial distance from nozzle to 4% by vol. H_2)	m
$X_{17\%}$ (Axial distance from nozzle to 17% by vol. H_2)	m
$X_{30\%}$ (Axial distance from nozzle to 30% by vol. H_2)	m
$X_{40\%}$ (Axial distance from nozzle to 40% by vol. H_2)	m
$X_{50\%}$ (Axial distance from nozzle to 50% by vol. H_2)	m
$X_{60\%}$ (Axial distance from nozzle to 60% by vol. H_2)	m

Name	Symbol	Value	Unit
H2 pressure in reservoir	p_1	7e+6	Pa
H2 temperature in reservoir	T_1	288	K
Orifice diameter	d_3	0.02	m
Ambient pressure	p_4	1.01325e+5	Pa
Axial distance from nozzle to C_B% by vol. H_2 where release becomes buoyant.	X	35.6746	m
Axial distance from nozzle to 4% by vol. H_2	$X_{4\%}$	44.2411	m
Axial distance from nozzle to 17% by vol. H_2	$X_{17\%}$	9.24329	m
Axial distance from nozzle to 30% by vol. H_2	$X_{30\%}$	4.5659	m
Axial distance from nozzle to 40% by vol. H_2	$X_{40\%}$	3.08551	m
Axial distance from nozzle to 50% by vol. H_2	$X_{50\%}$	2.43964	m
Axial distance from nozzle to 60% by vol. H_2	$X_{60\%}$	1.28028	m

Export to CSV | Change inputs | Dataset name | Save

An example of using e-Laboratory (1/3)

Practice

- What would be the distances to 4% and 30% and at what distance release becomes bouyant:

  a) 2 mm TPRD @350 Atm?

  b) 20 mm orifice @7000000 Pa?

  c) 15mm pipe @100 bar

at ambient pressure and T=20^{o}C?

Hy Responder

Unignited hydrogen releases outdoors and their mitigation

An example of using e-Laboratory (2/3)

H2 pressure in reservoir

p_1 7000000 Pa

H2 temperature in reservoir

T_1 288 K

Orifice diameter

d_3 0.02 m

Ambient pressure

p_4 101325 Pa

Calculate Reset

Name	Symbol	Value	Unit
H2 pressure in reservoir	p_1	7e+6	Pa
H2 temperature in reservoir	T_1	288	K
Orifice diameter	d_3	0.02	m
Ambient pressure	p_4	1.01325e+5	Pa
Axial distance from nozzle to C_B% by vol. H_2 where release becomes buoyant.	X	35.6746	m
Axial distance from nozzle to 4% by vol. H_2	$X_{4\%}$	44.2411	m
Axial distance from nozzle to 17% by vol. H_2	$X_{17\%}$	9.24329	m
Axial distance from nozzle to 30% by vol. H_2	$X_{30\%}$	4.5659	m
Axial distance from nozzle to 40% by vol. H_2	$X_{40\%}$	3.08551	m
Axial distance from nozzle to 50% by vol. H_2	$X_{50\%}$	2.43964	m
Axial distance from nozzle to 60% by vol. H_2	$X_{60\%}$	1.28028	m

The distance to 4% concentration at buoyant regime is 42.36m.

Export to CSV Change inputs Dataset name

At which distance and concentration release becomes buoyant for horizontal release

Name	Symbol	Value	Unit
H2 pressure in reservoir	p_1	7e+6	Pa
H2 temperature in reservoir	T_1	288	K
Orifice diameter	d_3	0.02	m
Ambient pressure	p_4	1.01325e+5	Pa

The distance from the nozzle to the turning point is 35.67m concentration for vertical release is 13.79%.

Export to CSV Change inputs Dataset name

At which distance and concentration release becomes buoyant for downward release

An example of using e-Laboratory (3/3)

Practice clue

a) 2 mm TPRD @350 Atm: **release is fully momentum!**

b) 20 mm orifice @7000000 Pa:
   - **4%=44.2m**
   - **30%=4.5m**
   - **buoyant @35.9m**

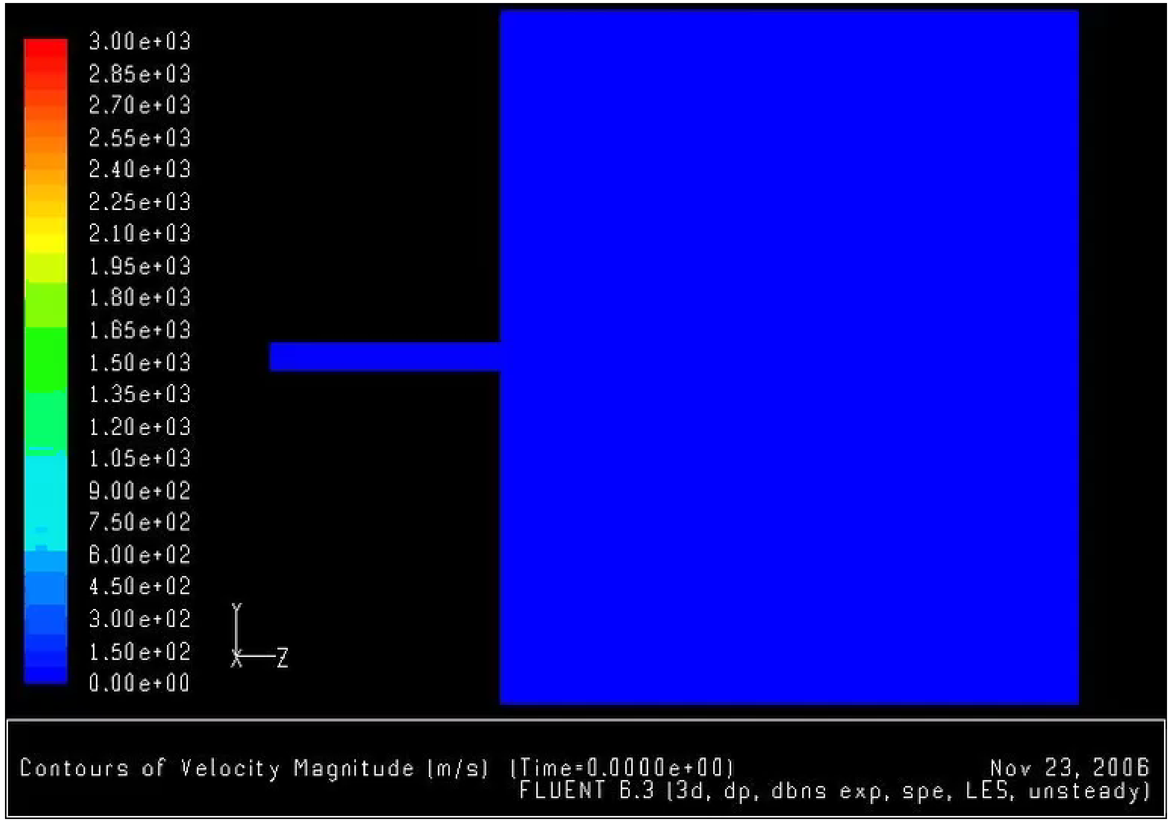
c) 15mm pipe @100 bar
   - **4%=39.4m**
   - **30%=4.07m**
   - **buoyant @33.8m**

Unignited hydrogen releases outdoors and their mitigation

Under-expanded jets: simulations (1/2)

- Tank pressure **16.1 MPa**
- Nozzle diameter **0.25 mm**
- Mass flow rate **0.46 g/s**
- **Simulations videos:**
  - *Velocity*
  - *Hydrogen mole fraction*
  - *Temperature*
- Concentration of hydrogen in a jet decays from 100% at the nozzle (point of leak) to the lower values along the jet axis.

Velocity profile

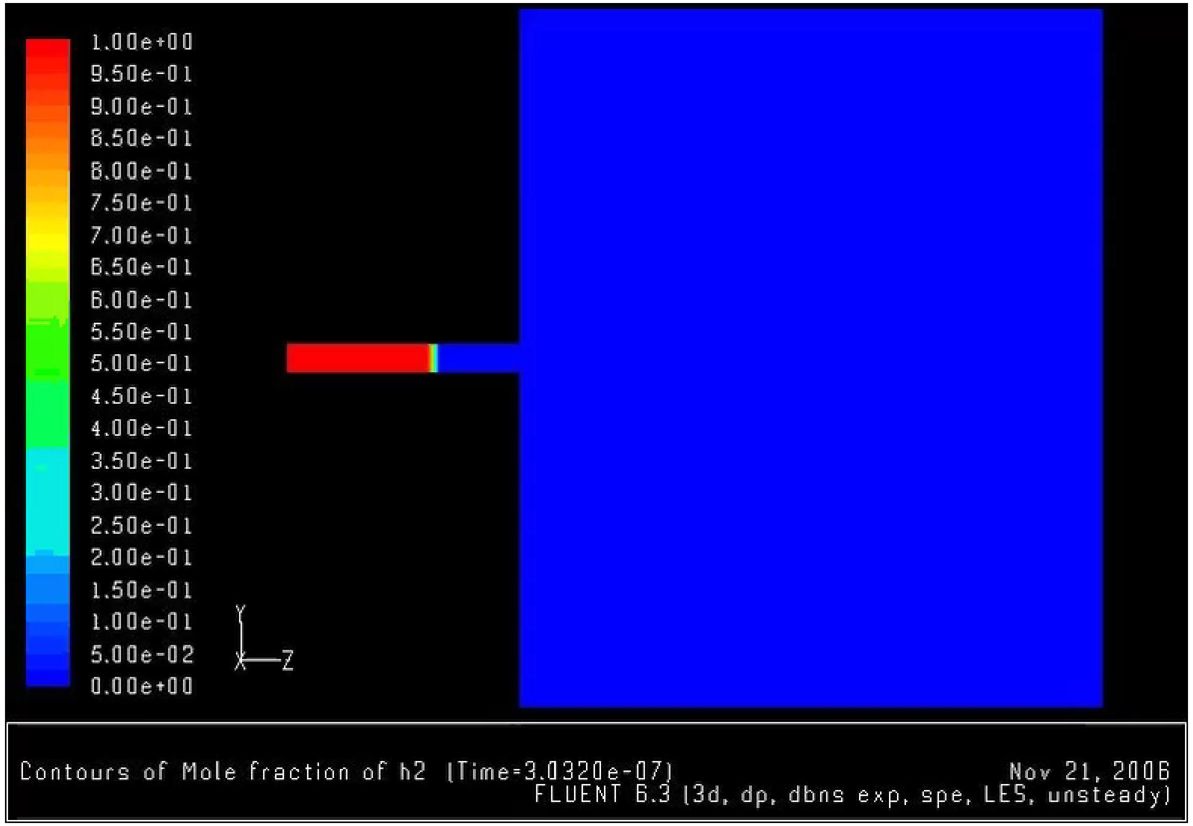


https://www.youtube.com/watch?v=j1Te8HaS5Sw&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=1

Unignited hydrogen releases outdoors and their mitigation

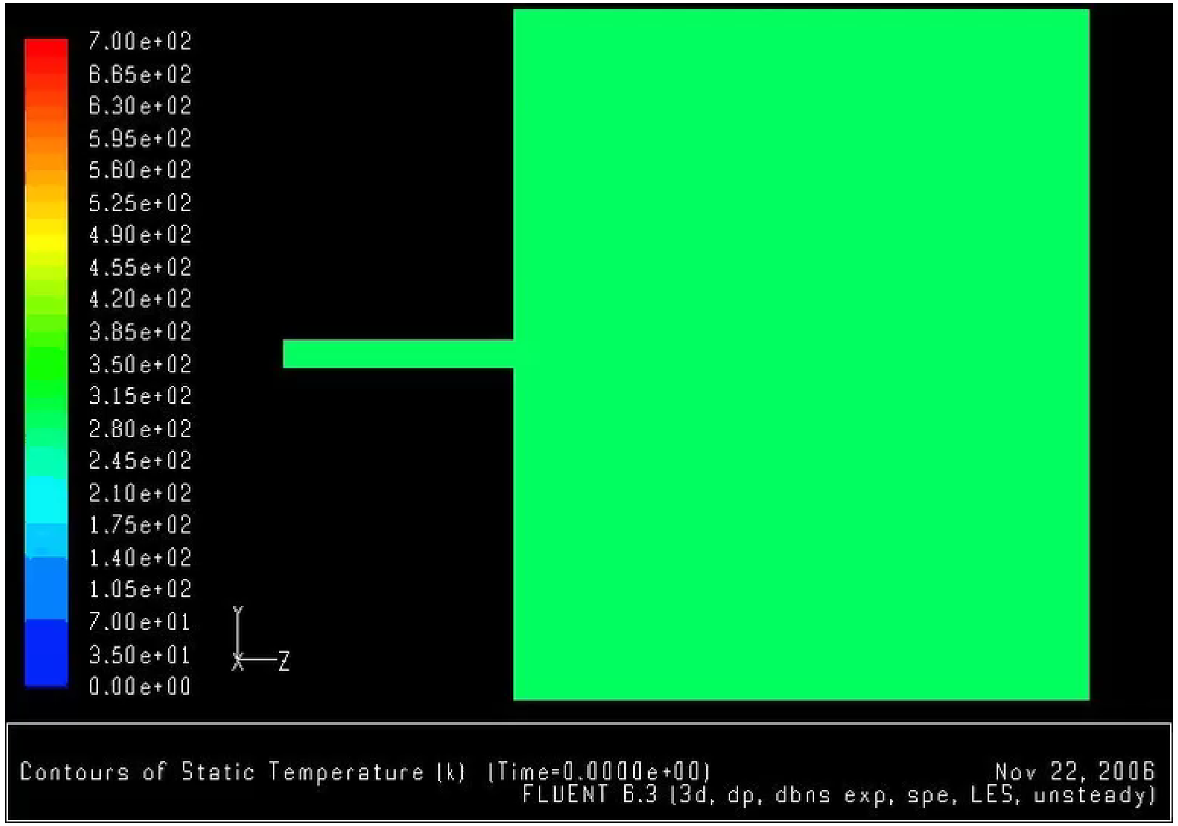
Under-expanded jets: simulations (2/2)

Hydrogen mole fraction profile



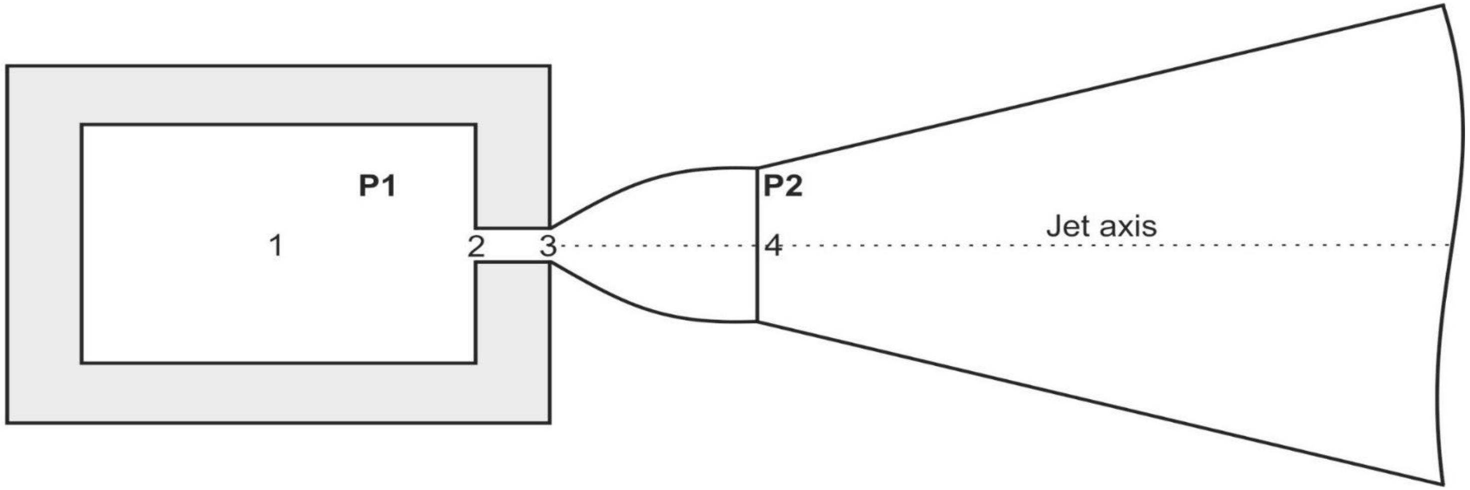
https://www.youtube.com/watch?v=7Csmssa24WA&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=5

Temperature profile



https://www.youtube.com/watch?v=xLsfa3CcZaY&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=7

The expanded and under-expanded jet scheme



1- High pressure vessel

2- Nozzle entrance

3- Nozzle exit (= notional nozzle entrance)

4- Notional (effective) nozzle exit (3-4: no entrainment)

The notional nozzle exit, 4, parameters correspond to fully expanded jet with the pressure equal to ambient and uniform flow velocity equal to local speed of sound. In some cases, there can be essential minor and friction losses in the flow pathway 2-3 that cannot be neglected, e.g. the case of very narrow crack.

P1 Storage pressure

P2 Atmospheric pressure (after jet expansion)

Flammable envelope

As discussed previously **combustion** is generally of a primary concern when considering harm criteria. In the event of an unscheduled hydrogen release, a **flammable jet** may result. In the event of its subsequent ignition people, structures, equipment and environment may be involved in a fire.

Thus, it is important to determine the furthest point from the leak, at which a jet can be ignited. This is generally defined by hydrogen concentration of 4 vol. %, i.e. by the lower flammability limit (LFL).

Although this choice of hydrogen content is subject to debate direct flame contact as a result of a flash fire will also occur if a person is within the 4 vol. % hydrogen envelope when hydrogen ignition occurs.

The flammable envelope size, i.e. distance to LFL of 4 vol. %, increases proportionally to the diameter of the leak.

What is a hazard distance?

- As per draft definition, ISO TC197 **hazard distance** is a distance from the (source of) hazard to a determined (by physical or numerical modeling, or by a regulation) physical effect value (normally, thermal or pressure) that may lead to a harm condition (ranging from “no harm” to “max harm”) to people, equipment or environment.

- The following factors affect the hazard distances:
  - the nature of the hazard,
  - The operating conditions and the design of the analysed equipment/facility,
  - the type of target/object (people, structures, equipment)
  - the environment between the latter and the source of hazard. In this way, the **harm potential** for people or structures can be evaluated and compared with **the harm criteria**.

Sources: LaChance, J (2009). Risk-informed separation distances for hydrogen refuelling stations. International Journal of Hydrogen Energy, Vol. 34, pp. 5838-5845.
EIGA Determination of safety distances, IGC Doc 75/07/E, Revision of Doc 75/07/rev.

Hydrogen concentration decay

- In order to define where the flammable hydrogen-air mixture is formed it is important to know how the concentration decays, from a 100 vol. % at the nozzle to a concentration of interest at a distance *x*.
- The original form of the **similarity law** (expanded jets) by Chen and Rodi (1980):

$$C_{ax,m} = 5.4\sqrt{\frac{\rho_N}{\rho_S}}\frac{D}{x}$$

The mass fraction of leaking gas → $C_{ax,m}$

The nozzle diameter → D

Distance from the nozzle → x

Density of the surrounding gas (i.e. air = 1.205 kg/m^3) → ρ_S

with **the only** one **unknown** parameter for under-expanded jets ρ_N - **density in the nozzle** (actual nozzle size is applied here).

The "unknown" density is calculated by the **under-expanded jet theory** developed at Ulster University (ρ_N affects the flammable envelope size of 4 vol. % i.e. 0.00288 mass fraction).

A simple estimate of density in the nozzle: $\rho_N = (\frac{p_1}{2} \times \rho_{H2}^{NTP})$

Useful information

- The mass fraction (C_m) calculated based on the volumetric (mole) fraction (C_V):

$$1/C_m = 1 + (1/C_V - 1) M_S / M_N,$$

where M_S and M_N are molecular masses of surrounding gas (air) and nozzle gas, respectively.

- The mass fraction of **0.0282** corresponds to the volumetric fraction of **0.295** (*stoichiometric mixture hydrogen-air*); the mass fraction of **0.044365** corresponds to the volumetric fraction of **0.401** (*maximum burning velocity*), **0.013037 – 0.16**, **0.008498 – 0.11**, **0.005994 – 0.08**, **0.00288 – 0.04 (***LFL***)**, **0.00141 – 0.02 (***1/2 of LFL***)**, **0.0007 – 0.01 (***1/4 LFL***)**.

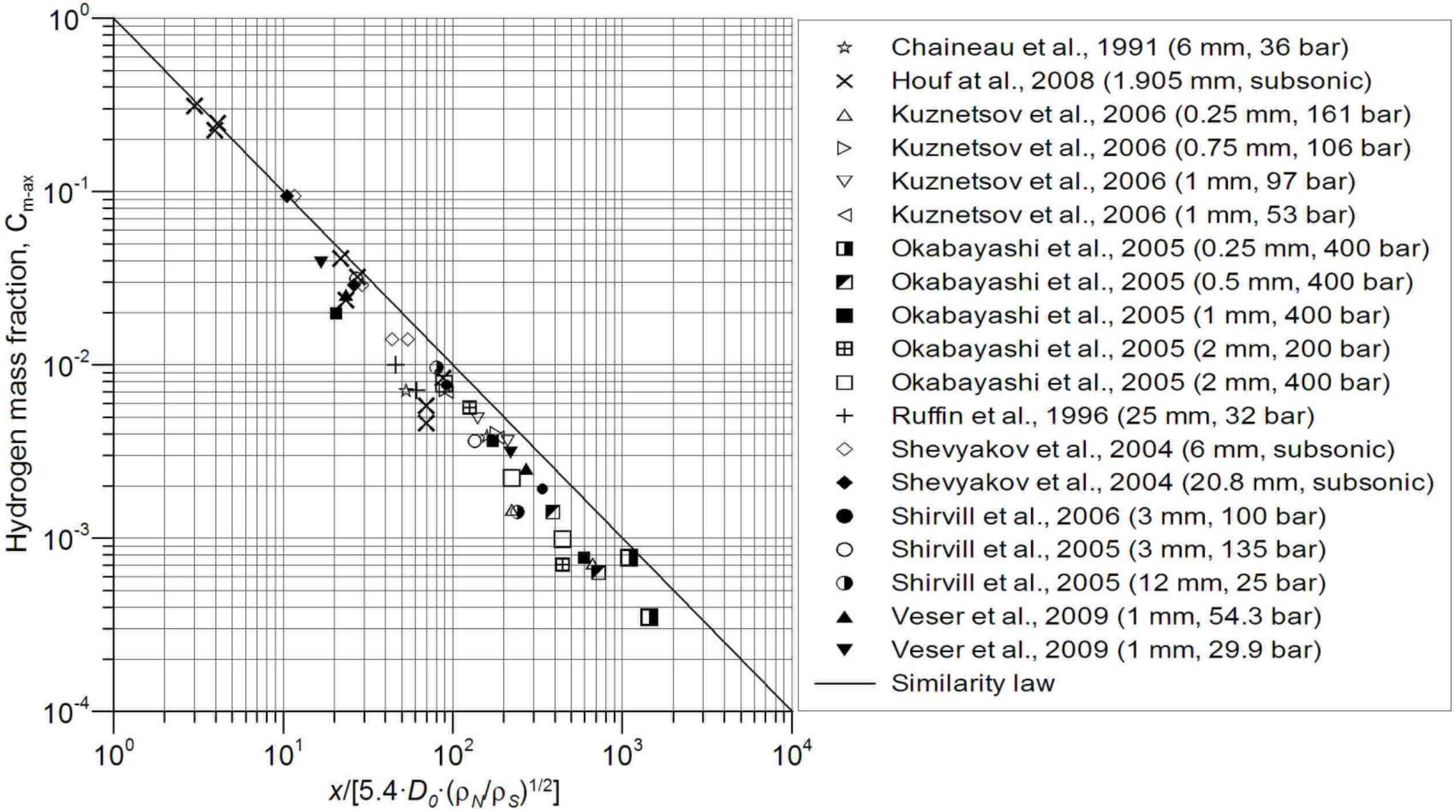
What is axial concentration of interest?

- The ratio of distance *x* to a concentration of interest to a nozzle diameter *D* (*x/D*): (with ρ_S/ρ_N=14.38, because ρ_N=0.0838 kg/m^3, ρ_S=1.205 kg/m^3 **in the case of fully expanded flow in a real nozzle**):
- $x/D_{30\%}$=49.1; $x/D_{4\%}$=491; $x/D_{2\%}$=1003; $x/D_{1\%}$=2019
- 30 vol. % stoichiometric hydrogen-air mixture
- 4 vol. % is LFL of hydrogen in air
- 2 vol. % - UK regulator applies 50% of LFL (alarm)
- 1 vol. % - shut-down systems.

Unignited hydrogen releases outdoors and their mitigation

How to calculate jet concentration decay?

The similarity law is conservative to tests - effect of losses

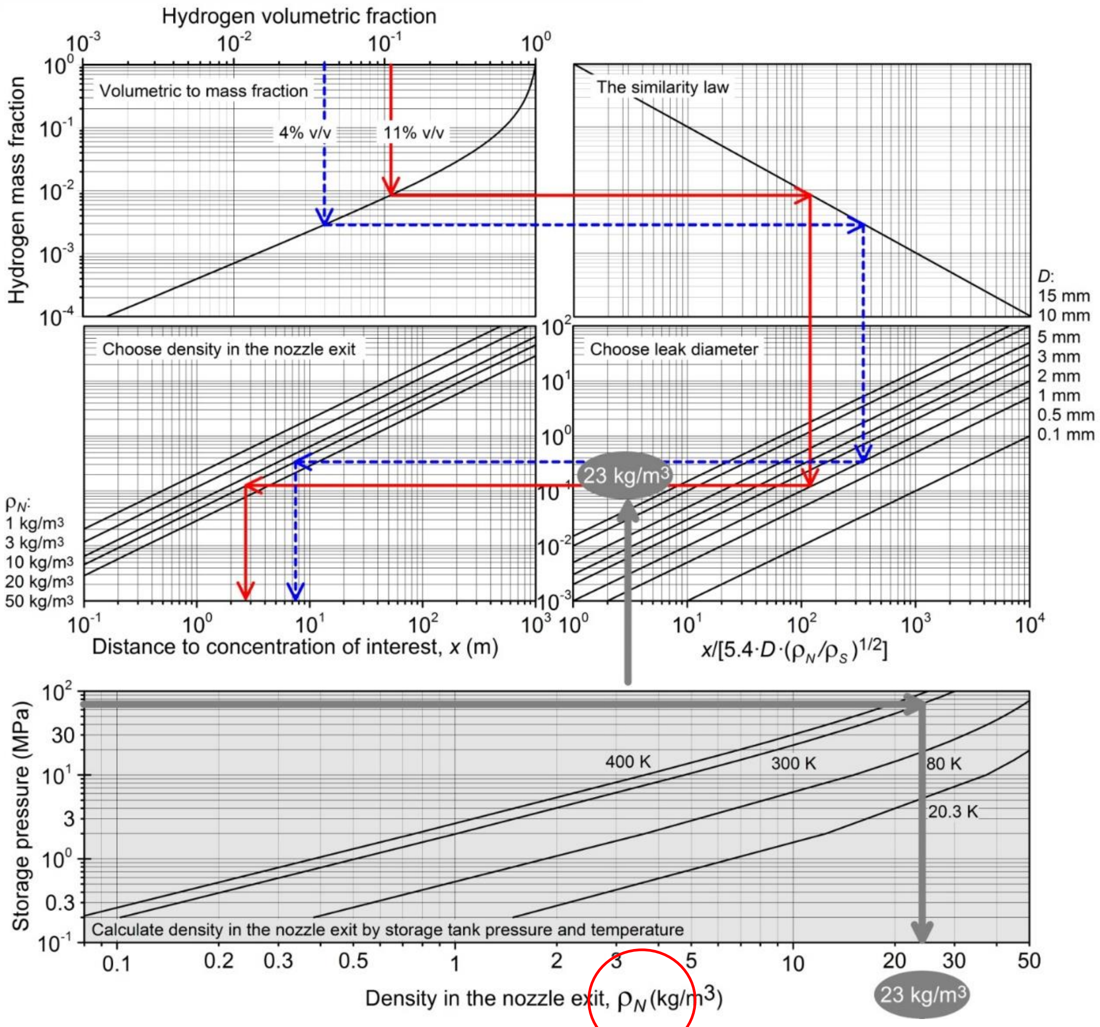


Distance to 4 vol. %:

$$x_{4\%} = 1708 \cdot \sqrt{\rho_N} \cdot D$$

Unignited hydrogen releases outdoors and their mitigation

Concentration decay in unignited jets: nomogram



$$C_{ax}^{m} = 5.4\sqrt{\frac{\rho_N}{\rho_S}}\frac{D}{x}$$

1. Choose the studied hydrogen volume fraction -> workout the mass fraction.
2. According to the similarity law -> $x/[5.4D(\rho_N/\rho_S)^{1/2}]$.
3. Choose the storage pressure -> workout the density in the nozzle exit, ρ_N.
4. Work out the distance to concentration of interest, x

Unignited hydrogen releases outdoors and their mitigation

Similarity law for concentration decay – e-Laboratory

Similarity law for concentration decay in hydrogen expanded and under-expanded jets and unignited jet hazard distances

Similarity law for concentration decay in hydrogen expanded and under-expanded jets and unignited jet hazard distances

H2 pressure in reservoir

p_1 35000000 Pa

H2 temperature in reservoir

T_1 293 K

Orifice diameter

d_3 0.005 m

Ambient pressure

p_4 101325 Pa

Ambient temperature

T_{atm} 293 K

Calculate Reset

Name	Symbol	Value	Unit
H2 pressure in reservoir	p_1	3.5e+7	Pa
H2 temperature in reservoir	T_1	293	K
Orifice diameter	d_3	0.005	m
Ambient pressure	p_4	1.01325e+5	Pa
Ambient temperature	T_{atm}	293	K
Axial distance from nozzle to 4% by vol. H2	$X_{4\%,H_2}$	32.6212	m
Axial distance from nozzle to 8% by vol. H2	$X_{8\%,H_2}$	15.6793	m
Axial distance from nozzle to 11% by vol. H2	$X_{11\%,H_2}$	11.0593	m
Axial distance from nozzle to 16% by vol. H2	$X_{16\%,H_2}$	7.20885	m
Axial distance from nozzle to 29.5% by vol. H2	$X_{29.5\%,H_2}$	3.33269	m
Axial distance from nozzle to ?% by vol. H2	$X_{?\%,H_2}$	5.50167	m

Export to CSV Change inputs Dataset name Save

Unignited hydrogen releases outdoors and their mitigation

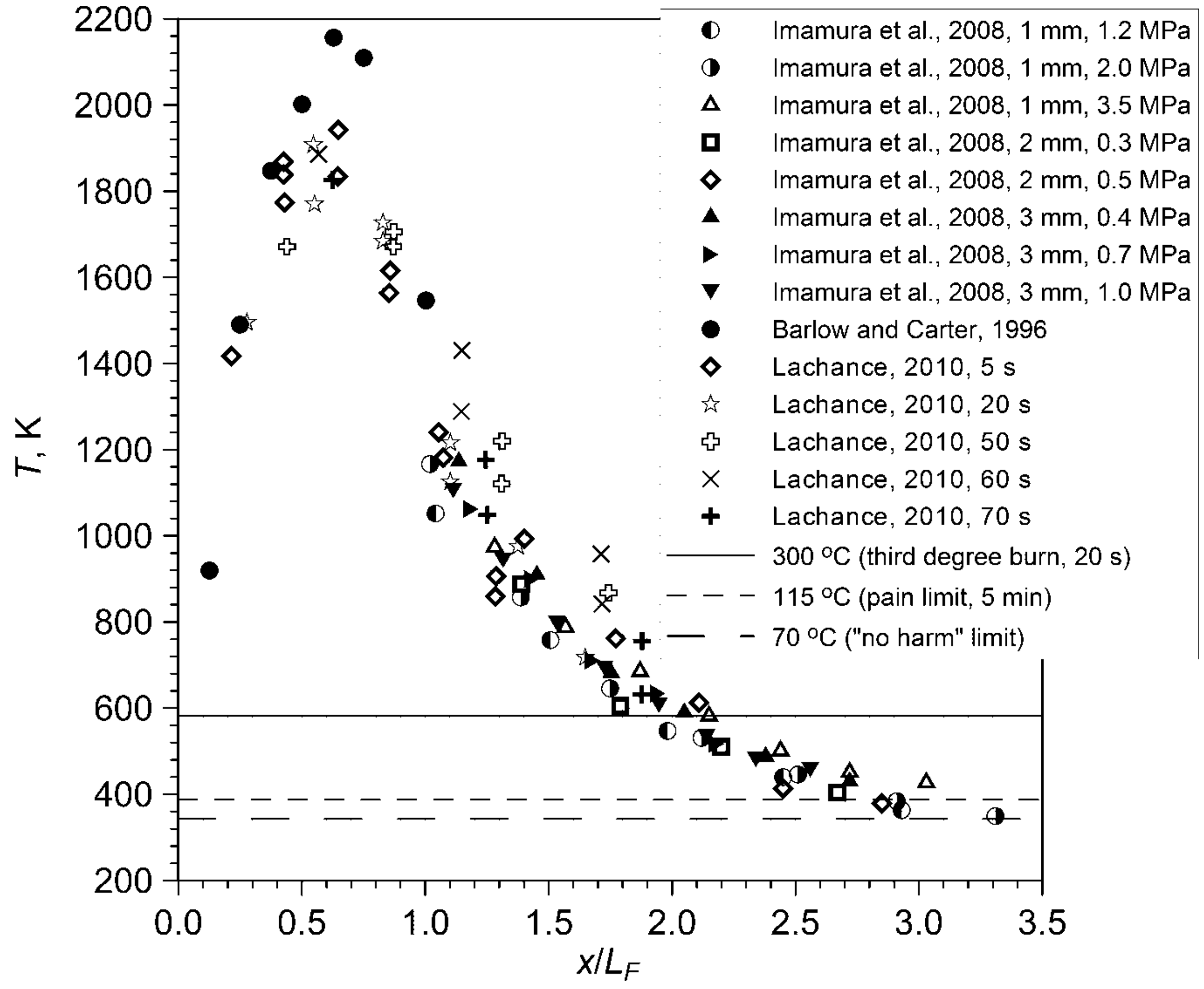
Temperature decay along jet fire axis

- **Momentum-dominated leak**
- **Jet fires (three hazard distances):**

$x = 3.5L_F$ for "no harm" (70 °C)

$x = 3L_F$ for pain limit (115 °C, 5 min)

$x = 2L_F$ for third degree burns (309°C, 20 s)



Unignited versus ignited jets

$$x_{4\%} = 1708 \cdot \sqrt{\rho_N} \cdot D$$

The ratios of a hazard distance to *LFL* (non-reacting jet) to three hazard distances based on the choice of harm criteria for jet fire are (**average flame tip location 11 vol. %** in non-reacting jet):

$x_{4\%}/x_{T=70C}=x_{4\%}/(3.5 \cdot x_{11\%})$=2.95/3.5=0.84 ("no harm");

$x_{4\%}/x_{T=115C}$= 2.95/3=0.98 ("pain limit");

$x_{4\%}/x_{T=309C}$ =2.95/2=1.48 ("death limit" – unprotected).

In the conservative case (**flame tip location 8 vol. %**) these ratios:

$x_{4\%}/x_{T=70C(8\%)}$=2.08/3.5=0.59 ("no harm");

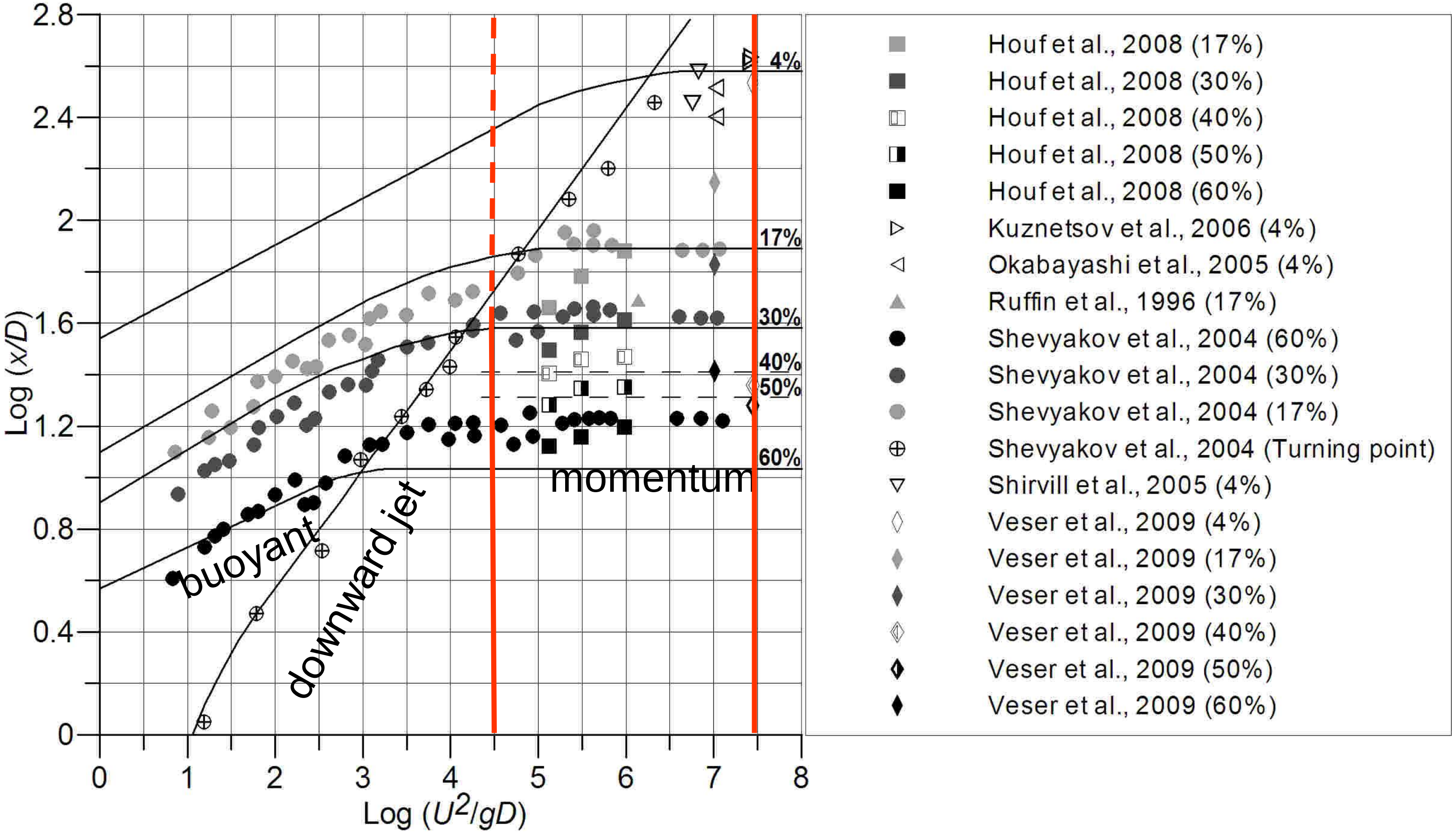
$x_{4\%}/x_{T=115C(8\%)}$=2.08/3=0.69 ("pain limit");

$x_{4\%}/x_{T=309C(8\%)}$ =2.08/2=1.04 ("death limit" – unprotected).

"Unexpected" conclusion - in the conservative case all three distances for jet fire are either longer or equal to the hazard distance based on LFL (non-reacting release).

Unignited hydrogen releases outdoors and their mitigation

When a jet becomes buoyant?



Start from the Froude number:

$Fr=U^2/gD$ (*U* and *D* real or notional nozzle)

Buoyant part of jet

Momentum part of jet

What is a safe TPRD diameter for FC forklifts?

- A forklift in a warehouse
- **Safety strategy:** in a case of upward release from the forklift on-board storage at p=**35 MPa** we would like to exclude formation of a flammable layer under a ceiling (**10 m** above the TPRD).
- To realize this strategy the concentration on the jet axis at distance 10 m should be equal or below 4 vol. % (mass fraction C_{ax}=0.00288).
- The under-expanded jet theory gives ρ_N **= 14.4 kg/m³** for storage pressure 35 MPa. Thus, the **TPRD diameter** can be calculated straight forward from the similarity law as **1.5 mm**

$$D = \frac{C_{ax}}{5.4}\sqrt{\frac{\rho_S}{\rho_N}}x = \frac{0.00288}{5.4}\sqrt{\frac{1.205}{14.4}}10 = 0.0015m$$

Blow-down of compressed hydrogen storage tank

- An adiabatic blow-down of the on-board storage tank

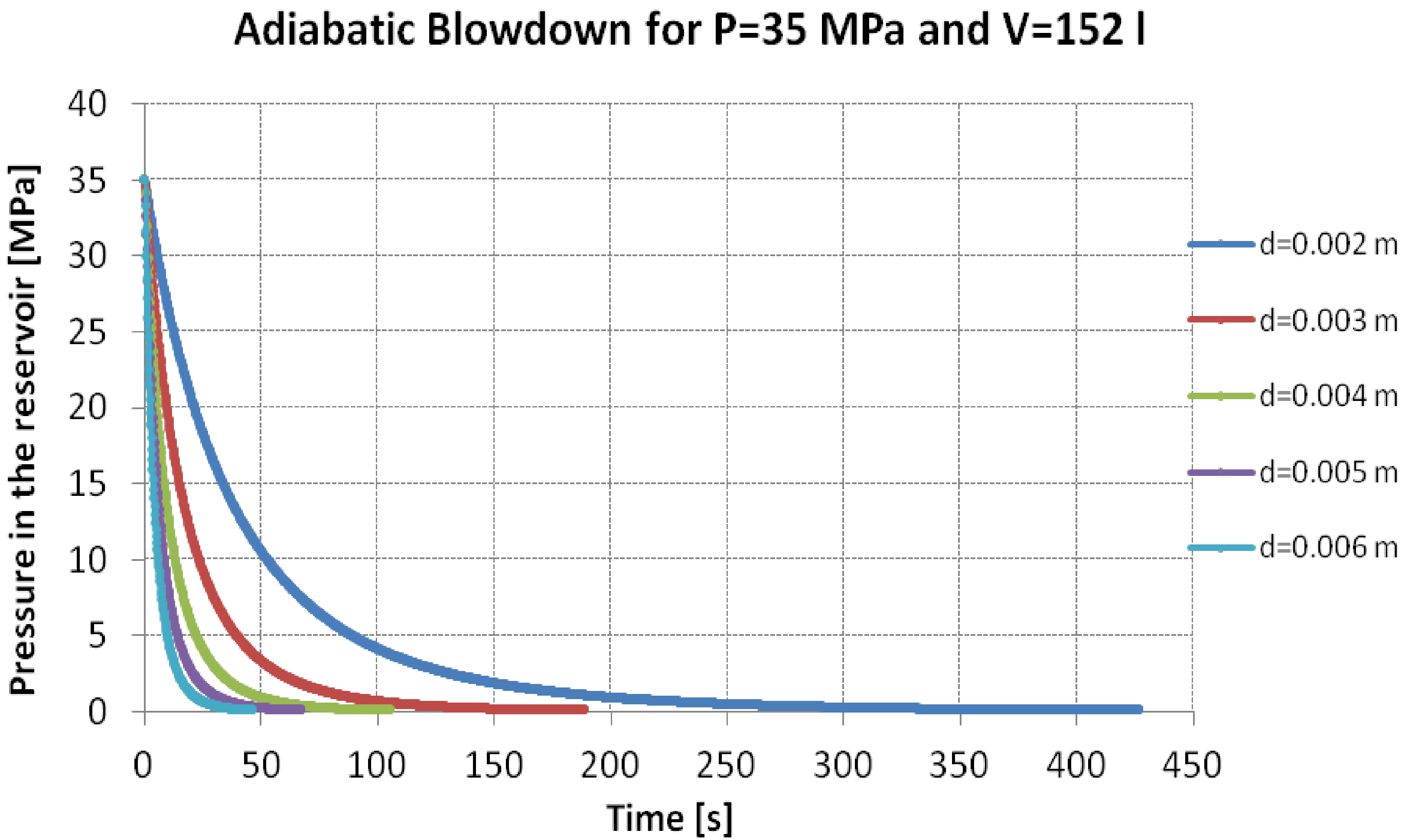
Veh	Manufacturer	Model	Pressure [MPa]	Volume [L]	Weight [kg]	Status
1	Hyundai	Tucson Hybrid FCEV	35	152	3.6	Demonstration
2	VW	Touran HyMotion	35	81	1.9	Prototype
3	Toyota	FCHV-adv (2008)	70	156	6.2	Prototype
4	VW	Tiguan HyMotion	70	81	3.2	Vehicle Testing

Leakage diameter [mm]	Blowdown time vehicle 1 [s]	Blowdown time vehicle 2 [s]	Blowdown time vehicle 3 [s]	Blowdown time vehicle 4 [s]
2	427	226	502	260
3	189	100	222	115
4	105	56	124	64
5	67	35	79	41
6	46	24	54	28

Hy Responder

Unignited hydrogen releases outdoors and their mitigation

Pressure drop inside the tanks during the blow-down

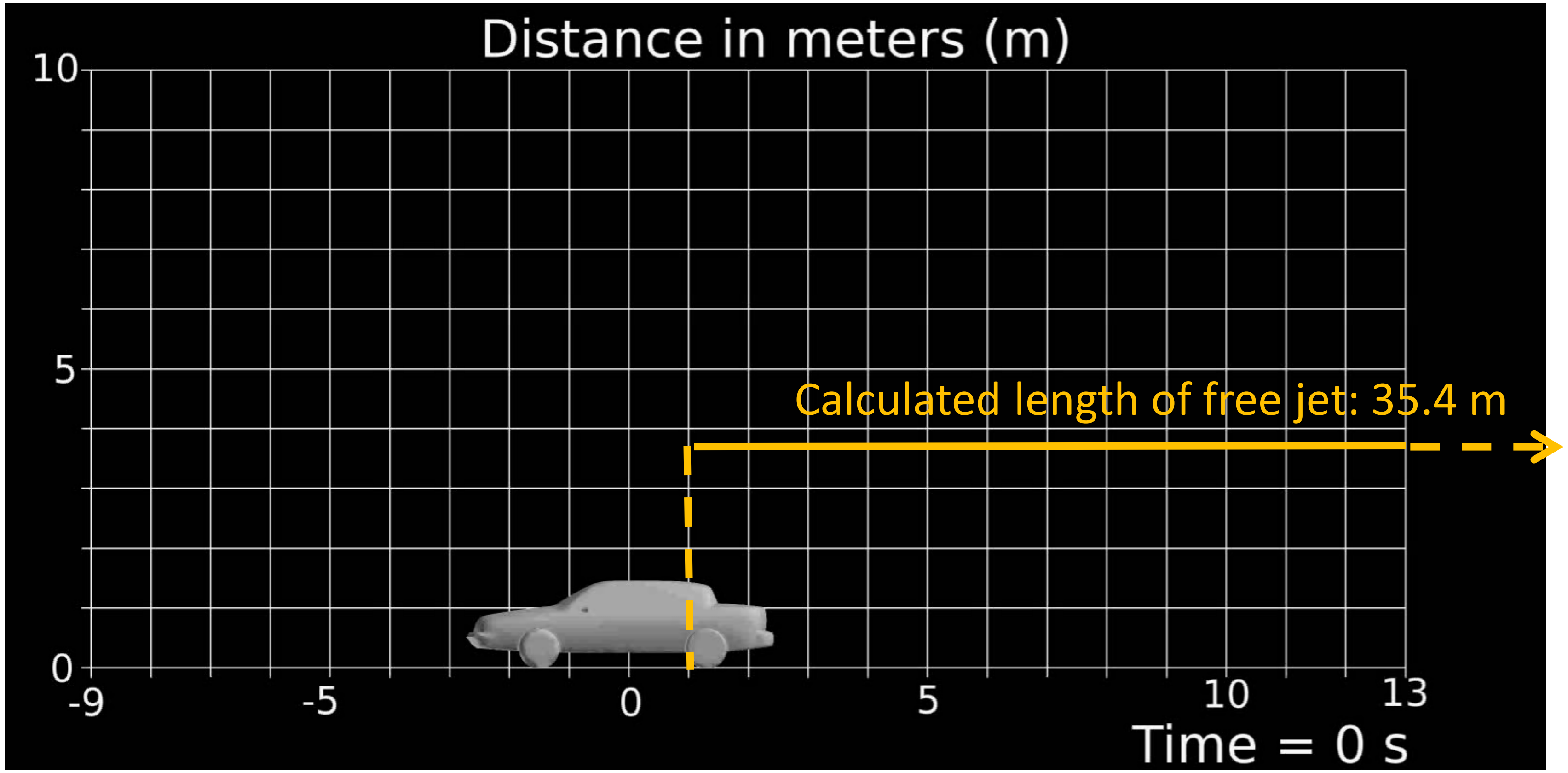


Hy Responder

Unignited hydrogen releases outdoors and their mitigation

Unignited release: 70 MPa

- 4 vol. % envelope
- 4.2 mm release diameter



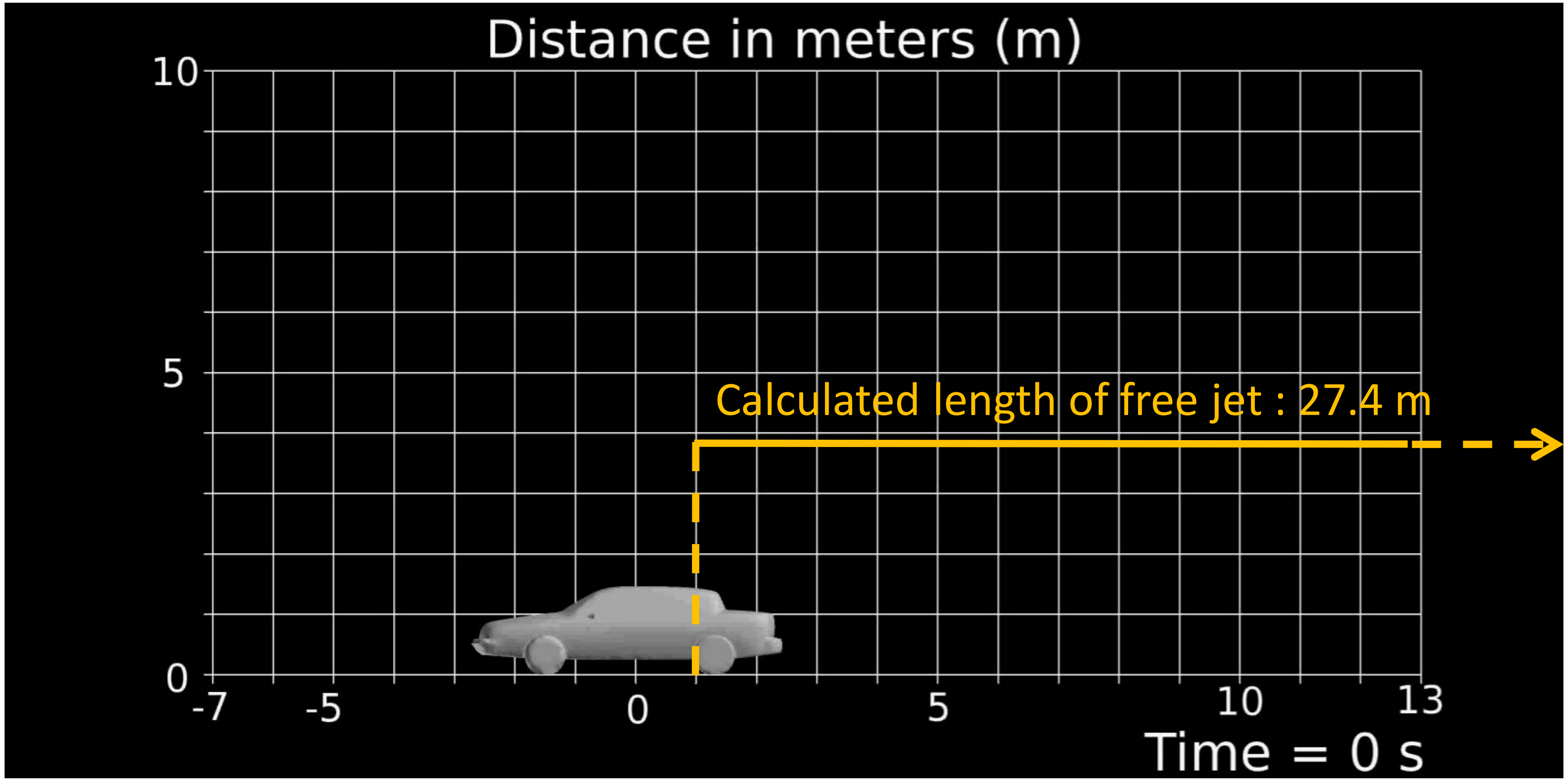
https://www.youtube.com/watch?v=Lml4dAODSGU&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=2

The largest flammable envelope occurs within 10 s – around **12 m**

Unignited hydrogen releases outdoors and their mitigation

Unignited release: 35 MPa

- Side view (4 vol. % envelope)
- 4.2 mm release diameter



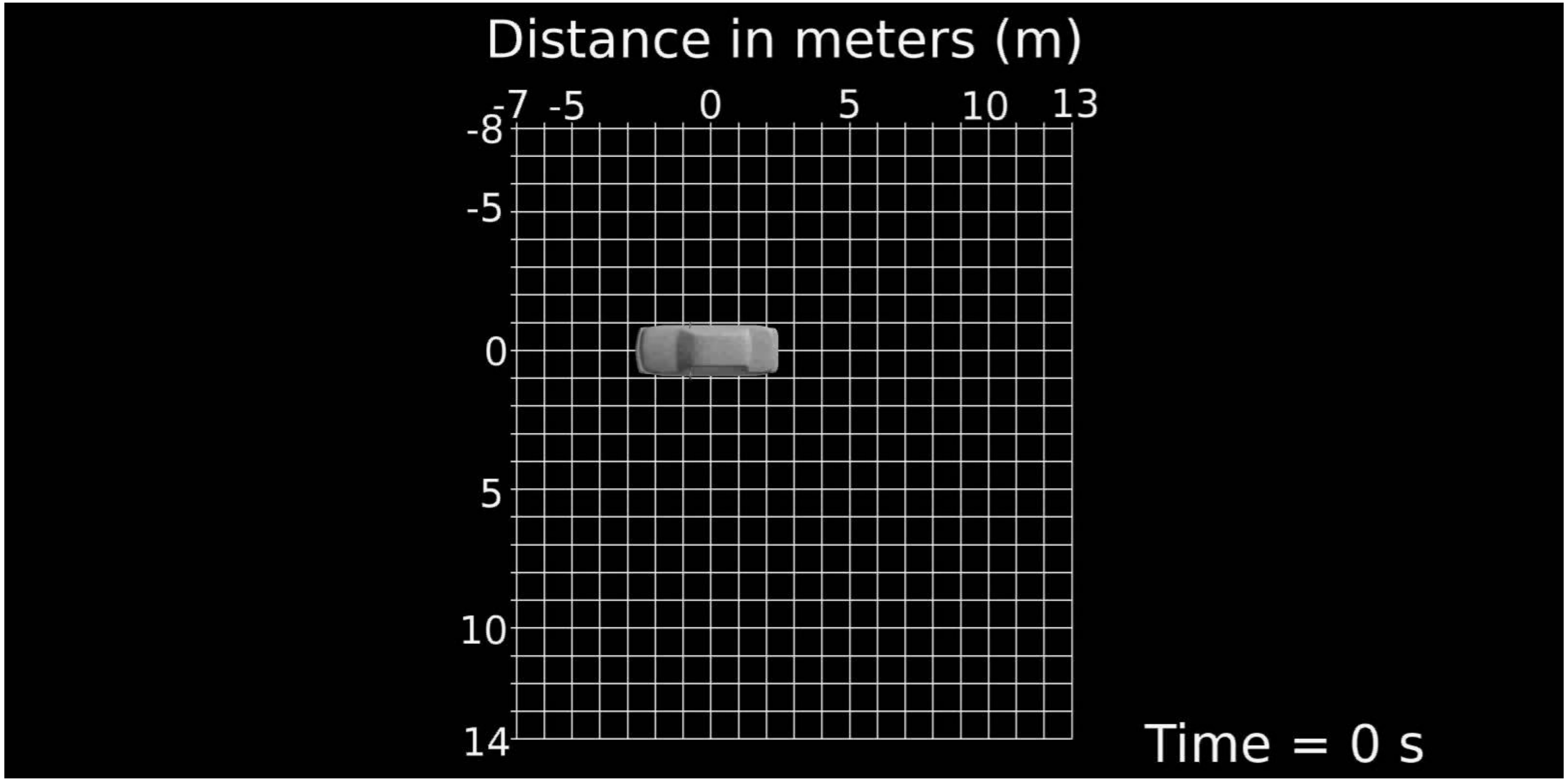
The largest flammable envelope occurs within 10 s **from 8 to 11 m**

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

Unignited hydrogen releases outdoors and their mitigation

Unignited release: 35 MPa

- Top view (4 vol. % envelope)



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

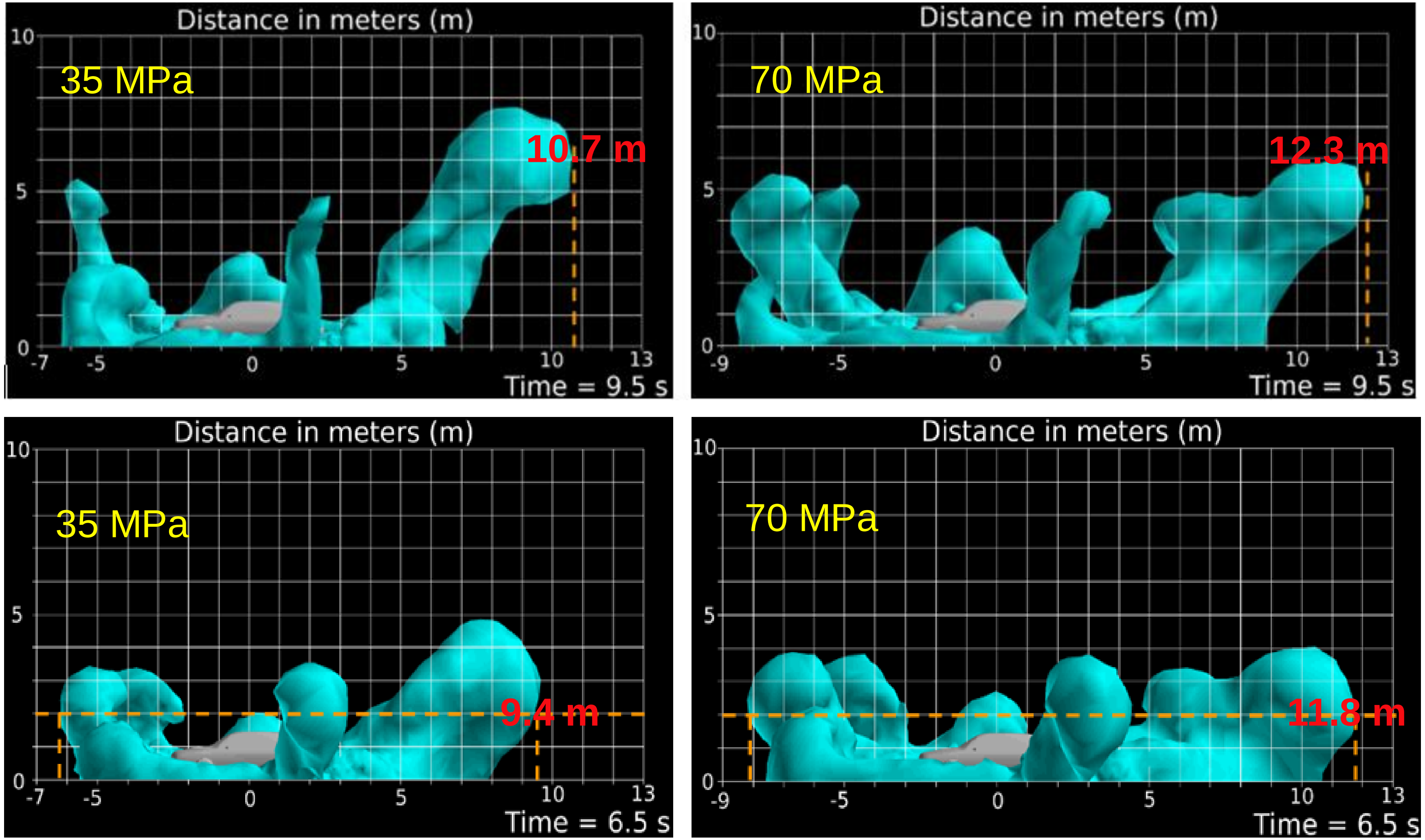
Unignited hydrogen releases outdoors and their mitigation

Unignited releases: summary

Hazard distances

For a building air intake

For people on the ground (height <2m)



Prevention of hydrogen leaks

- Inherently safer design of hydrogen systems.
- Careful materials selection.
- Minimize the quantity of hydrogen that is stored and involved in an operation.
- Equipment design validation.
- Periodic equipment inspection.
- Periodic leak test.

Detection of hydrogen leaks

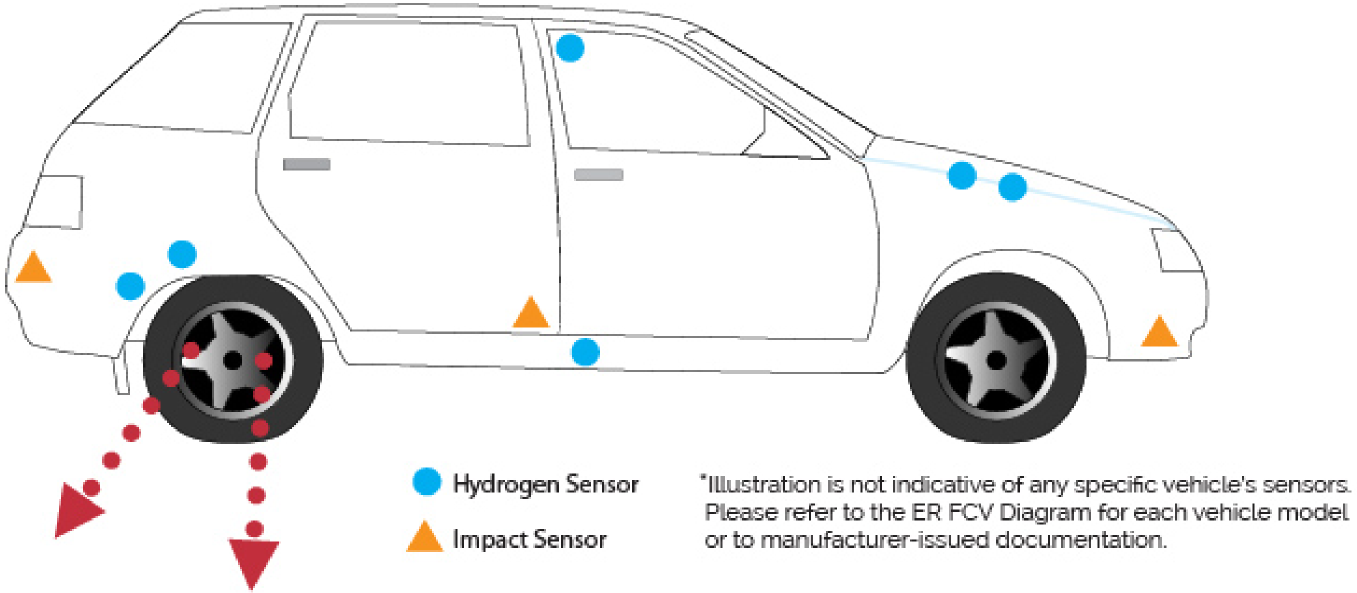
Detectors/sensors can be used to detect releases, automatically shut down systems, activate alarms, and notify First Responders.

- Suggested locations:
  - locations where hydrogen leaks or spills are possible;
  - at hydrogen connections that are routinely separated (for example, hydrogen refuelling ports);
  - locations where hydrogen could accumulate;
  - in building air intake ducts, if hydrogen could be carried into the building;
  - in building exhaust ducts, if hydrogen could be released inside the building.
- Hydrogen detectors locations for a Fuel Cell Electric Vehicle (FCEV):
  - Exhaust pipe (process control)
  - Passenger cabin (safety)
  - Engine (safety)
  - Fuel cell stack (safety)

Source: ISO/TR 15916 (2004). Basic considerations for the safety of hydrogen systems. International Organization for Standardization. ISO Technical Committee 197 Hydrogen Technologies. International Organization for Standardization, Geneva.

Unignited hydrogen releases outdoors and their mitigation

Possible locations of hydrogen sensors in a FC car



●	Hydrogen sensors detect hydrogen leaks in the passenger cabin and through the vehicle. It's very unlikely that the fuel system will leak, however if the sensors detect a leak a solenoid will close and seal hydrogen in the tank. In addition, electrical relays open to shut down the vehicle and isolate the high voltage.
▲	Impact sensors detect collision, just as air bag sensors do. This also seals fuel in the tank and isolates high voltage. (Buses do not have this sensor)

Source: California Fuel Cell Partnership, http://cafcp.org/toolkits/safety/safety_systems

Hydrogen detectors (1/2)

Apart from the stationary detection system hydrogen system operators should also have a portable hydrogen detector available for their use in and around a hydrogen system. A commonly used concentration level for main alarm is 1 vol. % hydrogen in air, which is equivalent to 25% of the LFL. This level normally should provide an adequate time to respond in appropriate manner, such as system shut-down, evacuation of personnel, or other measures as necessary. A warning may be given earlier.

- More than one sensor platform necessary to reach all target specifications.
- Combination of sensor platforms shows best results.

- Electrochemical detectors
- Metal oxides detectors
- Thermal conductivity detectors
- Field effect gas detectors (FED)
- Resistance-based palladium thin film
- Catalytic detectors
- Micro Electro Mechanic Systems (MEMS)
- Optical devices
- Research is on-going

Hy Responder

Unignited hydrogen releases outdoors and their mitigation

Hydrogen detectors (2/2)

Factors to consider while selecting detectors:

- Accuracy (1-10%),
- Reliability,
- Maintainability,
- Calibration,
- Detection limits (high and low),
- Response time (<10 s),
- Recovering or non-recovering in time,
- Long life time (more than 5 years)
- Low energy consumption (<10MW)
- Simple system integration

- Temperature, pressure, flow, humidity sensors for monitoring and control are commercially available

Source: Mark Bader, H2FC Technical School, 2014.

Reference (1/3)

1. Molkov, V (2012). Fundamentals of hydrogen safety engineering, Part I and Part II. Available from: www.bookboon.com, free download e-book
2. HyFacts Project. Chapter R. Hydrogen releases and dispersion. Available from: https://www.h2euro.org/hyfacts/category/education-training/ [accessed on 12.11.20].
3. EIGA, European Industrial Gases Association (2007). Determination of safety distances. IGC Doc 75/07/E.
4. EU No 406/2010, Commission Regulation of 26 April 2010 implementing Regulation (EC) No 79/2009 of the European Parliament and of the Council on type-approval of hydrogen-powered motor vehicles. Official Journal of the European Union. Vol. 53, 18 May 2010. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:122:FULL:EN:PDF [accessed on 12.11.20].
5. Saffers, JB, Makarov, DV and Molkov, VV (2011). Modelling and numerical simulation of permeated hydrogen dispersion in a garage with adiabatic walls and still air. International Journal of Hydrogen Energy. Vol. 36(3), pp. 2582-2588.
6. Adams, P, Bengaouer, A, Cariteau, B, Molkov, V and Venetsanos, AG (2011). Allowable hydrogen permeation rate from road vehicles. International Journal of Hydrogen Energy. Vol. 36, pp. 2742-2749.
7. Dulov, VG and Luk’yanov, GA (1984) *Gasdynamics of the outflow processes*. Nauka, Novosibirsk.
8. Ishii, R, Fujimoto, H, Hatta, N and Umeda, Y (1999). Experimental and numerical analysis of circular pulse jets. Journal of Fluid Mechanics. Vol. 392, pp. 129-153.
9. Birch, AD, Brown, DR, Dodson, MG and Swaffield, F (1984) The structure and concentration decay of high pressure jets of natural gas. Combustion Science and Technology, vol. 36, pp. 249-261.
10. Schefer, RW, Houf, WG, Williams, TC, Bourne, B and Colton, J (2007). Characterization of high-pressure, underexpanded hydrogen-jet flames. International Journal of Hydrogen Energy. Vol. 32, pp. 2081-2093.
11. Molkov, V, Makarov, D and Bragin, M (2009). Physics and modelling of under-expanded jets and hydrogen dispersion in atmosphere, In Fortov, VE et al. (eds). Physics of Extreme State of Matter 2009. Chernogolovka, Russia, pp.143-145.
12. LaChance, J, Tchouvelev, A and Engebo, A (2011). Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure. International Journal of Hydrogen Energy. Vol. 36 pp. 2381-2388.
13. Chen, CJ and Rodi, W (1980). Vertical turbulent buoyant jets - a review of experimental data, The Science Applications of Heat and Mass Transfer series, Vol. 4, Ed. by Chen C.J. 1980, Pergamon Press: Oxford, 83p.
14. Molkov, V and Bragin, M (2009) High-pressure hydrogen leak through a narrow channel. In: *Nonequilibrium Phenomena: Plasma, Combustion, Atmosphere*; Torus Press: Moscow, pp. 332-338.
15. International fire code (2006). International Code Council.

Reference (2/3)

16. NFPA 55, National Fire Protection Association (2010). Standard for the storage, use, and handling of compressed gases and cryogenic fluids in portable and stationary containers, cylinders, and tanks. Quincy, MA, 2010.
17. Shevyakov, GG, Tomilin, VP and Kondrashkov, YuA (1980). Influence of buoyancy on the mixing length in a free turbulent jet, Engineering Physical Journal. deposit with VINITI, N3671-80 (in Russian).
18. Shevyakov, GG and Savelieva, NI (2004). Dispersion and combustion of hydrogen jet in the open atmosphere. International Scientific Journal for Alternative Energy and Ecology. Vol. 1(9), pp. 23-27 (in Russian).
19. Li, Z, Makarov, D, Keenan, J, Molkov, V (2015). CFD study of the unignited and ignited hydrogen releases from TPRD under a fuel cell car. 6th International Conference on Hydrogen Safety, 19-21 October 2015, Yokohama, Japan.
20. Honda FCX Specifications (2009). Available from: https://global.honda/heritage/timeline/product-history/automobiles/2016Clarity-Fuel-Cell.html [accessed on 12.11.20].
21. Tamura, Y, Takabayashi, M and Takeuchi, M (2014). The spread of fire from adjoining vehicles to a hydrogen fuel cell vehicle. International Journal of Hydrogen Energy, Vol. 39, pp. 6169-6175.
22. HyFacts Project. Chapter RM. Prevention and mitigation of releases: Detection and ventilation. Available from: https://www.h2euro.org/hyfacts/category/education-training/ [accessed on 12.11.20].
23. ISO/TR 15916 (2004). Basic considerations for the safety of hydrogen systems. International Organization for Standardization. ISO Technical Committee 197 Hydrogen Technologies. International Organization for Standardization, Geneva.
24. Hydrogen, Fuel Cells & Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan Planned program activities for 2005-2015, (2007).
25. DOE FCTO Multi-Year Research, Development and Demonstration Plan, (2012). https://energy.gov/sites/prod/files/2015/06/f23/fcto_myrdd_safety_codes.pdf [accessed on 12.11.20].
26. Buttne W, Burgess R, Schmidt K, Wright H, Rivkin C et al. Hydrogen safety sensor performance and use gap analysis. 7th International Conference on Hydrogen Safety (ICHS 2017), Hamburg, Germany, Sep 11-13, 2017.
27. CFCP, California Fuel Cells Partnership, 2014. Available from: http://cafcp.org/ [accessed on 12.11.20].
28. Bader, M. Hydrogen sensors. H2FC European Technical School on Hydrogen and Fuel Cells, 2014.
29. HYPER (2008). FP6 STREP project "Installation Permitting Guidance for Hydrogen and Fuel Cells Stationary Applications". *Deliverable 4.3 Releases, Fires and Explosions*. WP4 Final Report. Available from: http://www.hyperproject.uk/page/4942/ [accessed 12.11.20].

Reference (3/3)

30. IEC 61779-1 (1998). Electrical Apparatus for the Detection and Measurement of Flammable Gases - Part 1: General Requirements and Test Methods. Standard IEC 61779-4: Performance requirements for group II apparatus indicating up to a volume fraction of 100 % lower explosive limit. International Electrotechnical Commission (IEC).
31. Blanchat, TK and Malliakos, A (1998). Performance testing of passive autocatalytic recombiners, NUREG/CR-6580, SAND97-2632.
32. ISO 26142:2010. Hydrogen detection apparatus -- Stationary applications. ISO Technical Committee 197 Hydrogen Technologies. International Organization for Standardization.
33. S. L. Brennan, D. V. Makarov, and V. Molkov, 'LES of high pressure hydrogen jet fire', Journal of Loss Prevention in the Process Industries, vol. 22, no. 3, pp. 353–359, May 2009.
34. C. Chen and W. Rodi, Vertical turbulent buoyant jets - a review of experimental data. Oxford: Pergamon Press, 1980.
35. V. Molkov and J.-B. Saffers, 'Hydrogen jet flames', International Journal of Hydrogen Energy, vol. 38, no. 19, pp. 8141–8158, Jun. 2013.

HyResponder

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (JU) under grant agreement No 875089. The JU receives support from the European Union’s Horizon 2020 research and innovation programme and United Kingdom, France, Austria, Belgium, Spain, Germany, Italy, Czechia, Switzerland, Norway

European Hydrogen Train the Trainer Programme for Responders