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BASICS OF HYDROGEN SAFETY FOR FIRST RESPONDERS

Lecture. Hydrogen fires

FCH
FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

Content

- Types of hydrogen fires
- Microflames
- Hydrogen jet fires and the flame length
- Radiation heat flux from hydrogen jet fires
- Jet fires of hydrogen compared to CNG and LPG
- Hydrogen fireballs
- Pressure effects of hydrogen jet fires
- Detection of hydrogen fires
- Mitigation and extinction of hydrogen fires

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Objectives of the lecture

- Distinguish between different types of hydrogen fires: from microflames to jet fires and fireballs
- Evaluate hydrogen flame lengths with the aid nomograms, dimensional and dimensionless correlations
- Assess the average location of jet flame tip
- Predict the hazard distances to protect people and structures
- Explain the effect of different factors on the flame length of jet fire: nozzle size and shape, jet attachment, buoyancy, barriers or walls
- Compare the flame lengths and heat fluxes of jet fires on hydrogen and other common fuels (CNG and LPG)
- Explain the pressure effects of hydrogen jet fires
- Identify the main hydrogen fires detection methods
- Recognise the mitigation techniques for hydrogen fires
- Implement the hydrogen fires extinction practices

Dimensionless numbers

- The Froude number, $\boldsymbol{Fr=U^2/gd}$, where U - velocity, d – characteristic size, g – acceleration due to gravity, is a ratio of **inertial to gravity** force (multiplied by the product of density by area ρA).
- The Reynolds number, $\boldsymbol{Re=Ud\rho/\mu}$, where ρ – density, μ – viscosity, is a ratio of **inertial to viscous** force.
- The Mach number, $\boldsymbol{M=U/C}$, where C – speed of sound, is a ratio of **inertial force to inertial force at sonic flow**.
- The speed of sound in gas is:

$$C = \sqrt{\gamma \frac{RT}{M}}$$

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Types of hydrogen flames/fires

- From microflames (10^{-9} kg/s) to high debit flames (10 kg/s).
- Laminar diffusion and turbulent non-premixed flames.
- Buoyancy- and momentum-controlled jets.
- Subsonic, sonic and under-expanded supersonic jet flames.
- Fireballs during storage tank failure in a fire.
- Liquefied hydrogen (LH_2) fires - little knowledge.
- Impinging flames.
- Jet flames in the presence of obstacles, surfaces and in enclosures.

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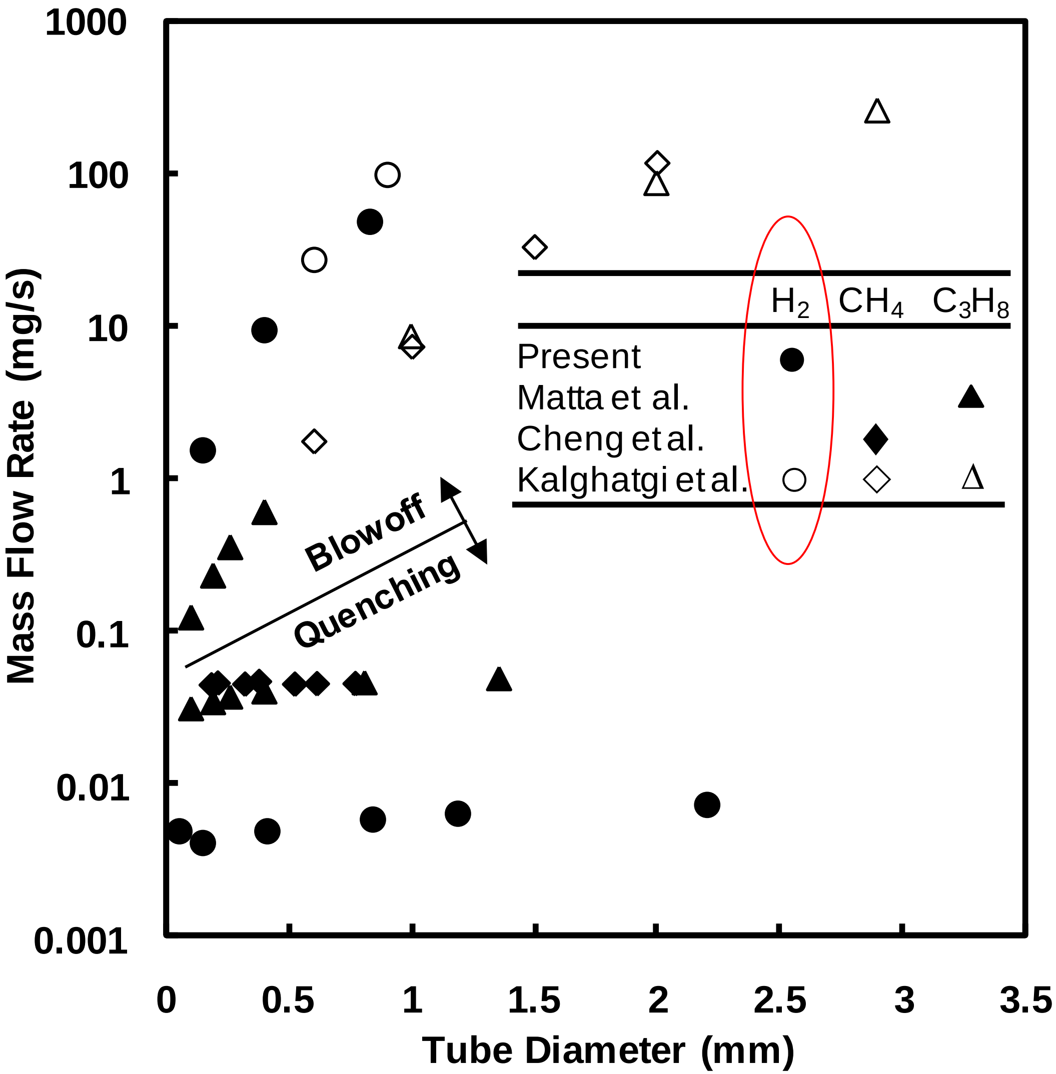
Quenching limits and blow-off



- Tube burner is used.
- **Quenching limits are nearly independent of diameter.**
- Hydrogen has the lowest quenching limit and the highest blow-off limit.

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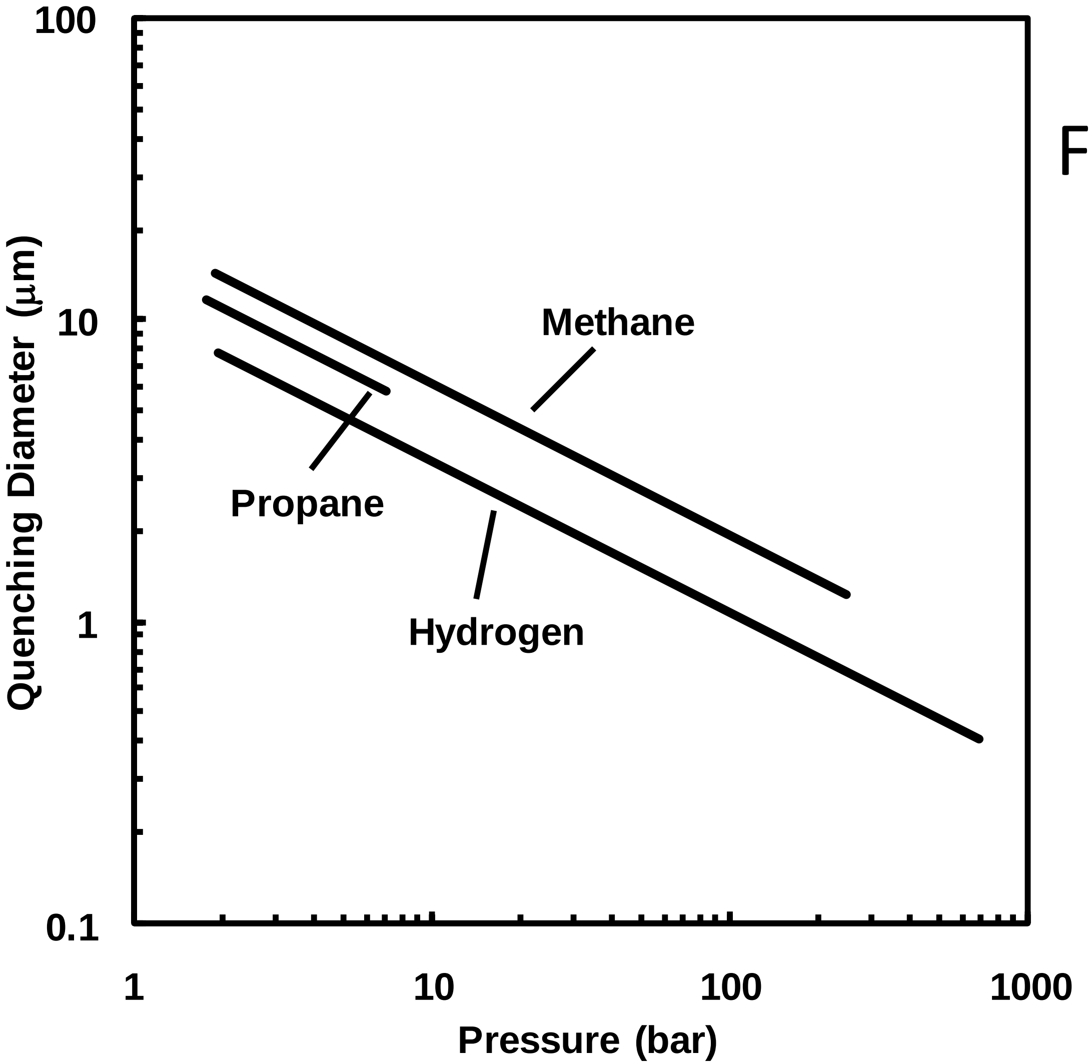
Quenching diameter



For hydrogen at 690 bar, **any hole larger than 0.4 μm will support a stable flame.**

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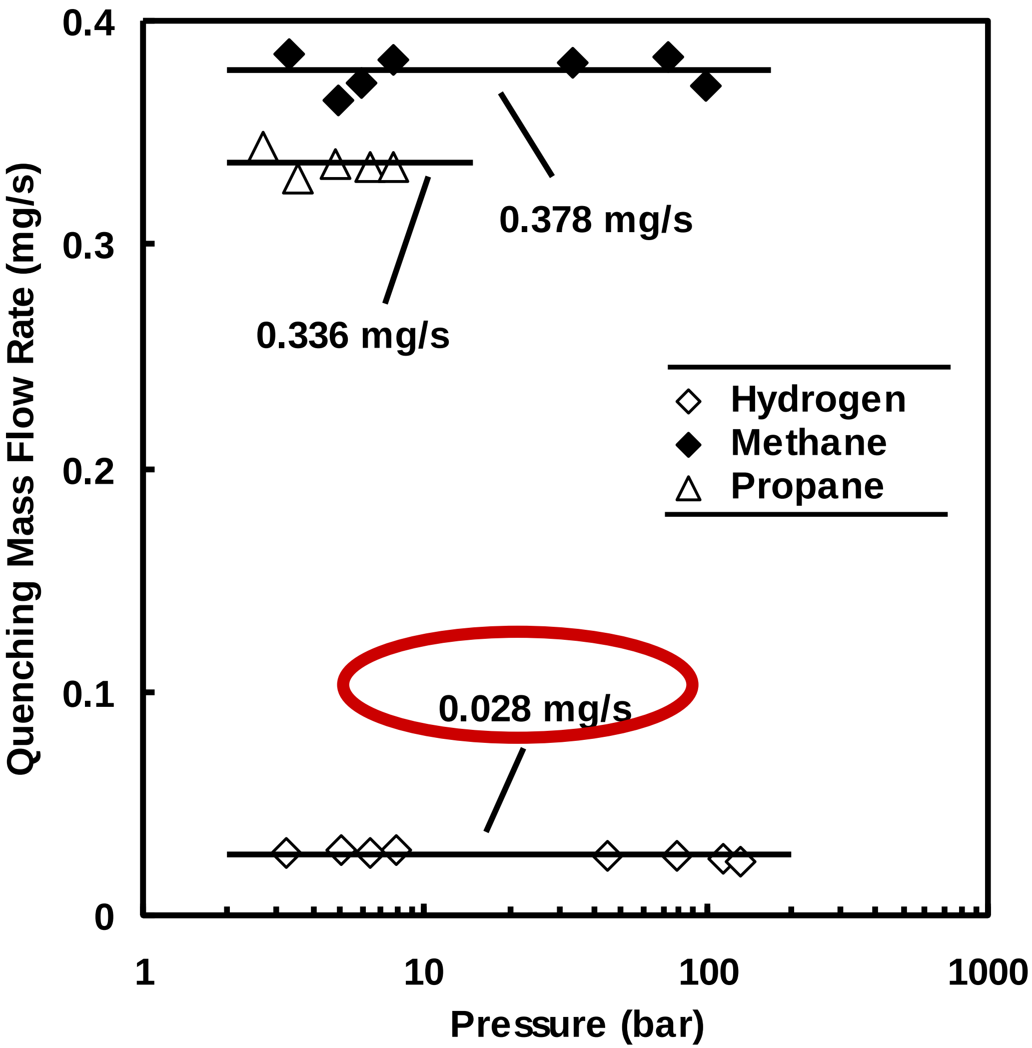
Leaky fittings



- Quenching limits for a 6 mm compression fitting are shown.
- Limits are independent of pressure.
- **Limits are about 10 times of those of tube burners.**
- Hydrogen limits are the lowest.

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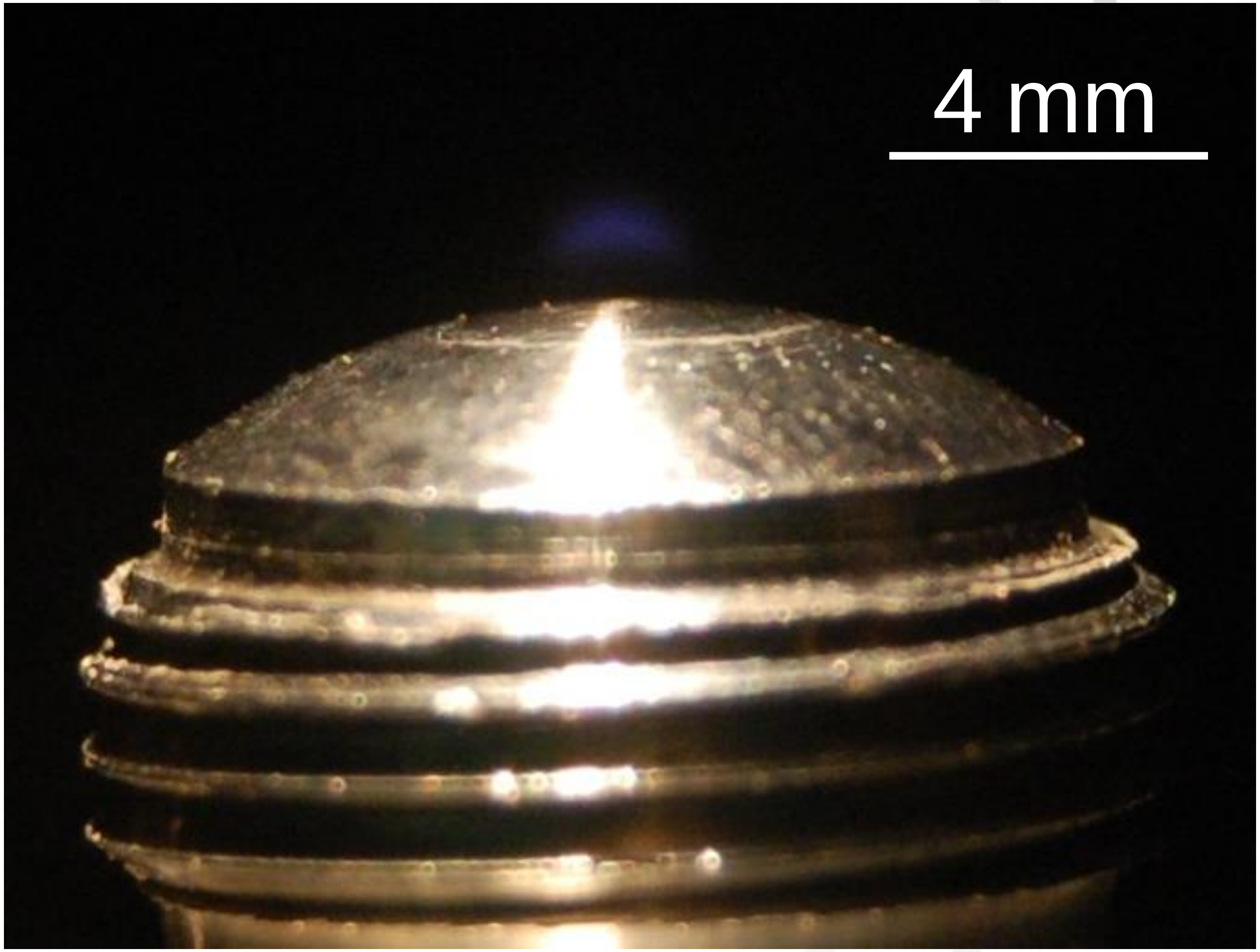
The length of microflames

- Test shown L_F=**1 mm**, *m*=7.5 mg/s, *D*=0.36 mm Stand-off height is 0.25 mm



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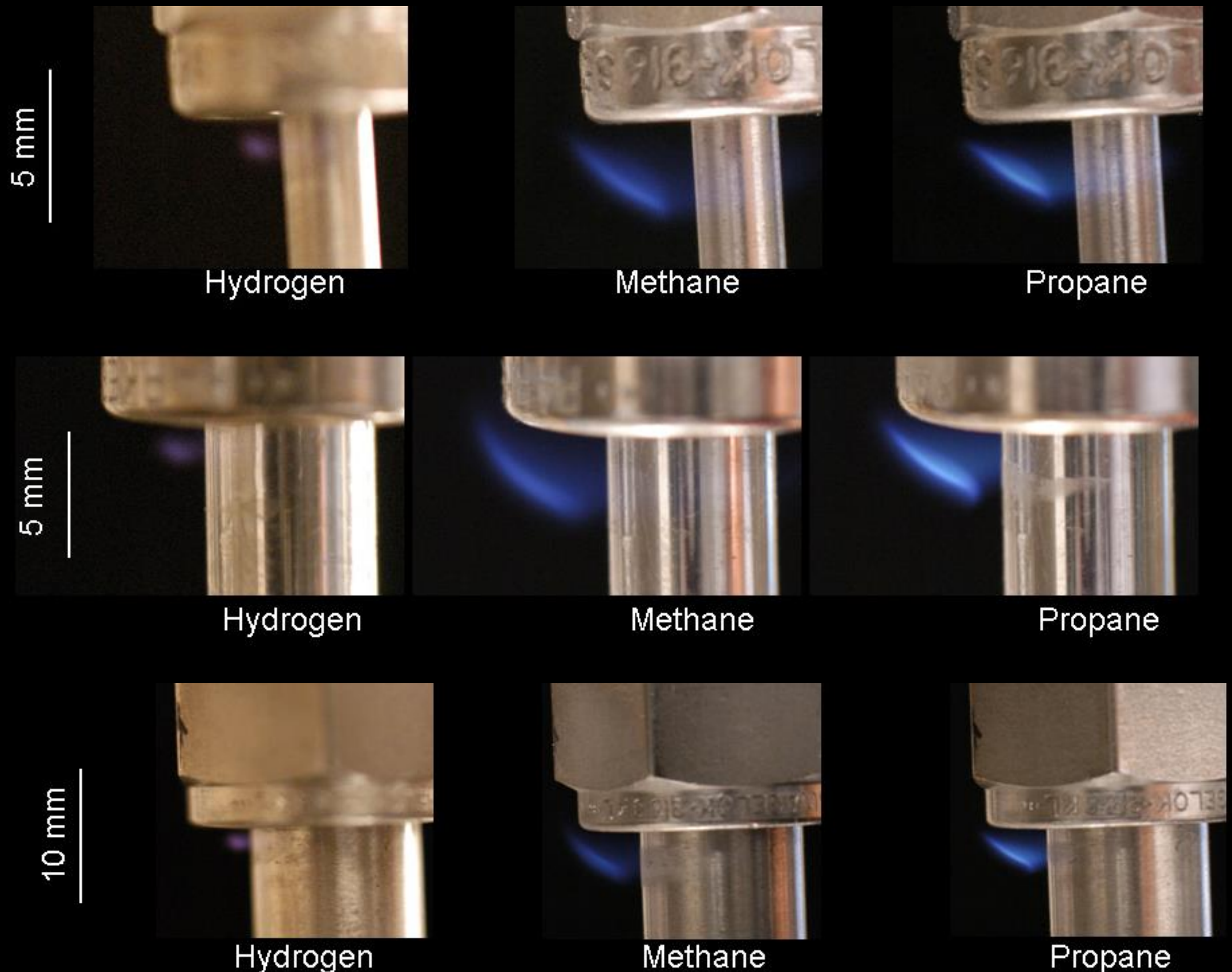
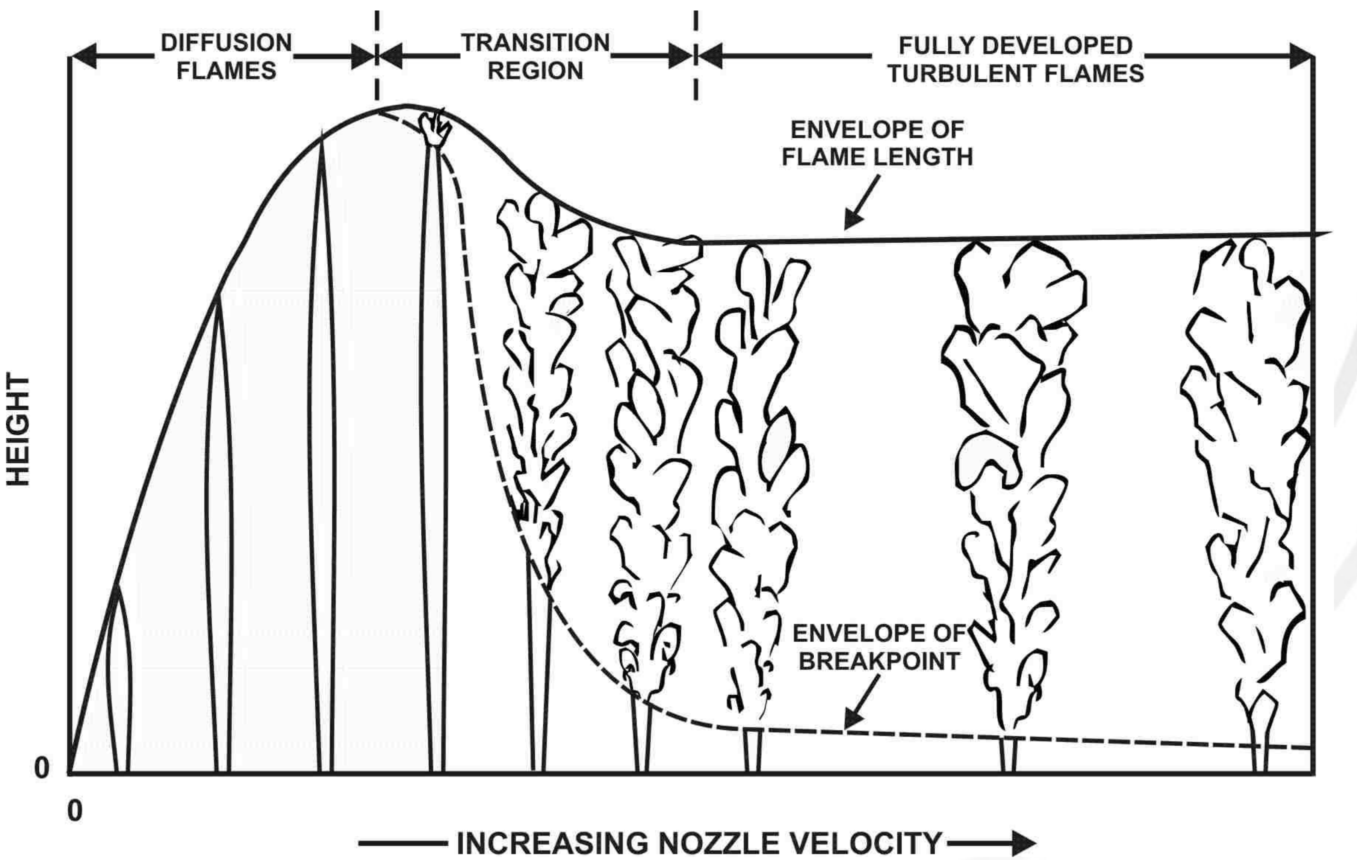

5 mm
Hydrogen
Methane
Propane
5 mm
Hydrogen
Methane
Propane
10 mm
Hydrogen
Methane
Propane

Laminar and turbulent jet flames

- The classic theoretical consideration of mixing and combustion in turbulent gas jets are given by Hottel and Hawthorne (1949).
- *“**The process of mixing is the controlling factor** in determining progress of the combustion”.*
- For the release of hydrogen into the still air **transition from laminar diffusion to turbulent flames** commences at **Reynolds number Re ~ 2000.**



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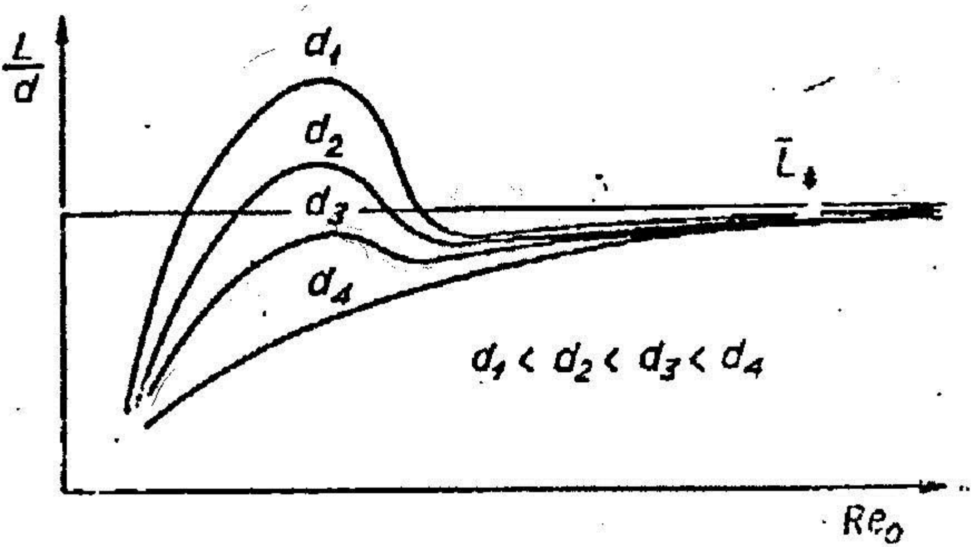
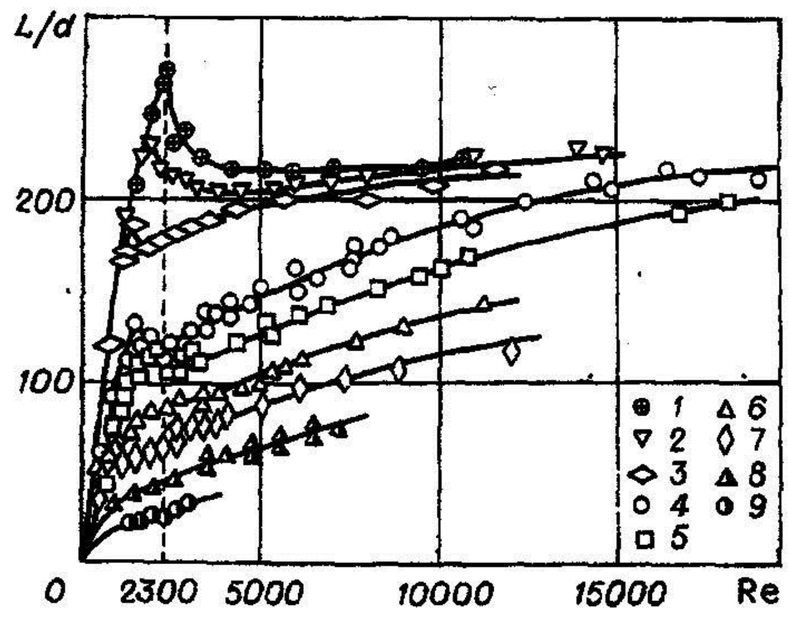
Flame length to diameter $L_F/d=f\ (Re)$

- Dependence of the flame length to diameter ratio (L_F/d) on Reynolds number Re for different nozzle diameters
- Turbulent flame length limit L_t



Source: Baev et al (1974)



1 – 1.45 mm; 9 – 51.7 mm

Source: Shevyakov and Komov (1977)

Can all these scattered data be correlated by one curve?

Fr-based flame length correlations

- ✓ Dimensionless flame length correlations suggested previously are based on the use of the Froude number (*Fr*) only, in one form or another.
- ✓ Recently *Fr*-based correlations were expanded to high pressure hydrogen jet fires (**under-expanded jets**). The general idea of this technique is to correlate experimental data with the **modified *Fr* number** that is built on so-called notional or **effective nozzle diameter** instead of real nozzle diameter. However, the size of the notional nozzle diameter and the velocity in the notional nozzle are dependent on the theory applied, including a number of simplifying assumptions.

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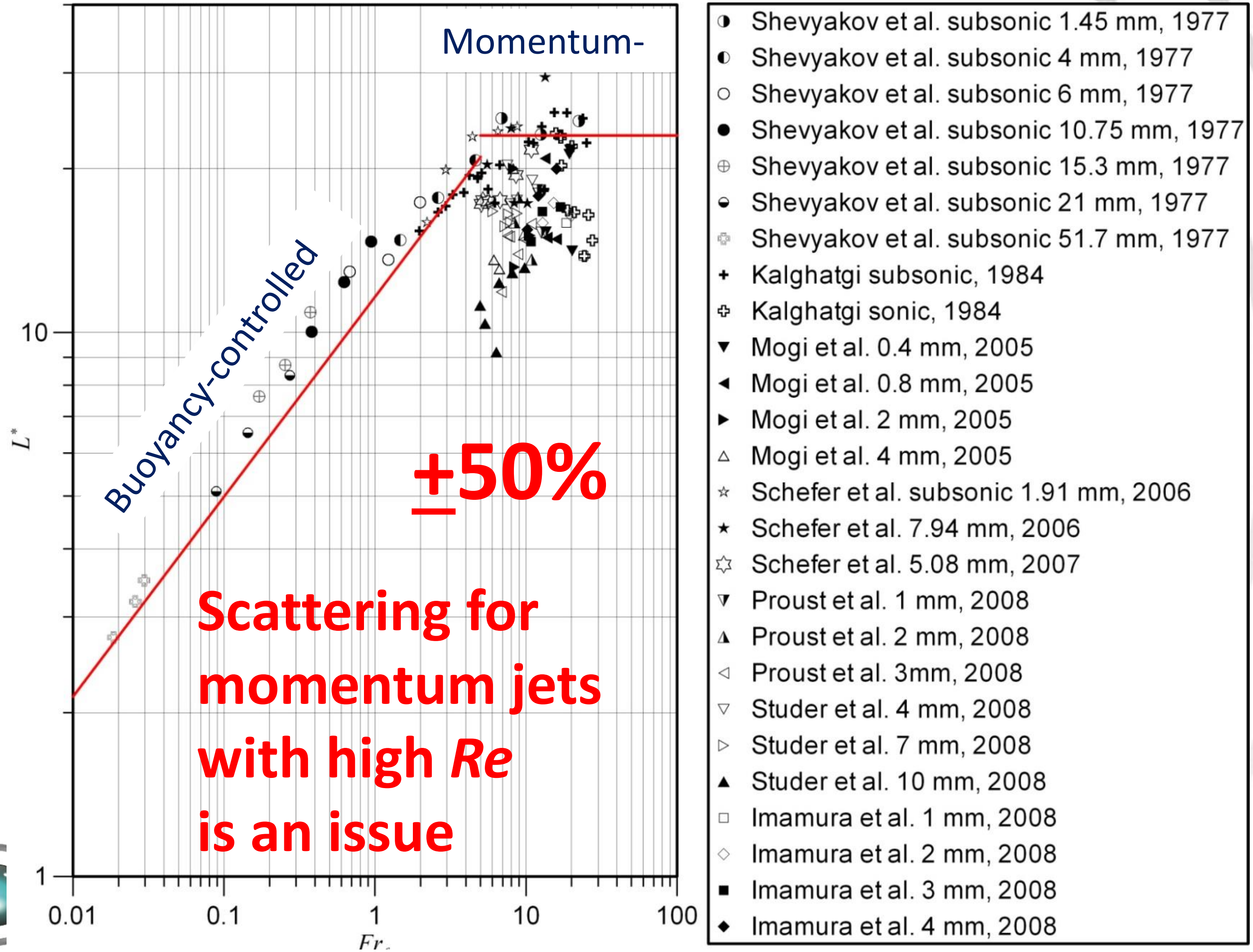
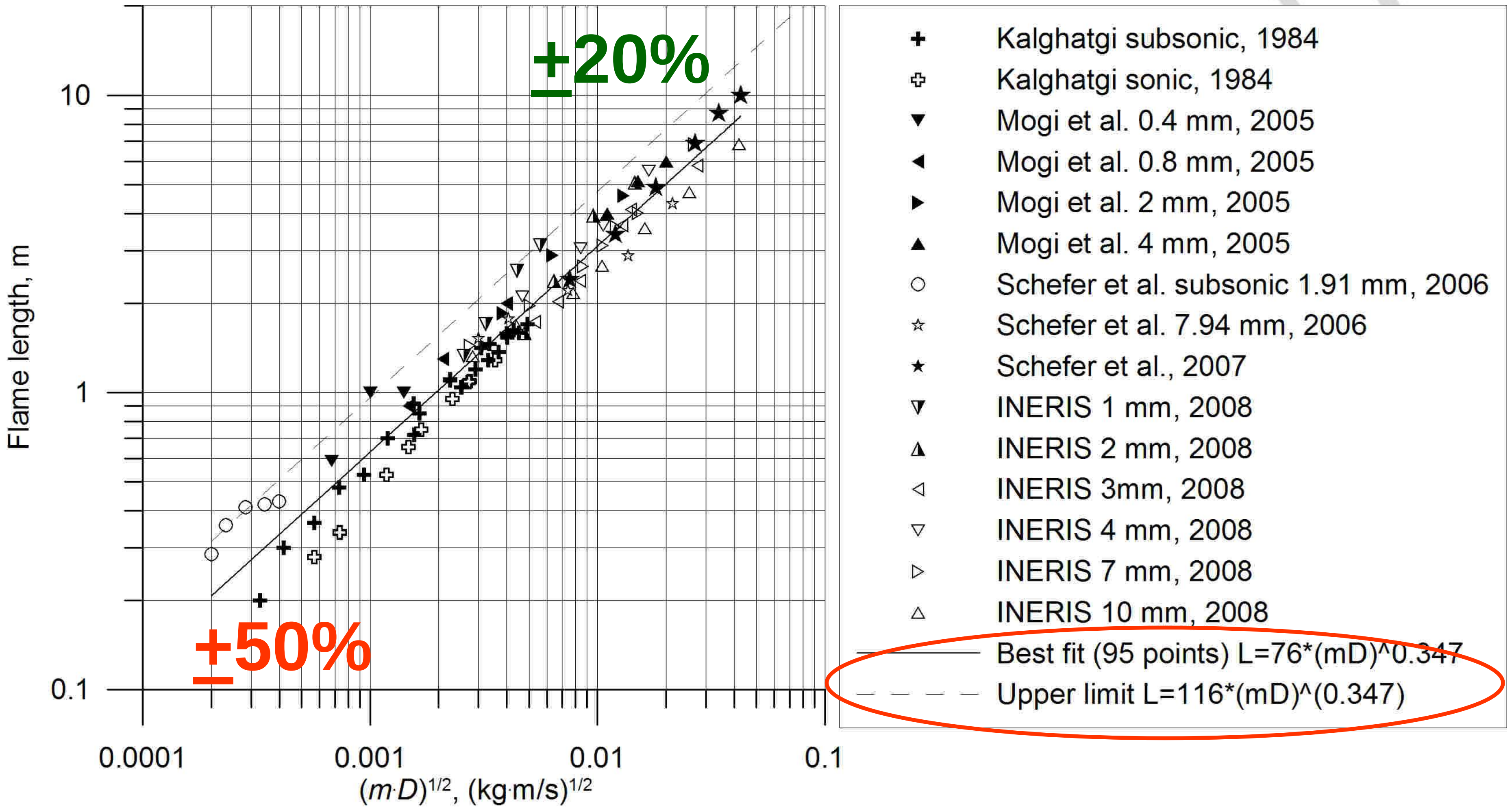
Fr-based correlation example



Under-expanded jets are included!

The dimensional correlation (2009)



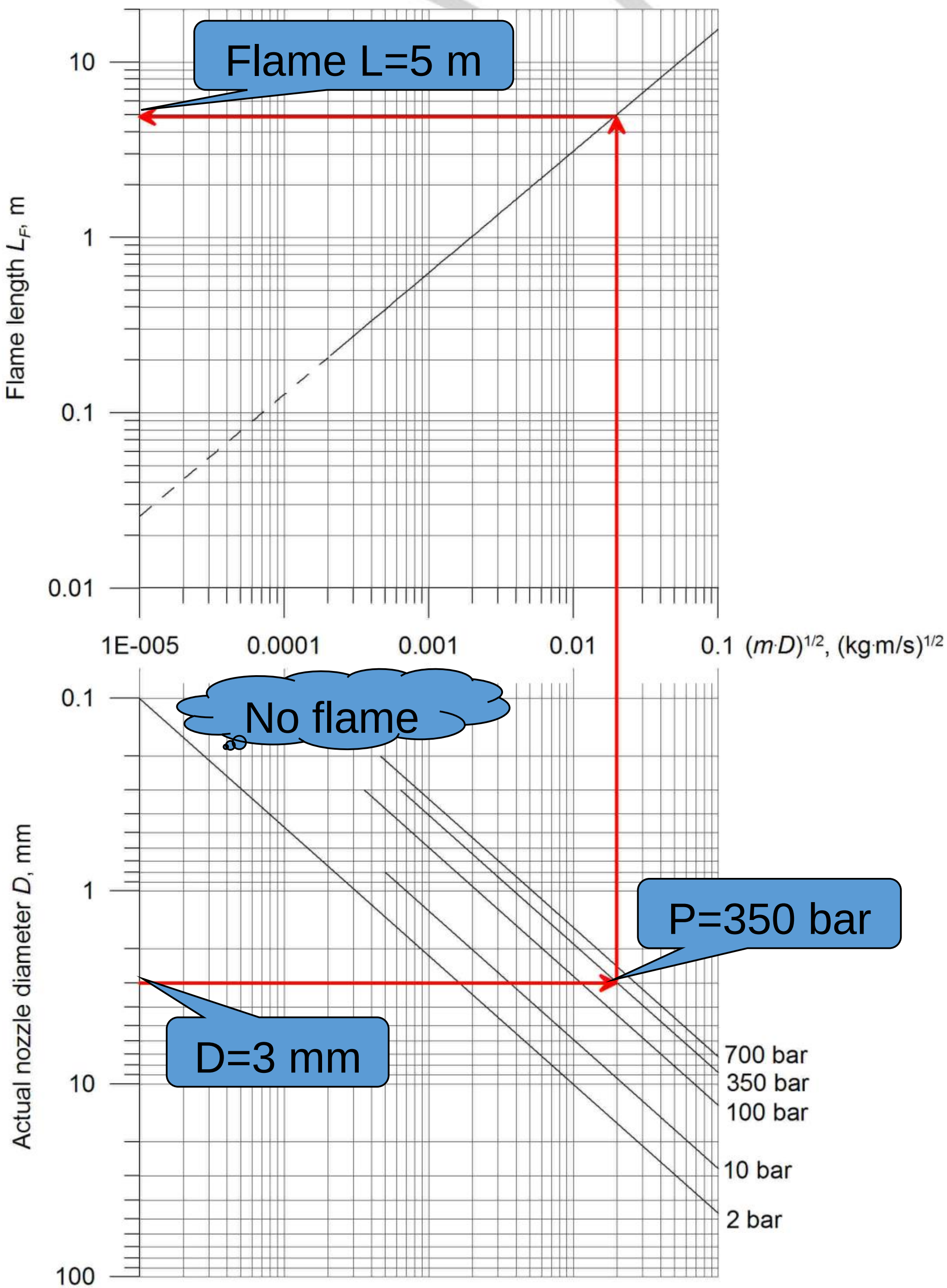
Good prediction for high and poor for small debit jets

The nomogram

Derived from the dimensional correlation (best fit curve; please multiply by 1.5 for a conservative estimate).

Special feature:

No stable flames (**“non-combustible”** hydrogen) were observed for nozzle diameters 0.1-0.2 mm – flame blew off although the spouting pressure increased up to 400 bar.



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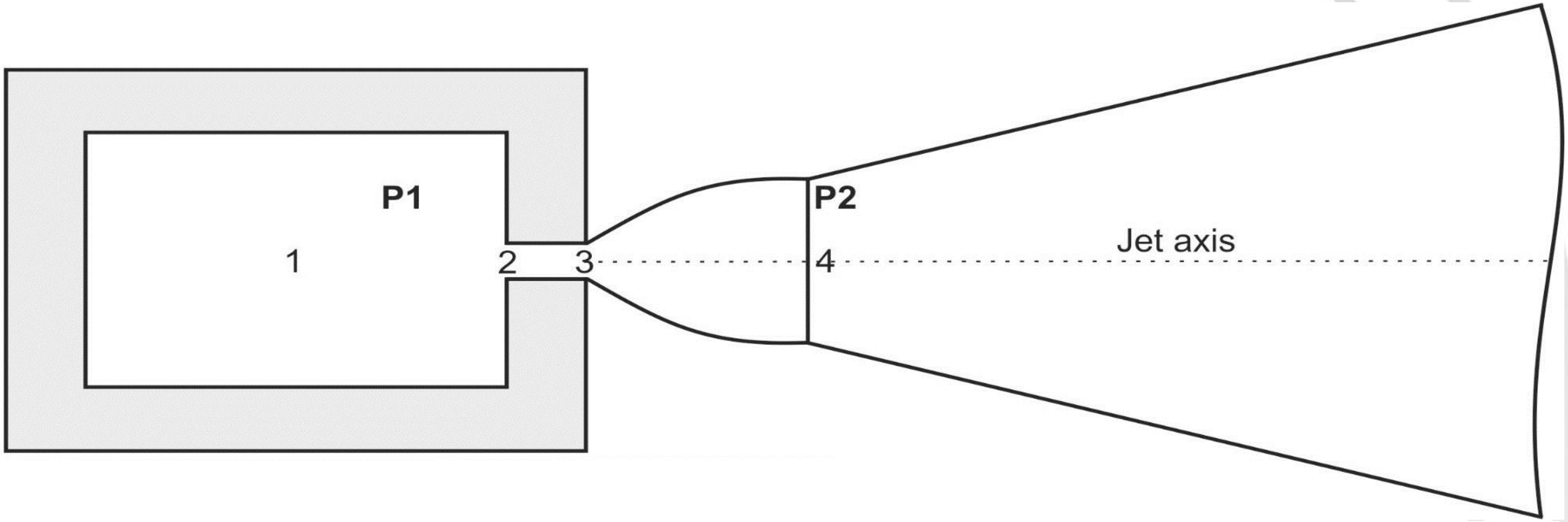
The under-expanded jet scheme



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)

A dimensionless correlation?

- The **dimensional** correlation for flame length is $L_F \sim (\dot{m} \cdot d)^{1/3}$
- Mass flow rate is proportional to the actual nozzle diameter squared $\dot{m} \sim d^2$
- This implies that **dimensionless flame length L_F/d** is an exponent function of **only density, ρ_N, and velocity, U_N, in the nozzle**
- The dimensionless density and velocity can be introduced: ρ_N/ρ_S and U_N/C_N, $C_N = \sqrt{\frac{\gamma \cdot R_{H2} \cdot T_N}{(1 - b \cdot \rho_N)}}$
- The correlation (next slide) is **validated:**
  - hydrogen storage pressures **up to 90 MPa;**
  - nozzle diameters **from 0.4 to 51.7 mm**.

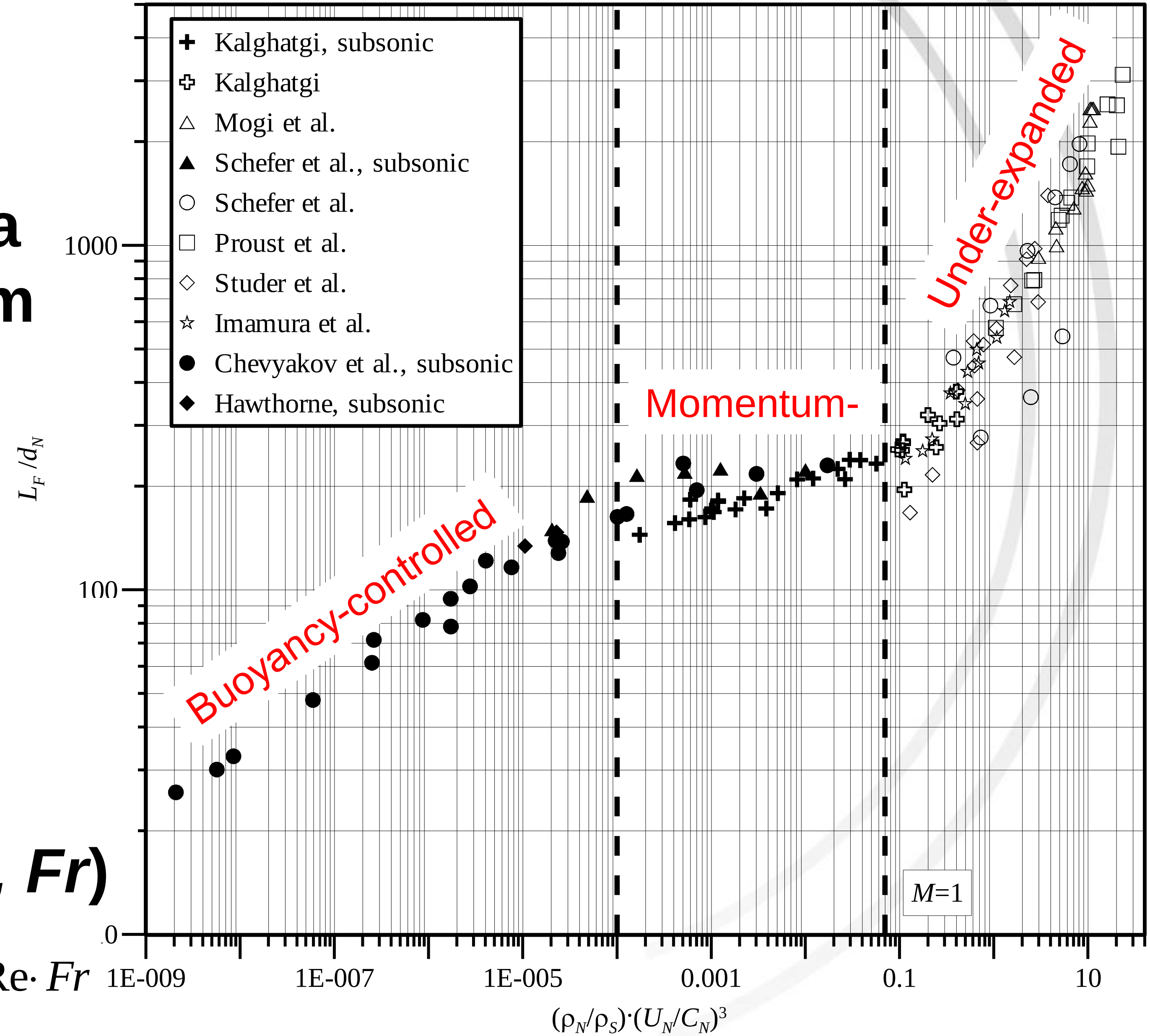
The dimensionless correlation (2011)

Validation:
***P* =0.1-90 MPa**
***d*=0.4-51.7 mm**
L/T; SS/S/SS

Line *M*=1
(choked flow)

***M* (*M*<1)-> (*Re, Fr*)**

$$\frac{\rho_N}{\rho_S}\cdot\left(\frac{U_N}{C_N}\right)^3=\frac{g\cdot\mu_N}{\rho_S\cdot C_N^3}\cdot\mathrm{Re}\cdot Fr$$



Change of *Fr, Re, M*

$$M = \frac{U_N}{C_N}$$

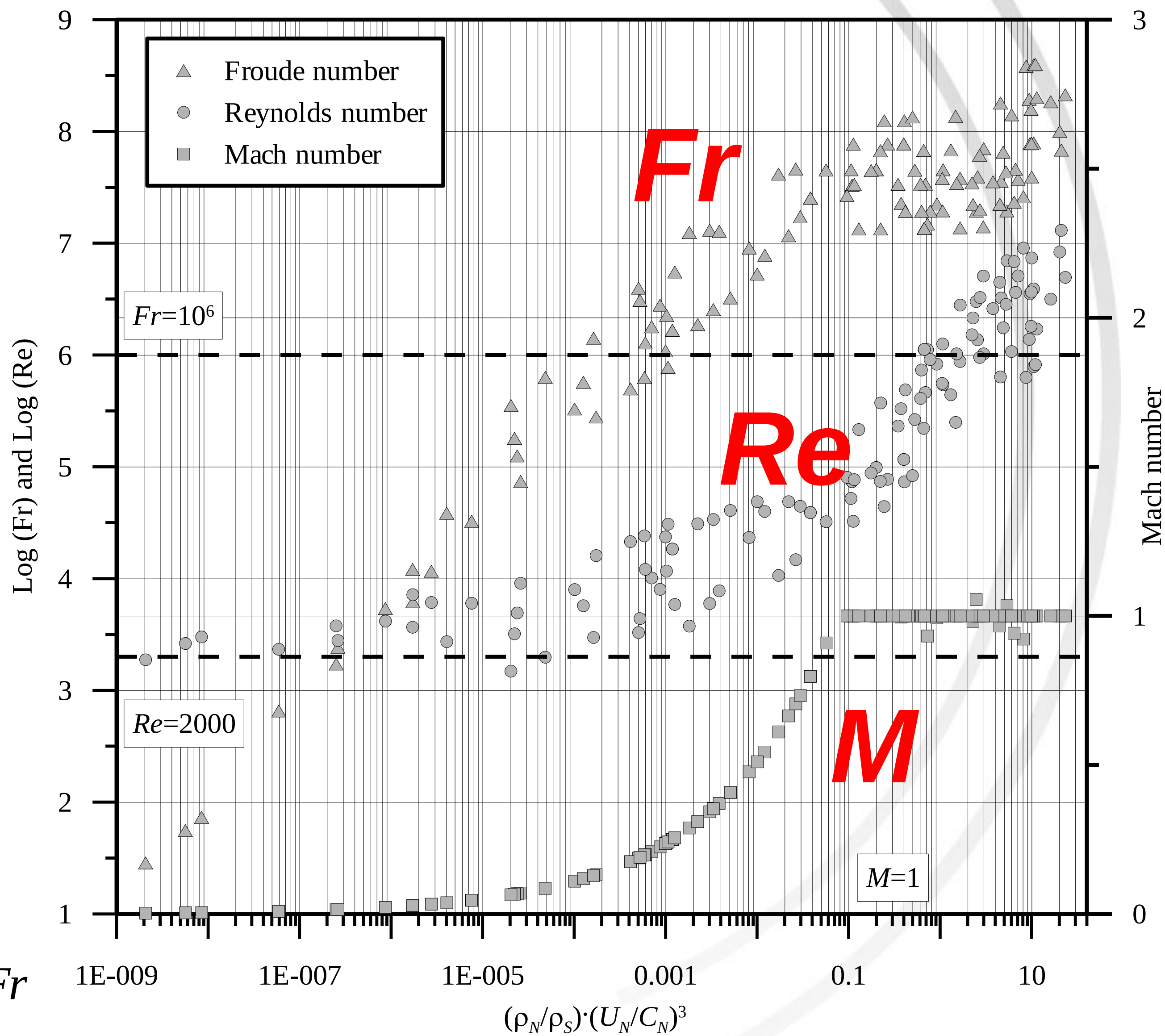
$$\mathrm{Re} = \frac{\rho_N \cdot d_N \cdot U_N}{\mu_N}$$

$$Fr = \frac{U_N^2}{d_N \cdot g}$$

***Re*=2000:** Laminar to turbulent

***Fr*=10^6:** Buoyancy to Momentum

$$\frac{\rho_N}{\rho_S} \cdot \left(\frac{U_N}{C_N}\right)^3 = \frac{g \cdot \mu_N}{\rho_S \cdot C_N^3} \cdot \mathrm{Re} \cdot Fr$$



How to determine the flame length?

- Y axis: L_f/d_n where L_f - flame length, d_n - nozzle diameter
- X axis: $(\rho_N/\rho_S)(U_N/C_N)^3$ where
- ρ_N - density at the nozzle exit,
  find the same way as with similarity law for unignited jets

  equal to 0.0838 kg/m^3 at normal temperature and pressure (NTP) for sub-sonic and expanded sonic jets

  If the jet is underexpanded then the density is calculated by an **under-expanded jet theory** developed at the University of Ulster
- ρ_S - density of the surroundings = 1.205 kg/m^3 for air
- C_N - is the speed of sound in hydrogen at the nozzle exit,

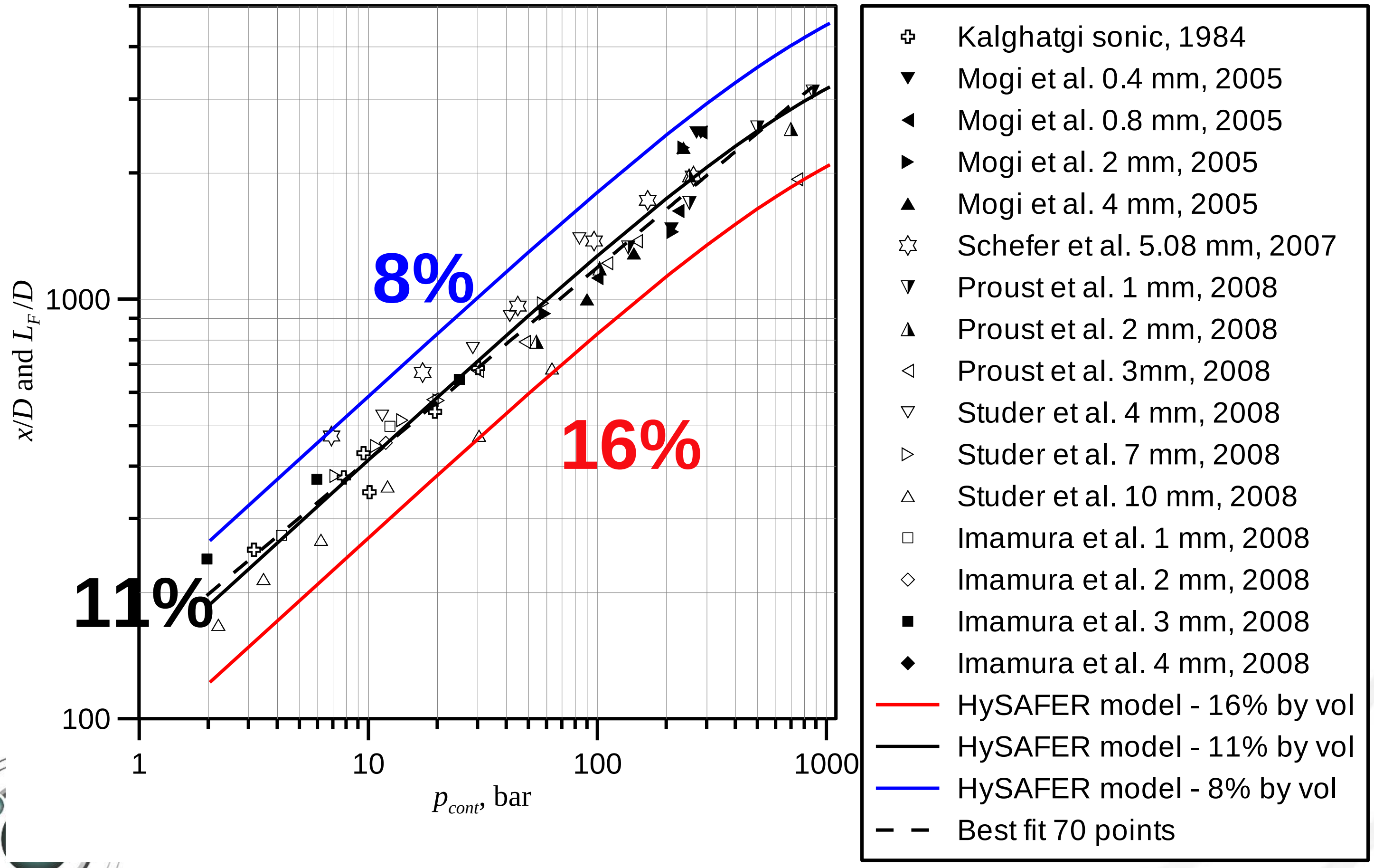
$$C = \sqrt{\gamma \frac{P}{\rho}} = \sqrt{\gamma \frac{RT}{M}}$$

- U_N - the velocity of the hydrogen at the jet exit
  $U_N = C_N$ for sonic and supersonic jets,
  for subsonic jets:

$$U_N = \sqrt{2\frac{\Delta P}{\rho}}$$

Where is a jet flame tip location?

- **Flammable envelope** = 4 vol. % (LFL)
- **Flame tip location** = 11 vol. % in **unignited jet** (8-16 vol.%)



Flame is 2.2 times (16%) or 4.7 times (8%) longer than the distance to axial concentration 29.5% (stoichiometric hydrogen-air mixture)!

Hazard and separation distances

- Hazard distance is a recently introduced term.
- In early publications (before 2015) you may find terms such as **separation distance**=safety distance=setback distance.
- As per draft definition, ISO TC197 **hazard distance** is a distance from the (source of) hazard to a determined (by physical or numerical modelling, 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 hazard distance will be different for:
  - Unignited releases;
  - Fires;
  - Blast wave;
  - Fireball

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Harm criteria

- Before calculating a hazard distance it is necessary to consider what you would like to protect against.
- In the case of free fires this would be temperature, heat flux and overpressure (in the case of enclosure fires - asphyxiation may also be relevant).
- For people direct flame contact as a result of a jet fire is generally assumed to result in third degree burns.
- For people not in the flame, there is still potential for exposure to high radiation heat fluxes.
- 70 ^{o}C - “no harm” limit; 115 ^{o}C - pain limit for 5 min exposure; 309 ^{o}C - third degree burns for 20 s (“fatality” limit).
- Harmful heat flux criteria will be presented in the Lecture ‘Harm criteria for people and damage criteria for structures’,

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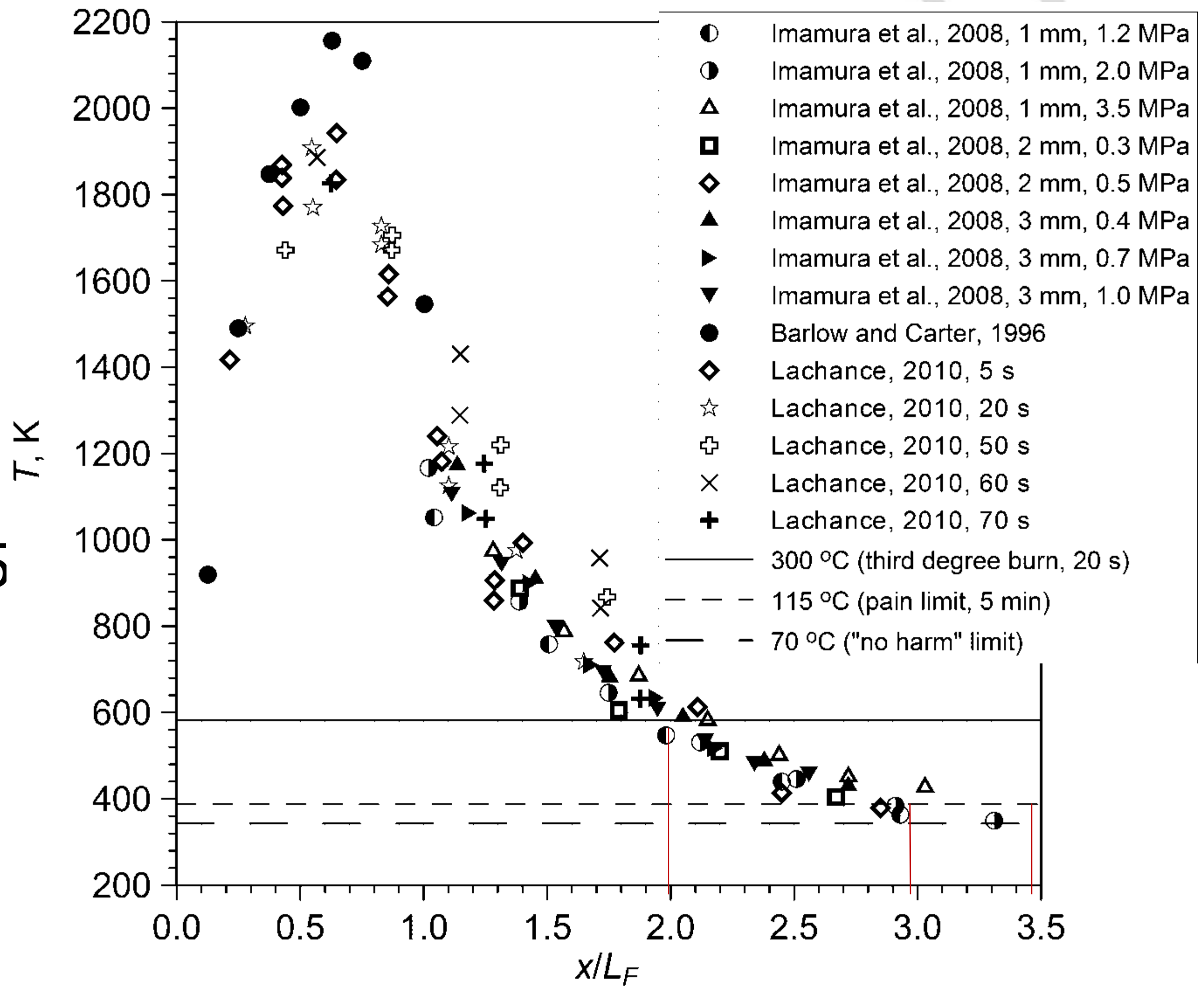
Temperature decay along jet fire axis

- **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)



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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 ("fatality 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 ("fatality 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).

Attachment effect on jet flame length

- 205 bar (20.5 MPa), ignition delay 800 ms.
- Attached jets – 0.11 m above the ground.
- Unattached jets – 1.2 m above the ground.
- Release along the ground or walls in proximity to them can **increase the flame length**.

Orifice diameter, mm	Flame length, m Attached jets	Flame length, m Unattached jets	Flame length increase, times
1.5	5.5	3	x1.83
3.2	9	6	x1.50
6.4	11	9	x1.22
9.5	13	11	x1.18

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Unattached jets

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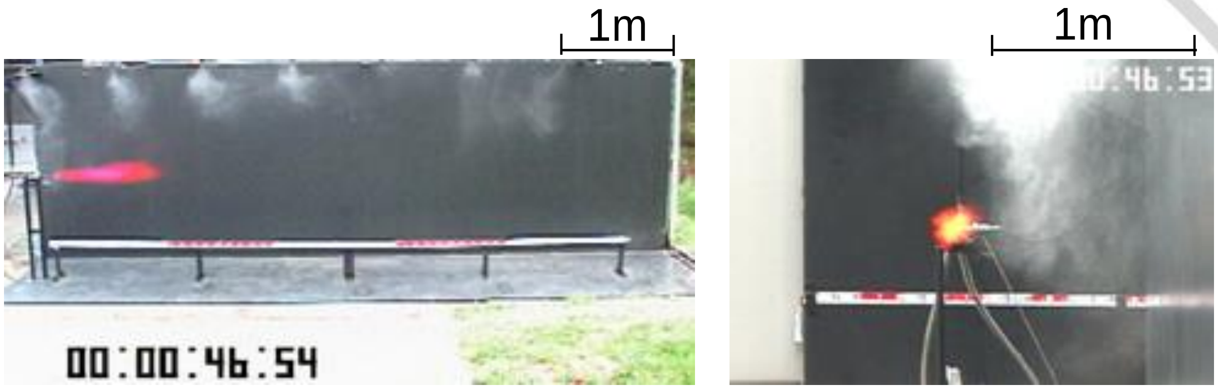
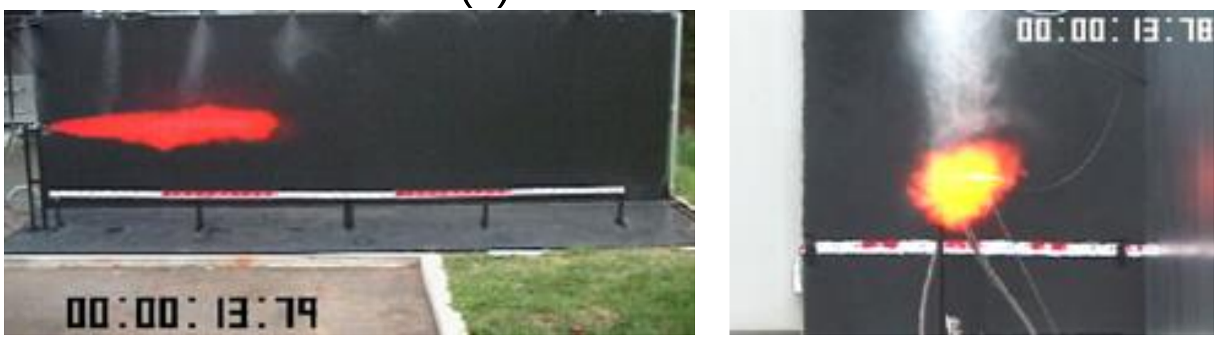
Attached jets

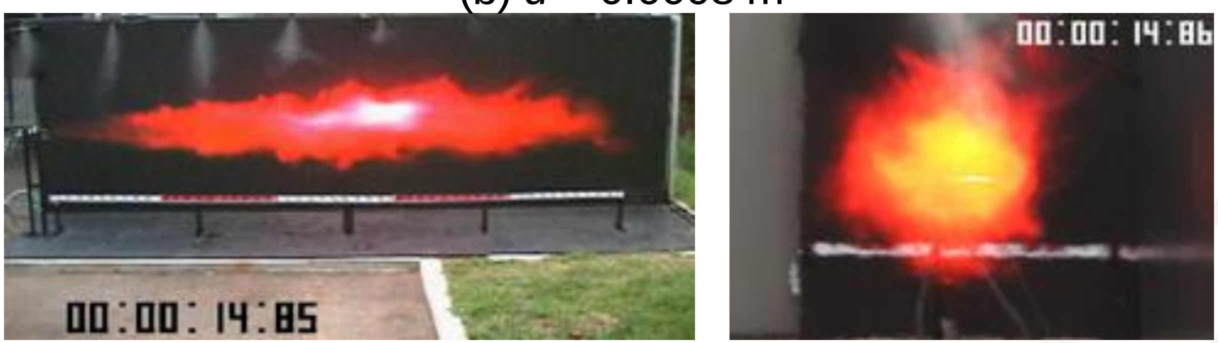
Round nozzles (p =35 MPa)



(a) d = 0.0004 m



(b) d = 0.0008 m

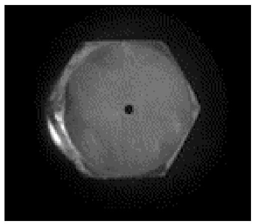
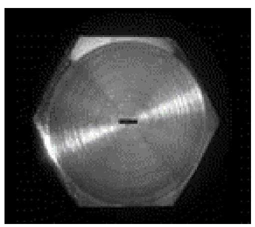
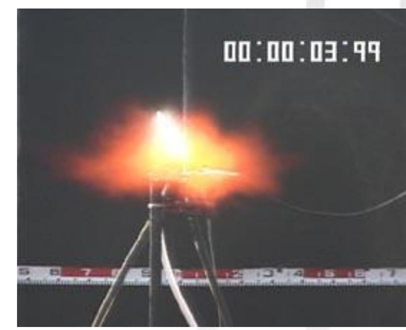
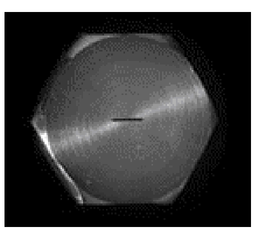


(c) d = 0.002 m

Flame length is proportional to nozzle diameter

Round and plane nozzles

p=40 MPa (constant nozzle area 0.8 mm^2) **(*A*=constant)**

Nozzle	Side view	Front view
 d = 0.001 m		
 0.0004 × 0.002 m (*AF* = 5)		
 0.00025 × 0.0032 m (*AF* = 12.8)		

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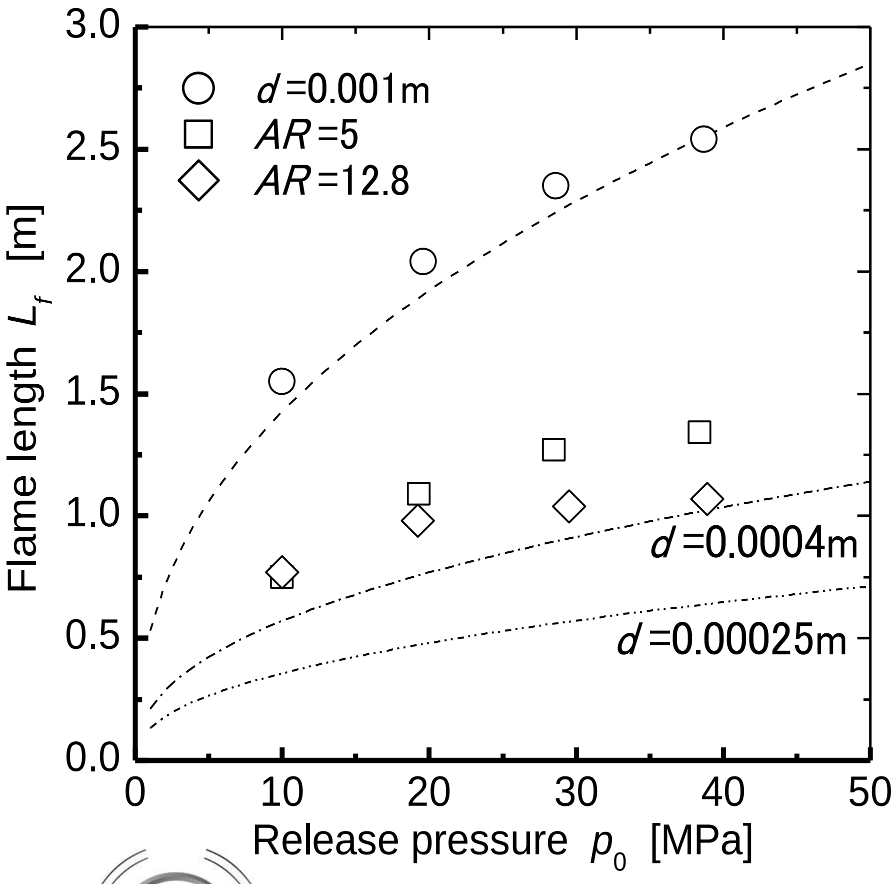
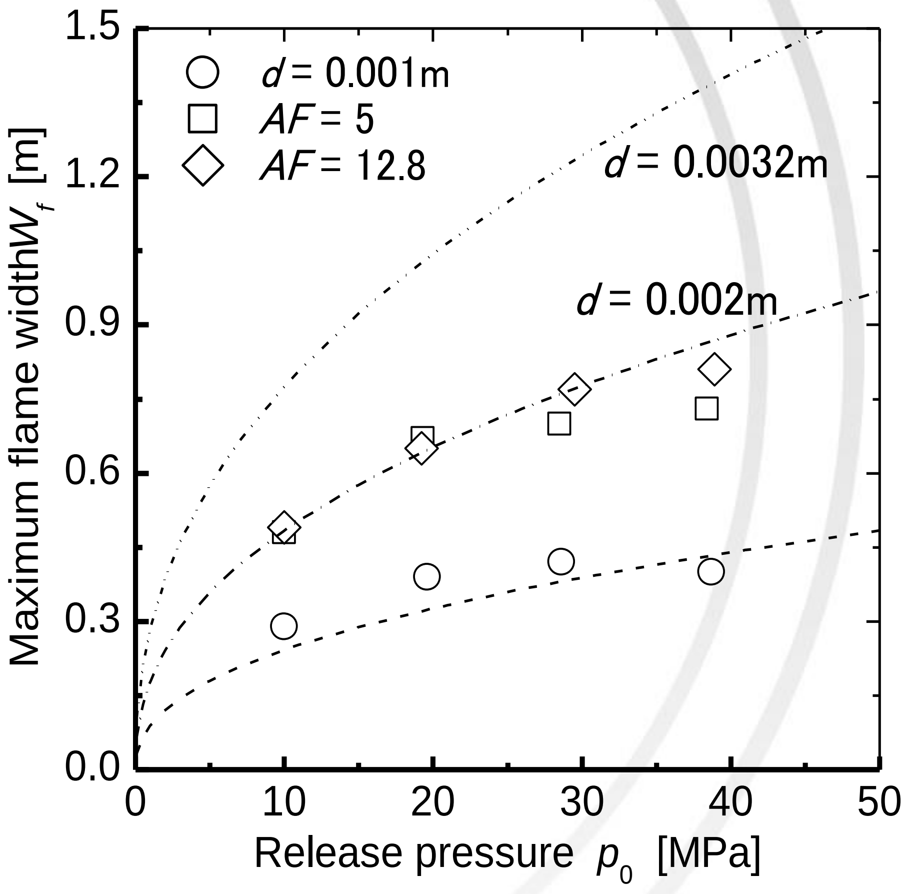
Nozzle shape effect on flame length





Length

Width

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Effect of a barrier wall on delayed ignition of hydrogen (1/2)

Barrier 90º: 9.5 mm, 800 ms (42 kPa; free jet only 16 kPa)

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Effect of a barrier wall on delayed ignition of hydrogen (2/2)

Barrier 60º: 9.5 mm, 800 ms (57 kPa; free jet only 16 kPa)

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Effect of an orifice diameter on overpressure

Orifice diameter, mm	Ignition delay, ms	Max overpressure, kPa
1.5	800	Not recordable
1.5	400	Not recordable
3.2	800	3.5
3.2	400	2.1
6.4	800	15.2
6.4	400	2.7-3.7
9.5	800	16.5
9.5	400	3.3-5.4

Conclusion:

- Reduce orifice diameter ALARP to reduce overpressure following ignition

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Effect of ignition source location on overpressure

Orifice d=6.4 mm. Fixed ignition delay 800 ms.

The ignition position (pyrotechnic system) was varied from 3 m to 10 m (h=1.2 m).

Ignition position, m	Max overpressure, kPa
3	5.0
4	2.1
5	2.1
6	Not recordable
8	Not recordable
10	No ignition

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Visibility of hydrogen flames

- Hydrogen burns with invisible in the daylight flame.
- Video 1 (day light) and Video 2 (IR camera).
- Real jet flame can be visible due to combustion of entrained particulates.
- Radiation emitted from hydrogen flames is very low.
  - The emissivity <0.1 (ADL,1960).
  - Sandia National Laboratory (US) research: emissivity <0.3.
- Hydrocarbon flames have emissivity around 1 (reference).

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Heat flux prediction (1/2)

1. Evaluation of the radiant fraction χ: fraction of total chemical energy release converted into energy radiated to the surroundings.

The expression of radiant fraction used in the model was derived by Molina:

$$\chi = 0.08916 \cdot log_{10}\left(t_f \cdot \alpha_f \cdot T_{ad}^4\right) - 1.2172$$

Turns and Myhr's equation for residence time evaluation:

$$t_f = \frac{\pi}{12} \frac{\rho_f \cdot W_f^2 \cdot L_f \cdot Y_s}{\dot{m}}$$

ρ_f is the flame density and it is evaluated through the following expression:

$$\rho_f = \frac{P_{amb} \cdot MW_{st}}{R_u \cdot T_{ad}}$$

t_f: flame residence time (milliseconds);
α_f: Plank's mean absorption coefficient for the product species ($\alpha_{f,H2O}$=0.23 m^{-1});
T_{ad}: adiabatic flame temperature;
Y_s: hydrogen stoichiometric mass fraction (Y_s =0.0281);
L_f : visible flame length,;
W_f: visible flame width;
$\dot{m}$: mass flow rate;
P_{amb} : ambient pressure;
MW_{st}: stoichiometric molecular weight of the hydrogen combustion products in air (MW_{st}=24.52 g/mol);
R_u: universal gas constant (R_u =8314.47 g/(kmol·K).

Heat flux prediction (2/2)

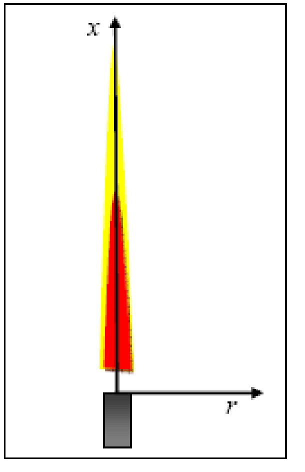
2. Evaluation of surface emissive power S: $S = \chi \cdot \dot{m} \cdot \Delta H_c$

ΔH_c: gas heat of combustion ($\Delta H_{c,H20} = -119\ MJ/kg$); $\dot{m}$: mass flow rate

3. Evaluation of the radiative heat flux at the observer location q is a product of the surface emissive power, of the view factor VF and the atmospheric transmissivity τ: $q = VF \cdot S \cdot \tau$

The view factor VF and the atmospheric transmissivity τ are **function of the model chosen to represent the flame**:

- <u>single source emitter</u>: the source is considered as a point located at the middle point of the predicted flame length.
- <u>weighted multi-source model</u>: decomposition of the jet flame axis in N points, with N decided accordingly to the characteristics of the problem. Afterwards, each point is considered as a radiation emitter and it has a different contribution on the final balance of the heat flux.



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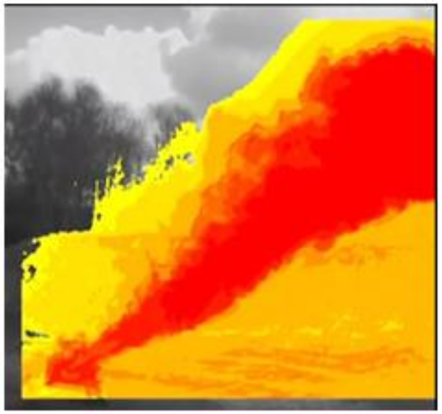
Sources: Houf et al (2013). International Journal of Hydrogen Energy, Vol. 38 8092-8099;
Ekoto et al (2014), International Journal of Hydrogen Energy, Vol. 39 39 , 20570-20577

Comparison of hydrogen jets to common fuels

- Jet fires: Thermal effects

H2 @ 200 bar

CNG @ 200 bar



LPG @ 10 bar (liquid phase)

- Jet fires: Flame length

Equivalent Ø: 3,1 mm
H2 length flame: 5,5 m

Equivalent Ø: 3,1 mm
CNG length flame: 8 m

LPG length flame

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Fireballs (rupture of a storage tank in a fire)

Hydrogen fireball about 70 ms after tank rupture (under the vehicle)

Hydrogen fireball about 170 ms after tank rupture (under the vehicle)

Two tests: 1) stand alone hydrogen tank. Catastrophic rupture after 6 min 27 s. Diameter $D_{fb} = 7.7\ m$; time $t_{fb} = 4.5\ s$

2) hydrogen tank installed on a typical SUV. Catastrophic rupture after 12 min 18 s. Diameter $D_{fb} = 24\ m$; time $t_{fb} = 4.5\ s$ (please see two images above)

Source: Zalosh, 2007

Delayed ignition: Test conditions (HSL)

- ✓ Storage pressure: **205 bar** (two 50 litre cylinders).
- ✓ Stainless steel tubing ID=11.9 mm, a series of ball valves with internal bore of **9.5 mm**. Restrictors of 2 mm length and diameter: **1.5, 3.2, 6.4 mm**.
- ✓ Ignition by a match head with small amount of pyrotechnic material. Ignition **1.2 m** above the ground.
- ✓ The release point is **1.2 m** above the ground.
- ✓ Ignition point is located **2-10 m** from the release point.
- ✓ Piezo-resistive transducers pointed out upwards (except for wall mounted). Sensors are located at **axial distance 2.8 m** from the nozzle, **1.5 m** (then +1.1 m and +1.1 m) perpendicular to the axis, at height **0.5 m**.
- ✓ 260 ms to fully open the valve, 140 ms for hydrogen to reach 2 m, i.e. **400 ms is shortest ignition delay**.

Free jet fire: 9.5 mm, 800 ms (16.5 kPa)

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Infrared 4.1-5.3 microns (16.5 kPa)

Effect of ignition delay on overpressure

Orifice d=6.4 mm. Ignition 2 m from the orifice.

Ignition delay, ms	Max overpressure, kPa
400	3.7
500	18.4
600	19.4
800	15.2
1000	11.7
1200	12.5
2000	9.5

Spontaneous ignition should reduce overpressure of self-ignited release (no SI observed with a valve use).

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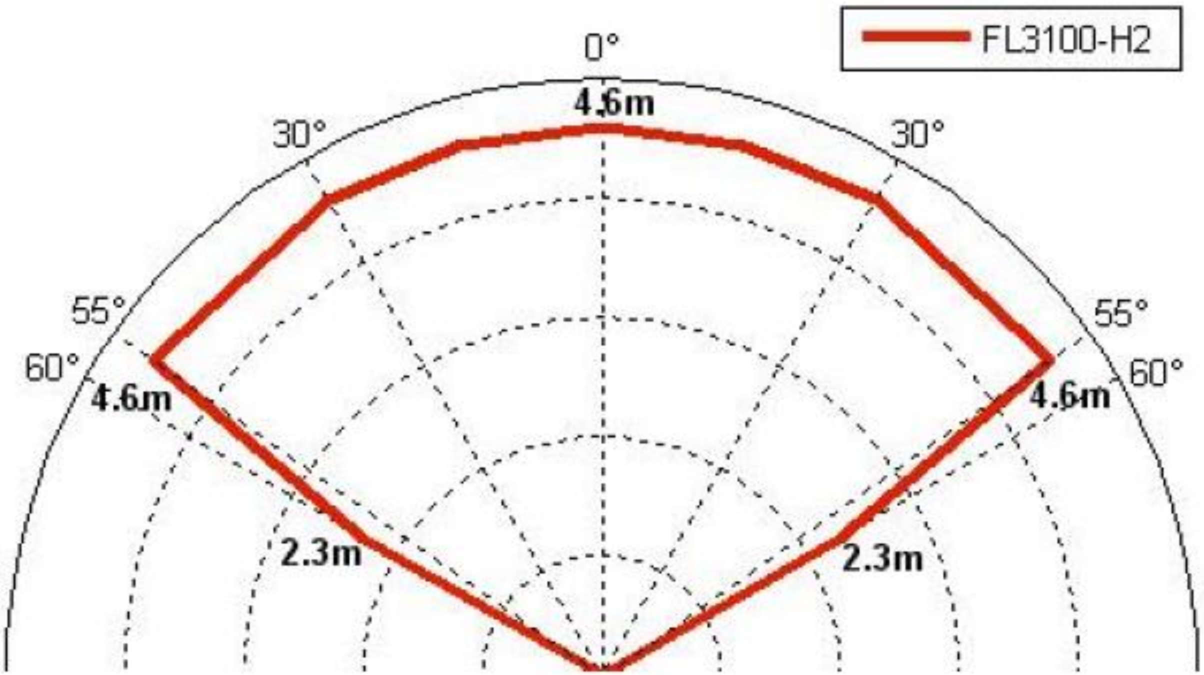
Hydrogen fire sensors

Type	Pluses	Minuses
UV/IR	Moderate speed. Moderate sensitivity. Low false alarm rate. Not blinded by CO_2 fire protections discharges. Automatic self-test.	False alarms possible in case of combination of IR and UV sources. Blinded by thick smoke and vapours. Price.
Triple IR	Very high sensitivity. Very high speed.	Price
IR/vis imaging	Images the flame. Used by NASA.	Price

HyResponse

UV/IR Hydrogen fire detectors

- The detection range of a hydrogen-specific flame detector for a plume 15–20 cm (6–8 inches) high and 15 cm (6 inches) in diameter. This flame detector can detect the on axis range of 4.6 m (15 ft) up to $\pm 55^{\circ}$, providing broad angular coverage.



Detection range of a General Monitors FL3100 UV/IR – H_2 detector.
Size of hydrogen fire: 15 cm (6 in) diameter and 15 – 20 cm (6 – 8 in) high.

HyResponse

Overview of vehicle fires

Statistics:

- UK - 28,800 road vehicle fires in 2011-12
- USA - 172,500 automobile fires in 2012
- Types of vehicles: motor cars, heavy goods vehicles, light goods vehicles, public transport vehicles etc.

According to Fire statistics (2011-2012) in Great Britain:

- The majority (65%) of fires occurred in cars, 10% were in vans, 4% were in lorries and 2% in buses or minibuses.
- Fire causes: accidental, deliberate or unknown
- The majority of deliberate fires (43%) involved road vehicles – 13,900 fires.
- The number of fatalities in road vehicle fires in 2011-12 was 37.

Source: Fire statistics, Great Britain, 2011-2012. Department of Communities and Local Government

Risks and statistics

- Recent data shows that about **10% of vessel failure is catastrophic!** This means that catastrophic failure cannot be ruled out of the risk assessment [1].
- **Currently (!!!) due to more severe consequences, the risk is higher for FC vehicles compared to conventional cars!**
- People/customers would not be happy to know that they might die with a probability of 10^{-4} or 10^{-6}. They wish to know that everything is done for safety.

❖ During 2000-2006: 20 documented CNG tank failures, 11 have been attributed to vehicle fires [2]. Of these 11 incidents, the evidence suggests that the majority of the PRDs failed to activate (localized fire).

❖ CNG and hydrogen storage tanks: "testing has shown that all fuel tanks regardless of working pressure are highly susceptible to rapid degradation due to localized fires" [2].

HyResponse

Sources:
[1] The relative frequency of failure modes. http://www.h2safe.com/case_safety.html
[2] Gambone, L.R. and Wong, J.Y., Fire Protection Strategy for Compressed Hydrogen-Powered Vehicles, ICHS2, 2007).

Upward release from a TPRD

A vehicle equipped with two cylinders (34 L capacity, at 35 MPa) fitted with a **TPRD, 5 mm in diameter.** PRD was actuated after 14 min 36 sec (Watanabe et al, 2007).

Is 10-15 m flame length from a car acceptable?
“No harm” distance is 25-40 m and a high pitched noise from the jet!
What if a car parked in a garage or in a multi-storey parking facility (“domino” effect)?

TPRD release directed downwards

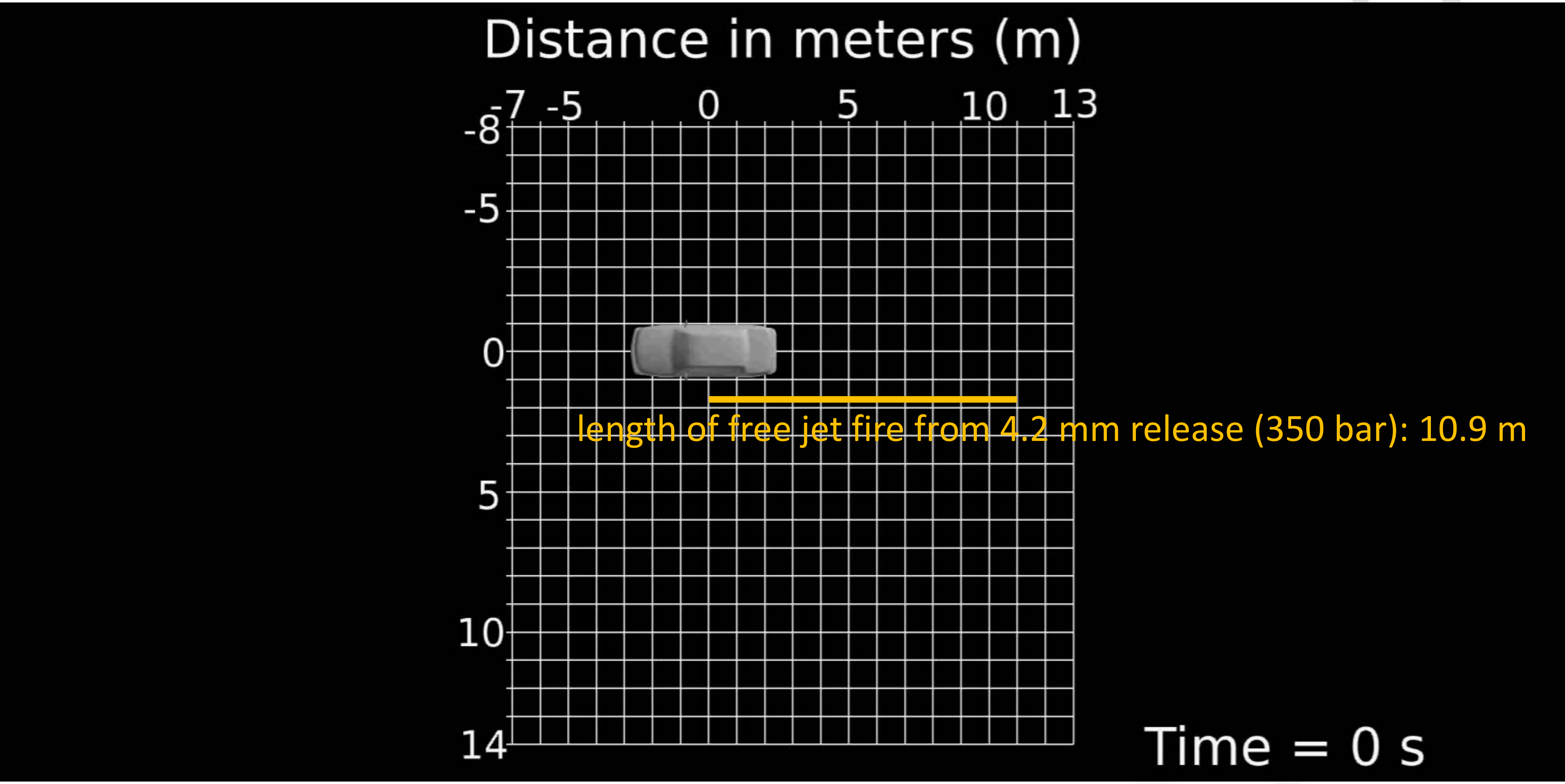
- A fire was initiated on the instrumentation panel ashtrays. The PRD was actuated in 16 min 16 sec (downward). **Blow-down in less than 5 min** (**no catastrophic tank failure, but…**).

Current size of TPRD does not allow self-evacuation and rescue operations.

What if a car is indoors?

Flame length: 10.9 m down to 5.2 m

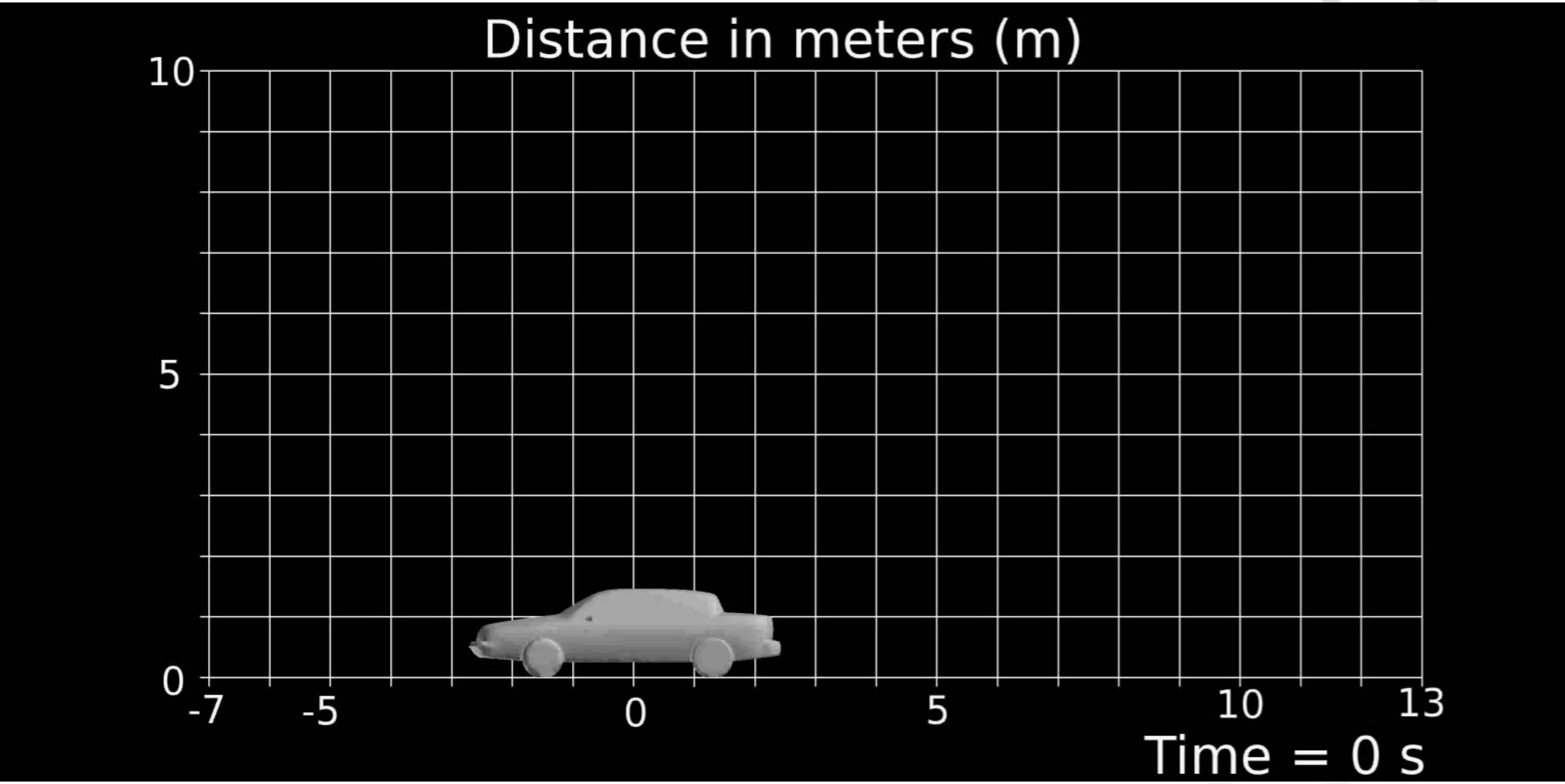
- Release 0º (flame temperature 1300ºC)



Flame length 10.9 m (correlation), 5.2 m by CFD (longest in 2 s)

No harm distance: 38 m down to 6 m

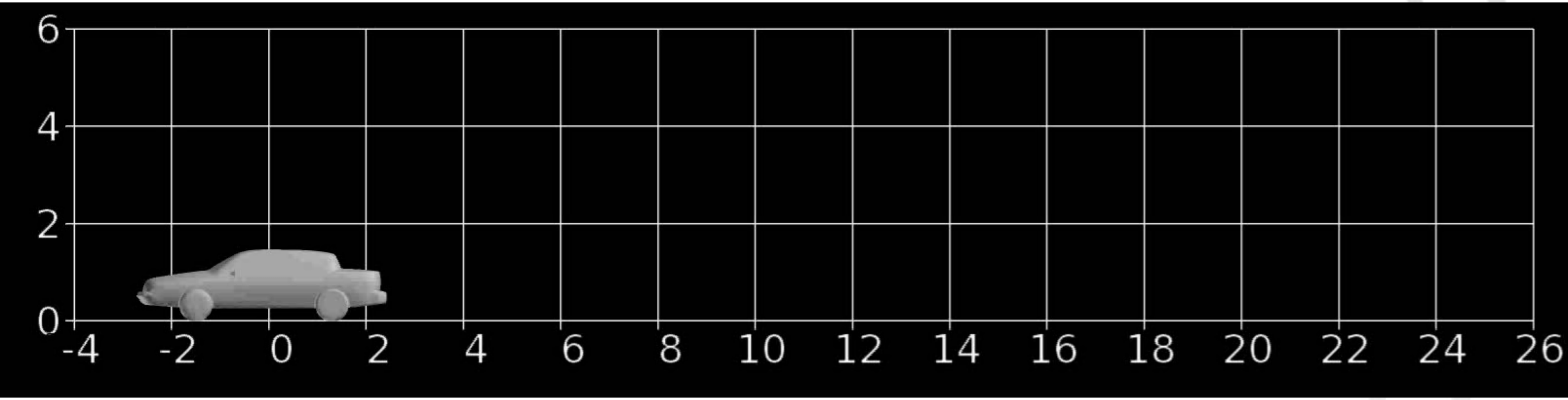
- Release 0^{o} (temperature 70^{o}C envelope)



No harm (horizontal!) 10.9x3.5=38 m (correlation), 6 m (CFD)

Flame length: 10.9 m down to 9.7 m

Release 30º (evacuation route still blocked)



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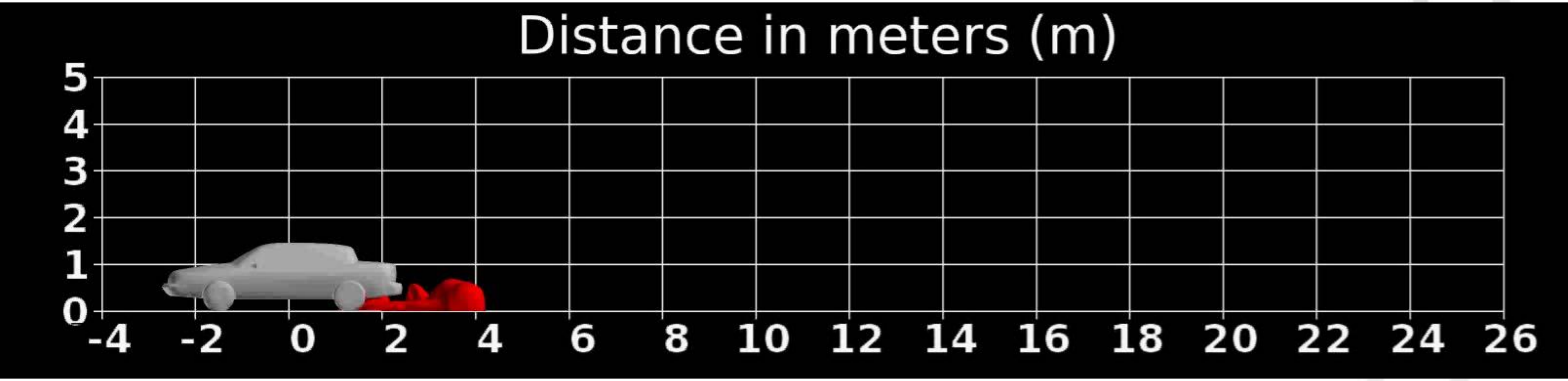
Flame length: 10.9 m “down” to 10.5 m

Release 45º (evacuation and rescue possible)



No-harm distance decreases from 38 m (correlation) to 23 m (CFD)

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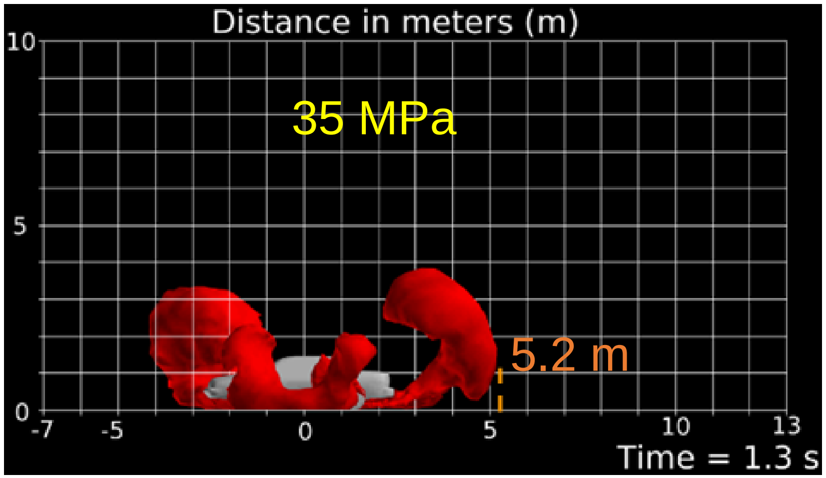
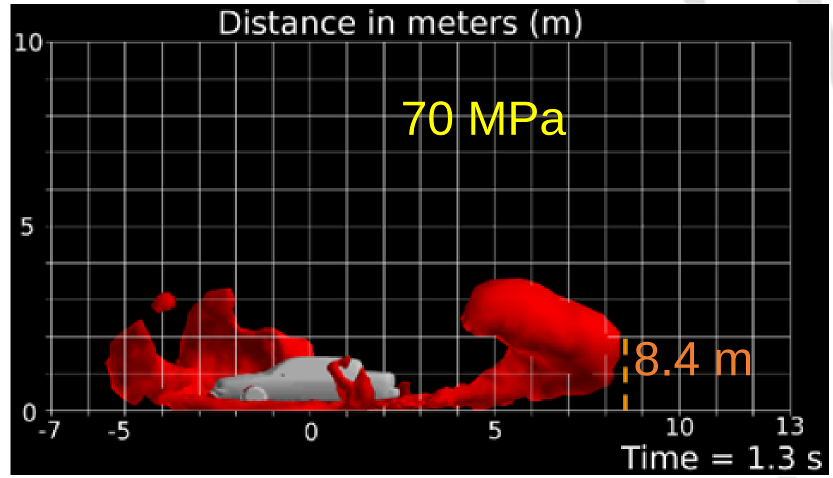
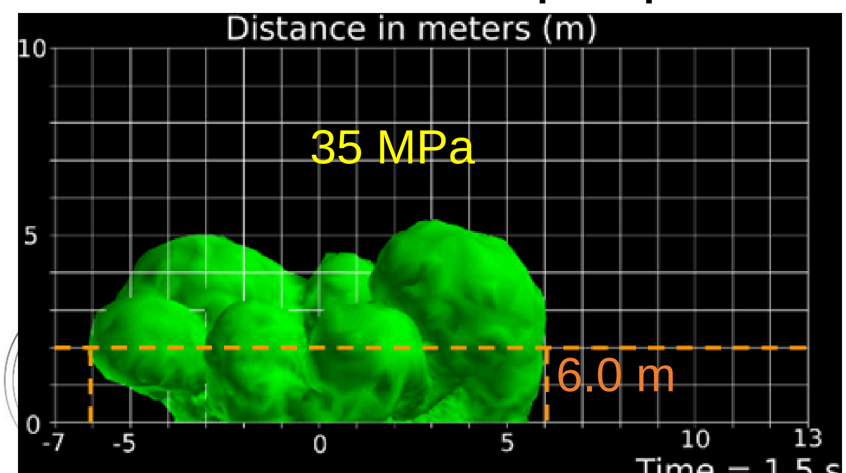
Hazard distances

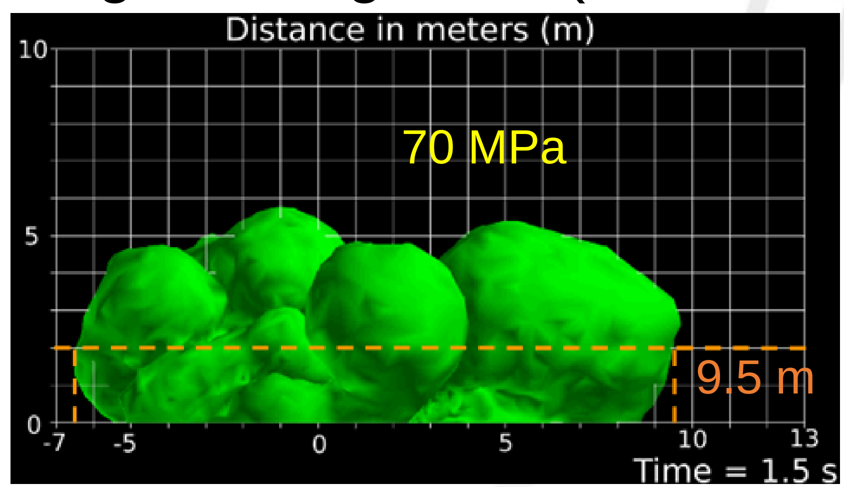
Hazard distance from visible hydrogen fire (1300 ºC flame)





Hazard distance for people standing on the ground (below 2m)





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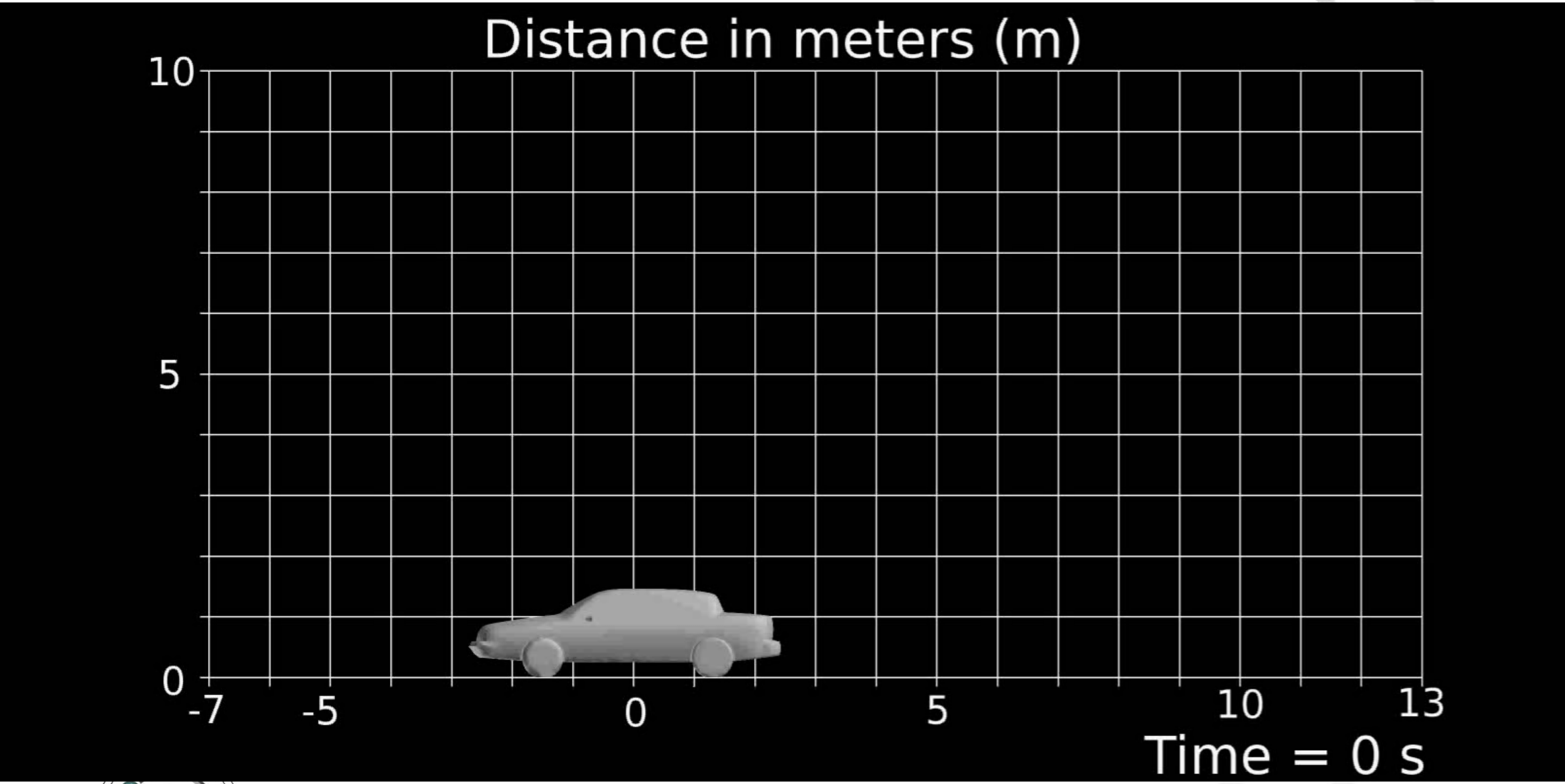
70 ºC envelope (70 MPa)



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Jet fire prevention and mitigation

- Direction of the jet flow

The flow shall be directed so that it will not reach people or equipment. For example, flanges (components where leaks are likely) should be placed and directed in such way that a potential leak would not cause any domino effects.

- Shielding or barriers

It will reduce the rate of heat transfer to the potential targets in the vicinity of a hydrogen fire. Flame shields are specifically intended to reduce the radiant heat flux by preventing direct flame impingement on systems or equipment. The correct choice of materials for shields or barriers is very important.

- Reduction of flame length

For example through the use of innovative PRDs with decreased diameter and use of plane nozzles (see next slide).

HyResponse

Innovative PRD-1 (350 bar)

Flame length reduction: 7.5 –> 1.8 m

Innovative PRD-2 (350 bar)

Flame length reduction: 6.1 –> 1.8 m

Innovative PRD: shorter flame

Current PRD **Current PRD**

Short flame PRD **Short flame PRD**

HyResponse

Use of thermal insulation

- The purpose of thermal insulation is to reduce the rate of heat transfer to potential targets, e.g. hydrogen tanks located near hydrogen jet fire
- The equipment is usually protected with the materials which:
  - Have relatively low heat conductivity
  - Are non-combustible and do not produce smoke or toxic gases when subjected to high temperatures
  - Provide uniform protection
  - Allow efficient and uniform application
  - Durable and have sufficient bond strength
  - Weather-resistant

Fire protection coatings (e.g. intumescent) for hydrogen storage tanks (research on-going at Ulster)

Tank with 2 mm intumescent coating

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Extinction of hydrogen fires

The recommendations from the US National Hydrogen and Fuel Cell Emergency Response Training, 2014

First Responders should:

- listen for venting gas, and watch for thermal waves that would signal hydrogen flames
- if only one FC vehicle is involved, approach from a 45° angle per standard procedures, and from a downhill and upwind position
- if a hydrogen fire is present:
  - Allow the hydrogen supply to burn out if safe to do so and protect adjacent exposures; then approach and extinguish.
  - If a hydrocarbon fire is also present, attack the fire with a straight water stream from a distance, but avoid directing the water stream into the hydrogen tank's pressure-relief-device vent line. Control fire spread and cool exposures.
  - If possible, direct venting hydrogen that is not burning away from ignition sources and dissipate if necessary with fog nozzle streams.
  - Spray foam on petrol or diesel leaks near FC vehicle.

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