Hydrogen Safety Basics

Kees van Wingerden

General course of events involving release of flammable gas or liquid

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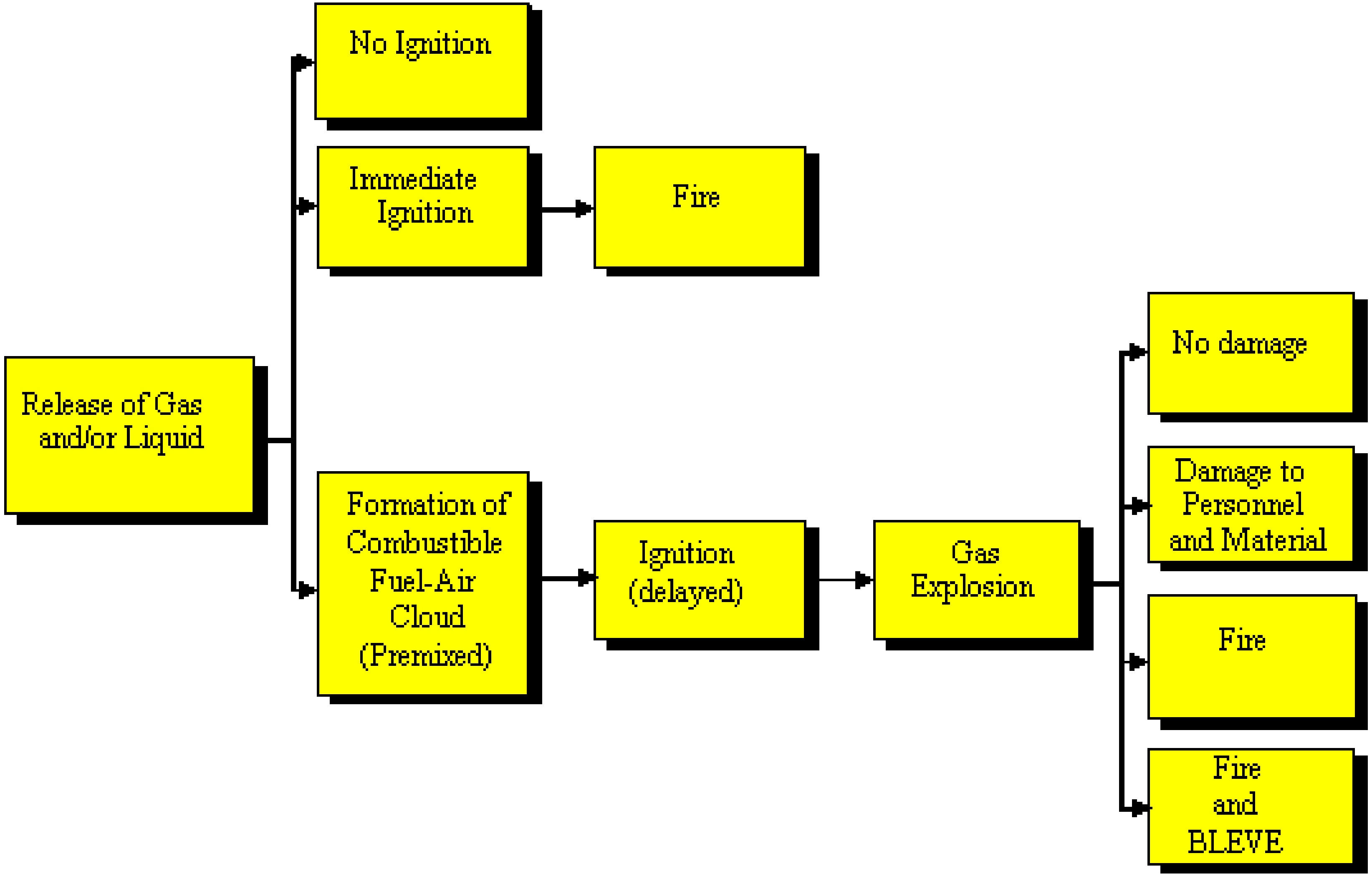
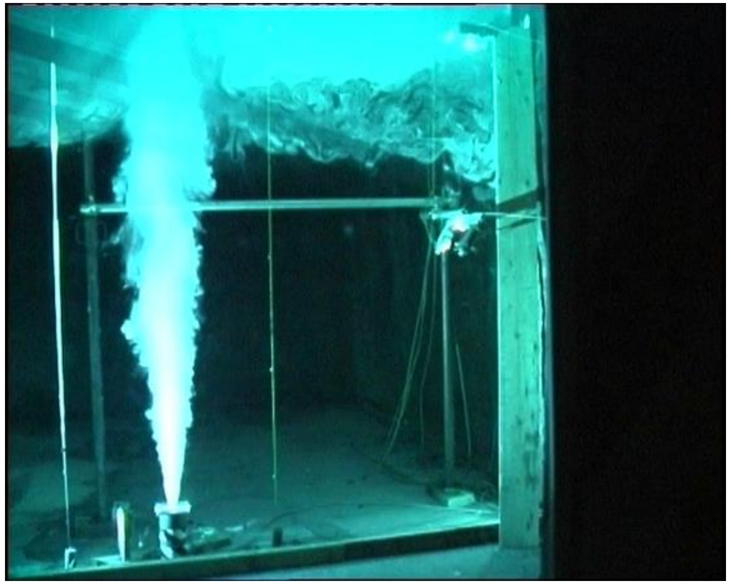
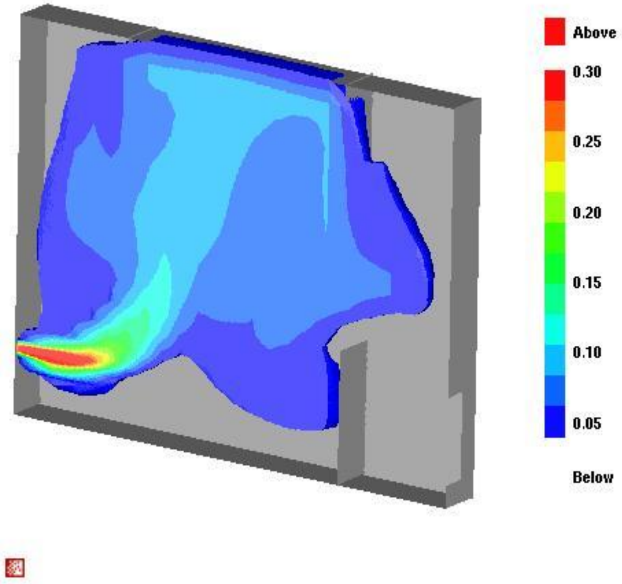
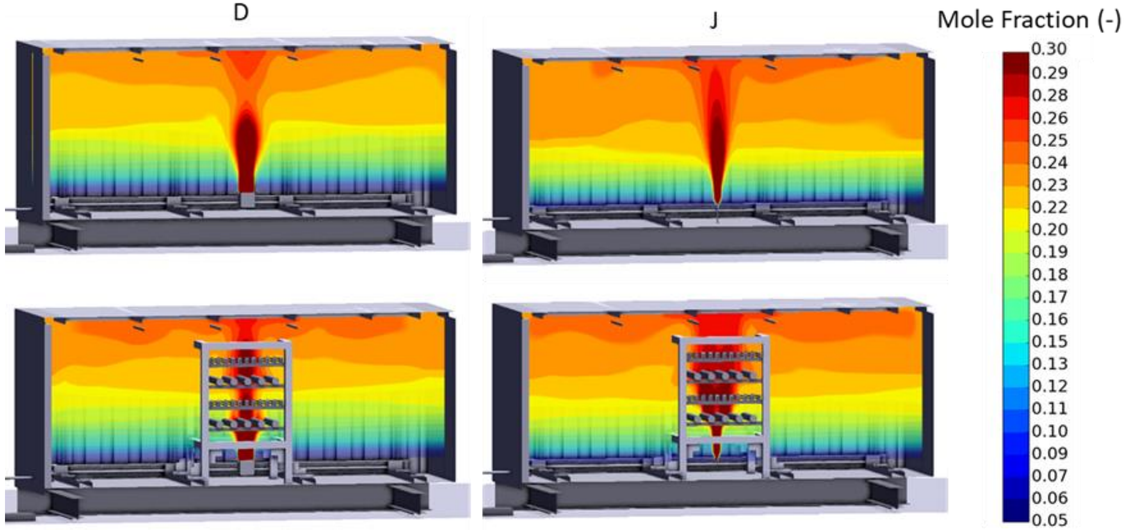


Hydrogen leaks

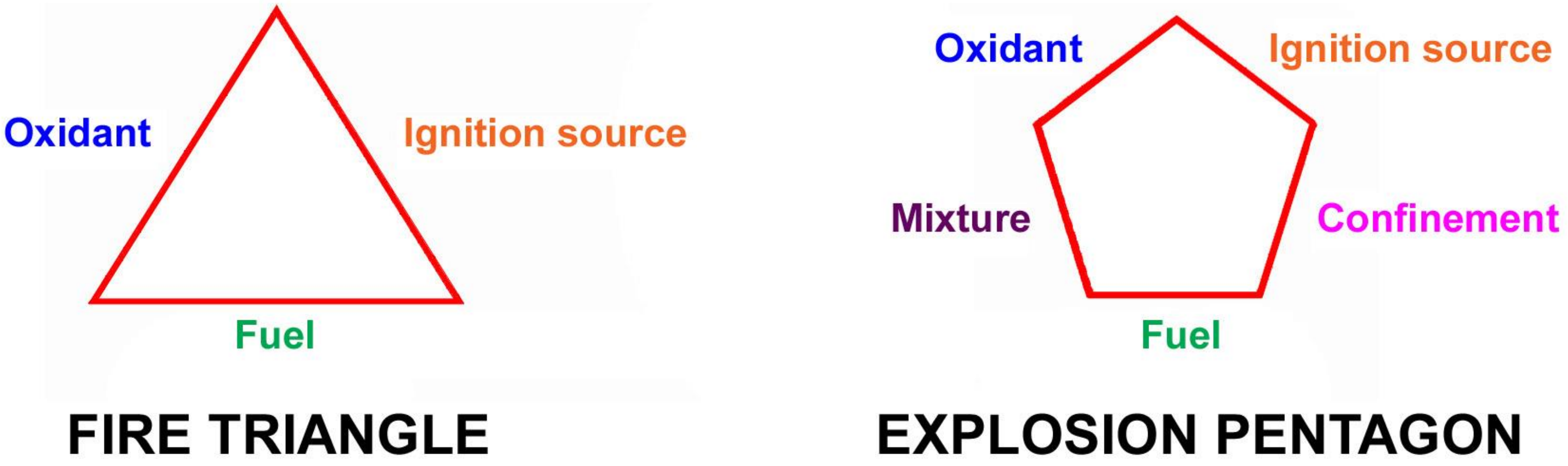
Hydrogen has a low density causing it to disperse upwards and generate flammable gas layers against the ceiling







Fire triangle and explosion pentagon



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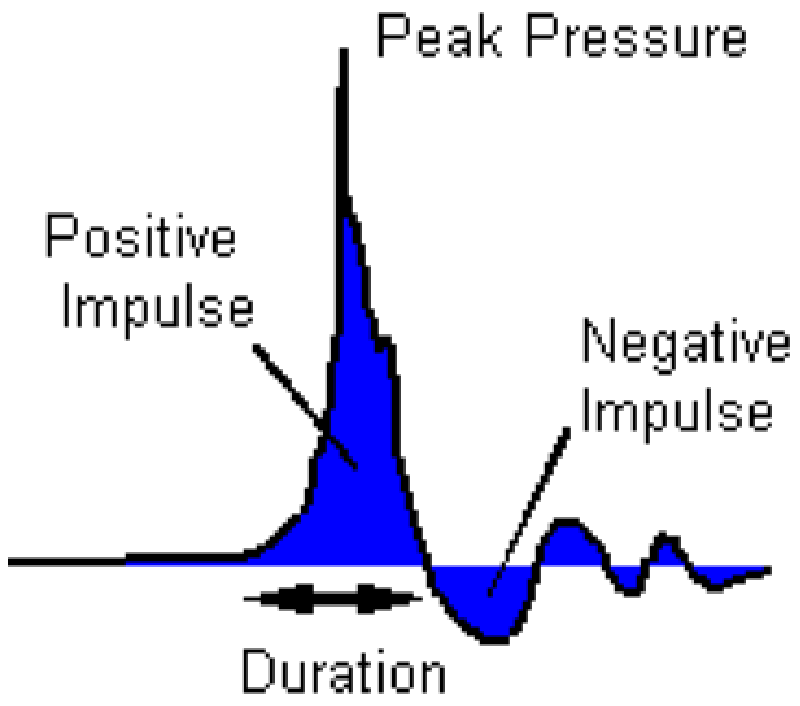
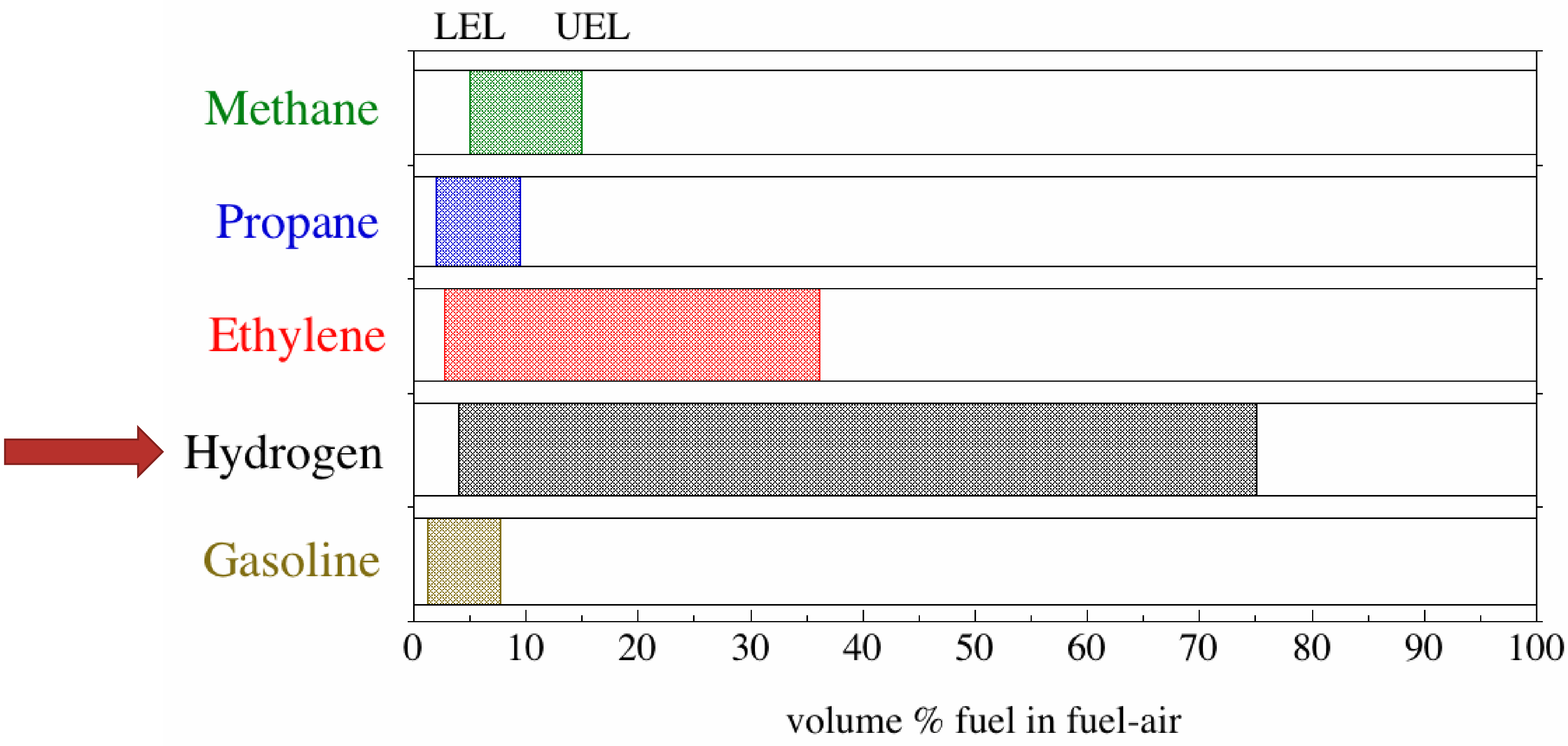
Definition explosion

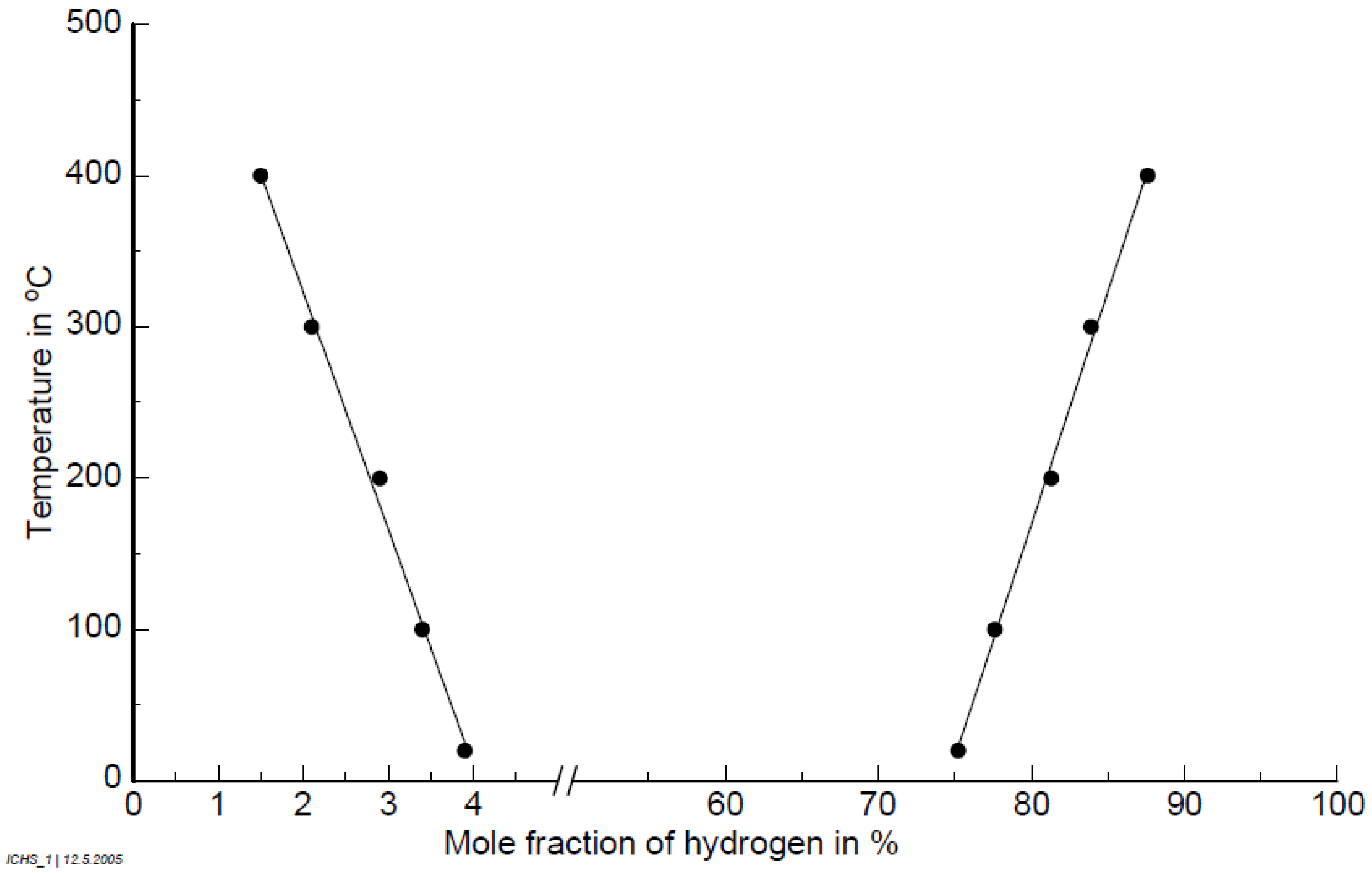
"An explosion is a chemical process which causes a very fast and considerable pressure increase"



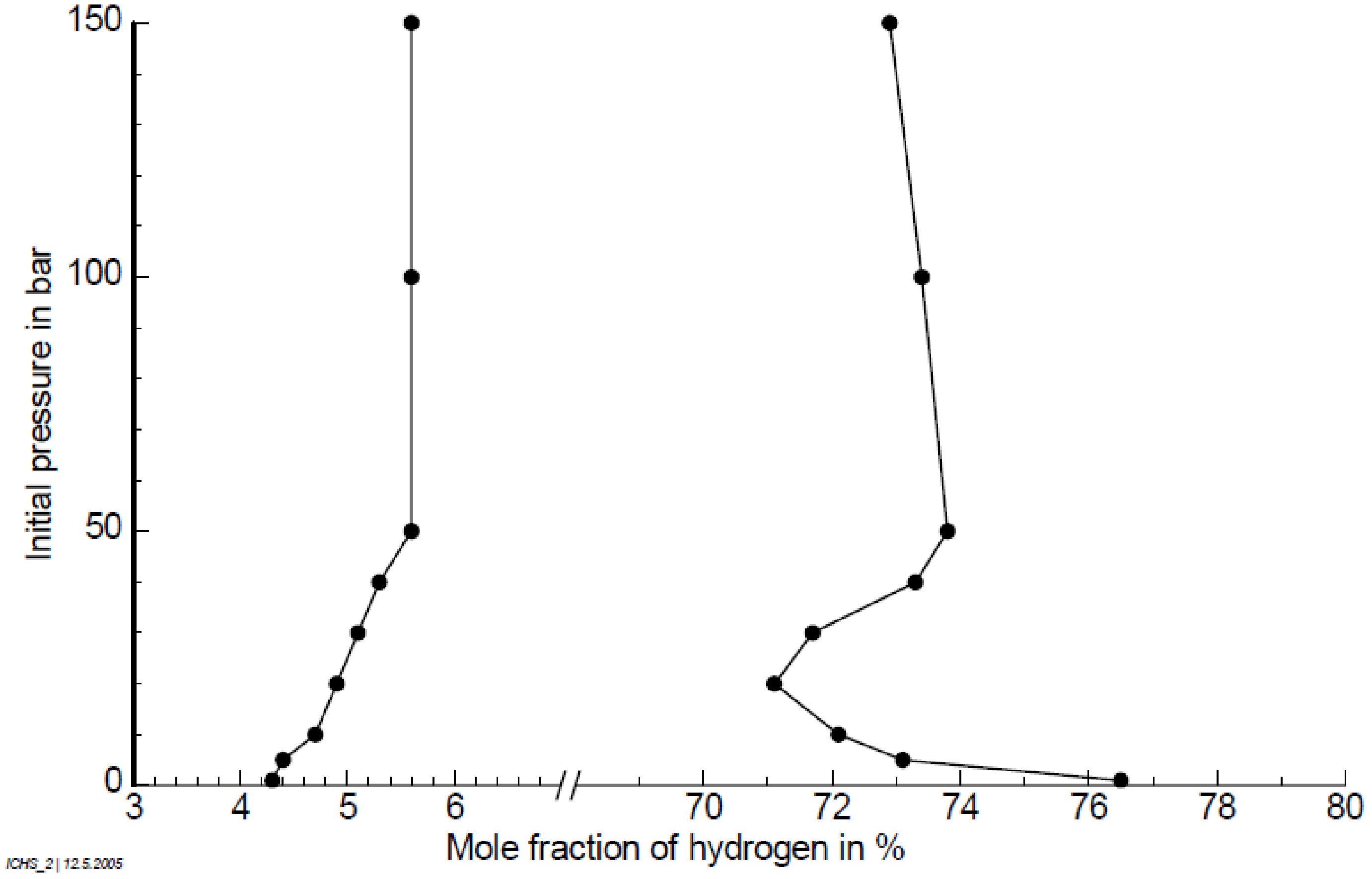
Explosive part of cloud



Effect of temperature on explosion limits hydrogen



Effect of pressure on explosion limits hydrogen



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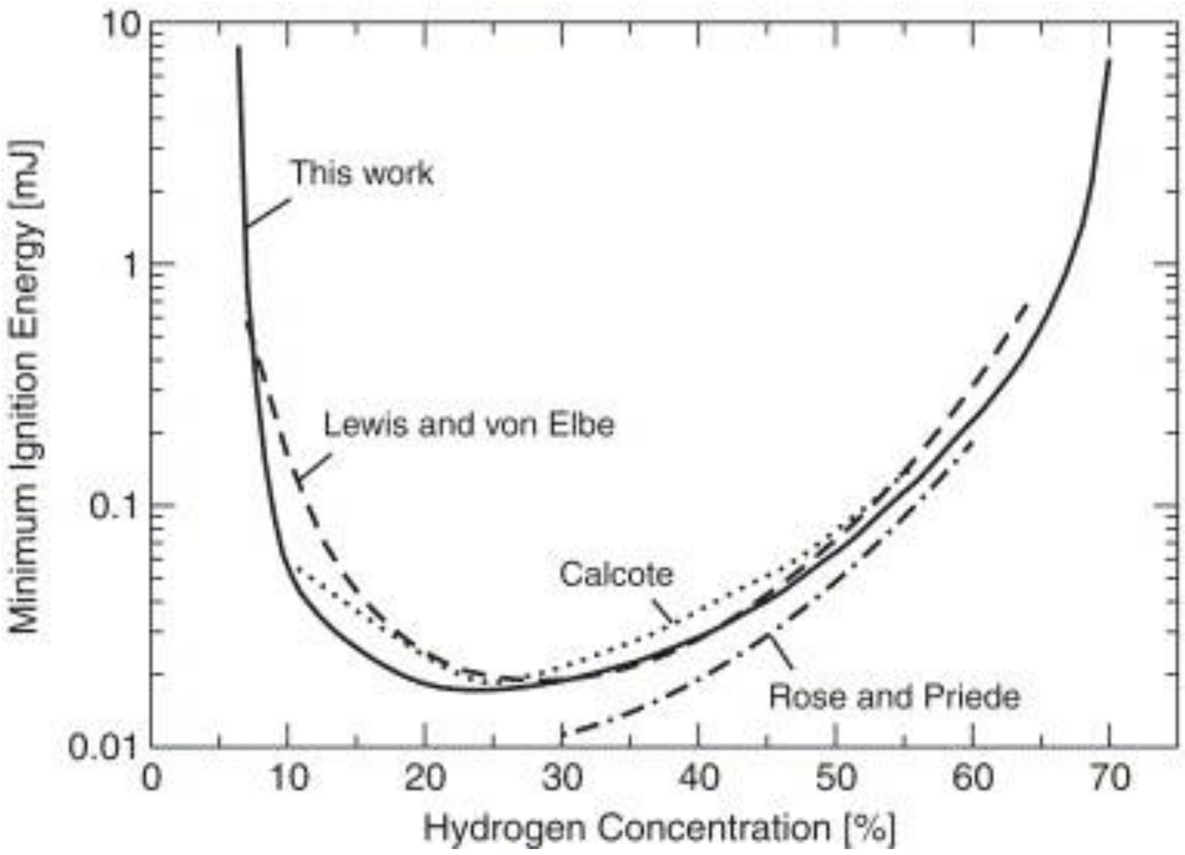
Minimum ignition energy (electric spark)



• Acetone	1.15 mJ
• Methane	0.28 mJ
• Butane	0.26 mJ
• Ethylene	0.07 mJ
• Acetylene	0.017 mJ
• Hydrogen	0.011 - 0.017 mJ
• Carbon disulphide	0.009 - 0.015 mJ

Auto-ignition temperature (hot surfaces)

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- The lowest temperature of a hot surface at which a mixture of fuel and air can ignite
  - Hydrogen 580 ^{0}C
  - Methane 537 ^{0}C
  - Propane 493 ^{0}C
  - Acetone 535 ^{0}C
  - Ethanol 363 ^{0}C
  - Petrol ca 250 ^{0}C
  - Diesel ca 220 ^{0}C

Chemical reaction

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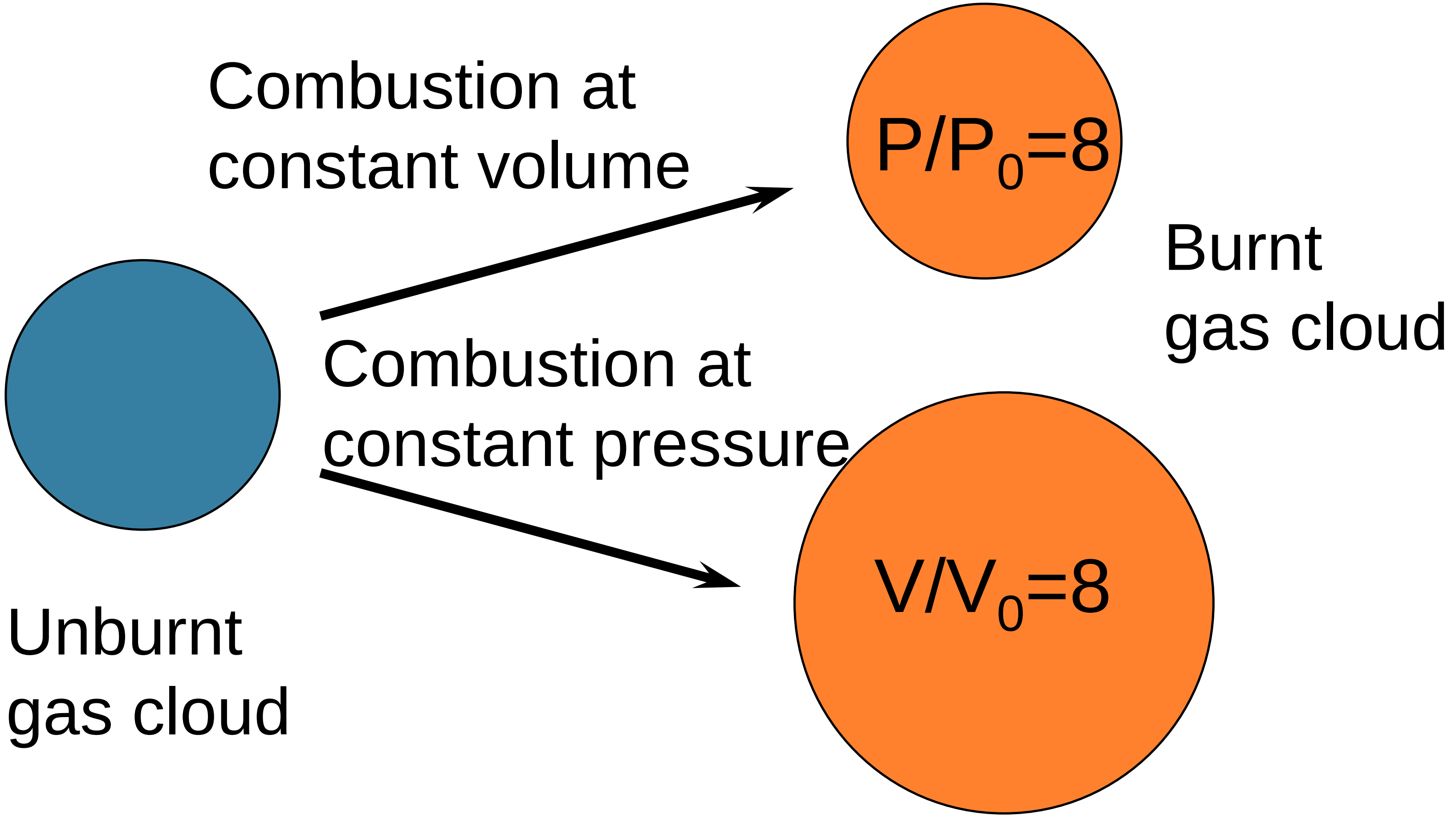
Simplified equation:

$$2H_2+O_2+3.76N_2 \rightarrow 2H_2O+3.76N_2 + \underline{\textbf{heat}}$$

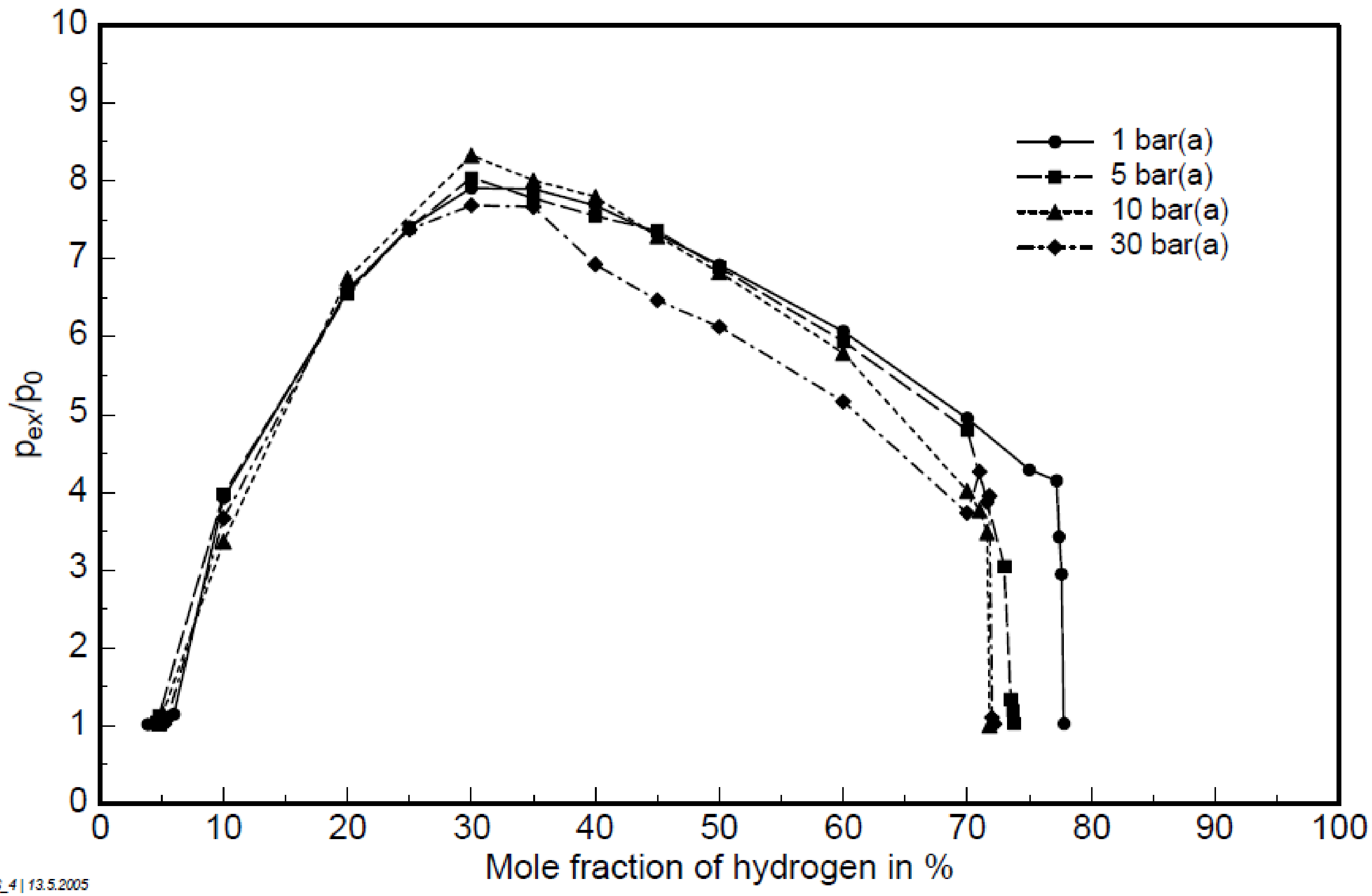
In reality: ≈57 reactions, 268 species equations

Product composition depends on mixture, temperature, pressure

Combustion at constant pressure and volume



Closed vessel explosion: maximum explosion pressure



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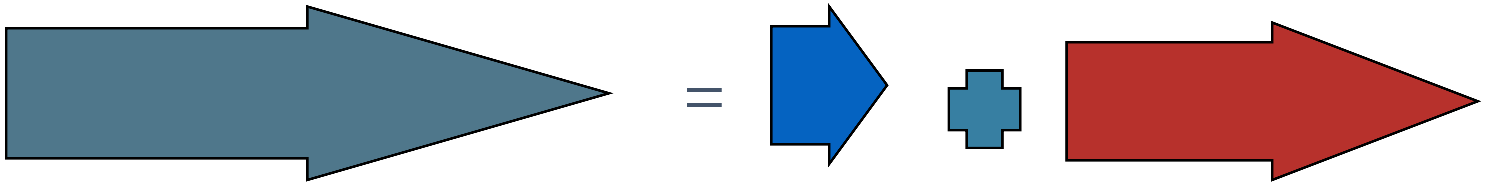
Flame propagation and acceleration mechanisms

- Laminar combustion
- Flame instabilities
- Explosion generated turbulence dominated flame propagation
- Deflagration-Detonation-Transition (DDT), Detonation
- Detonation

Laminar flame propagation

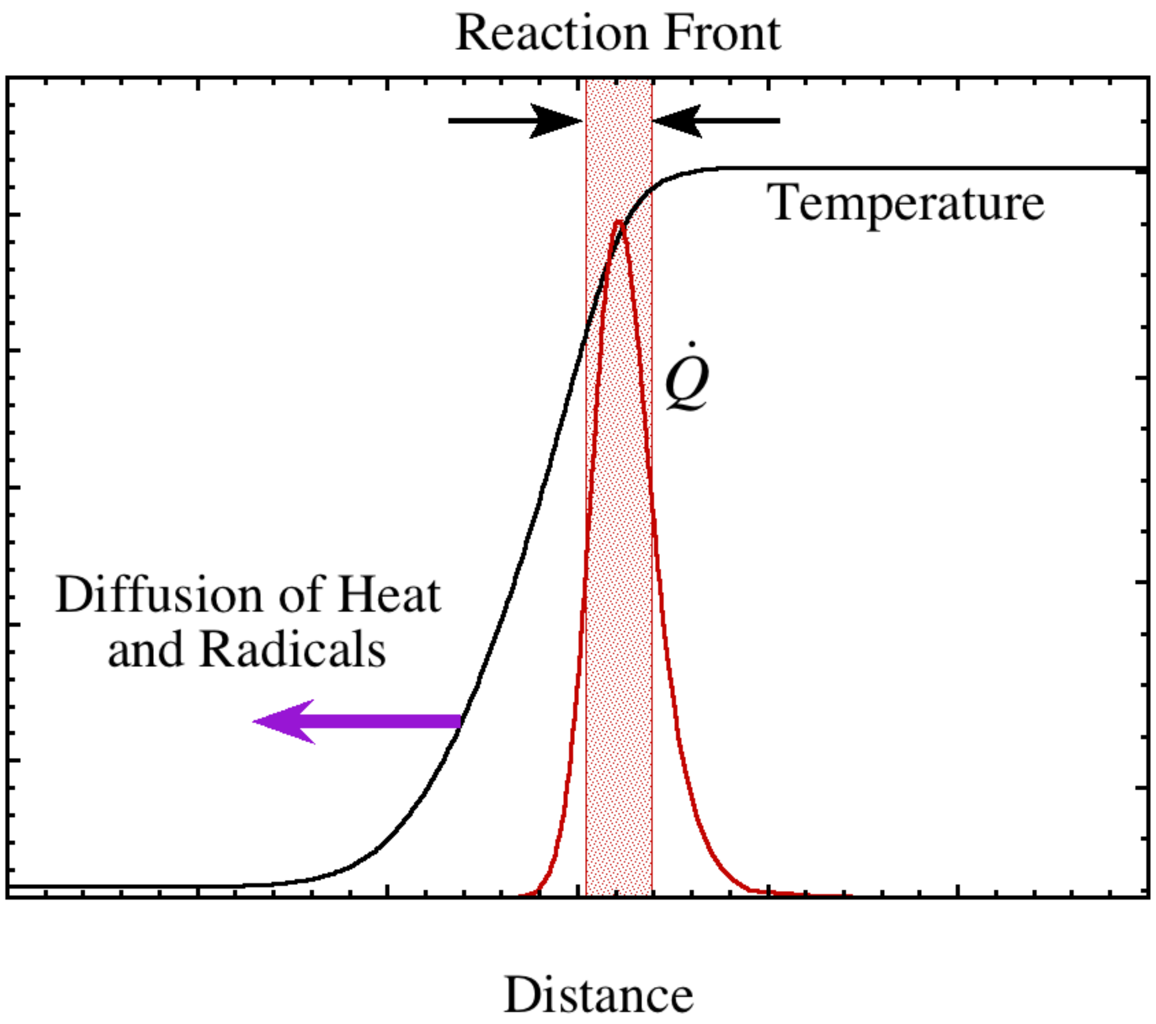
- Slow process (dominated by diffusion)
- Typical velocities (burning velocities): 0.5 m/s
- Expansion velocity: total velocity becomes: 3-4 m/s



$$S_f = S_u + S_g$$

$$S_f = S_u \rho_u / \rho_b$$

Laminar flame propagation



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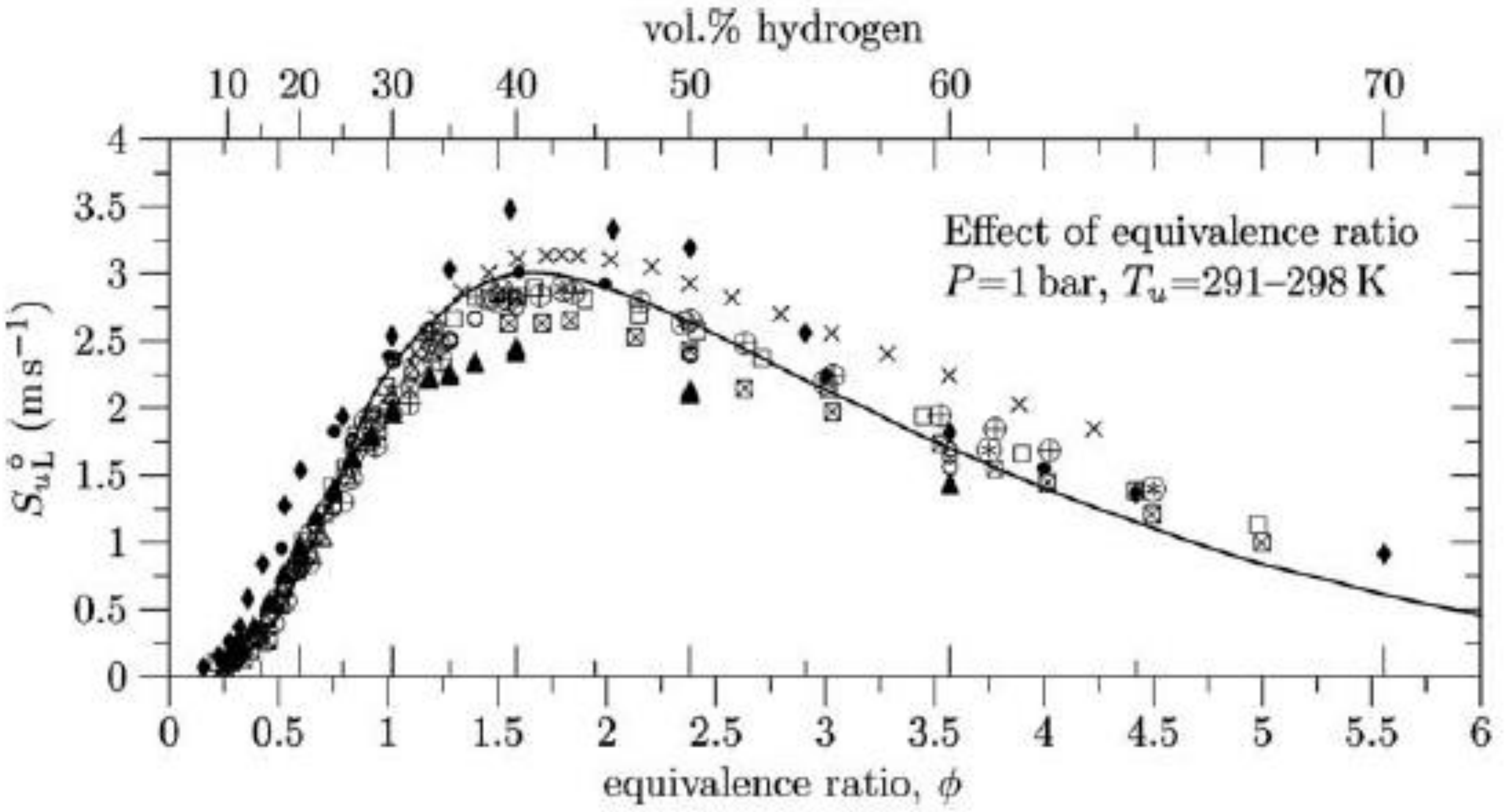
Laminar combustion

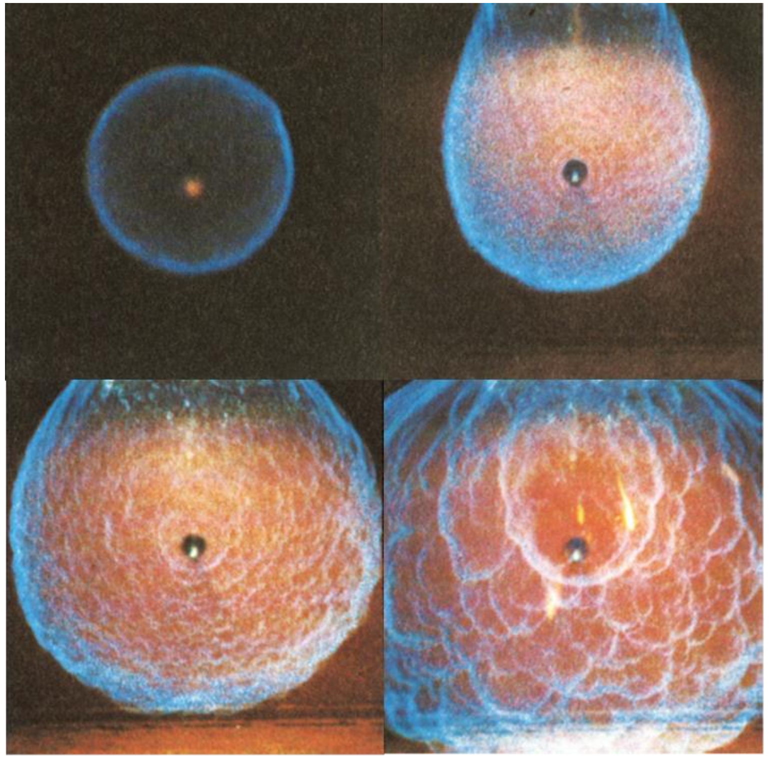
- Typical laminar burning velocities
  - methane: 0.40 m/s
  - propane: 0.46 m/s
  - ethylene: 0.75 m/s
  - acetylene: 1.55 m/s
  - hydrogen: 3.25 m/s
- Expansion ratio typically 7-10 ($a=n_2T_2/n_1T_1$)

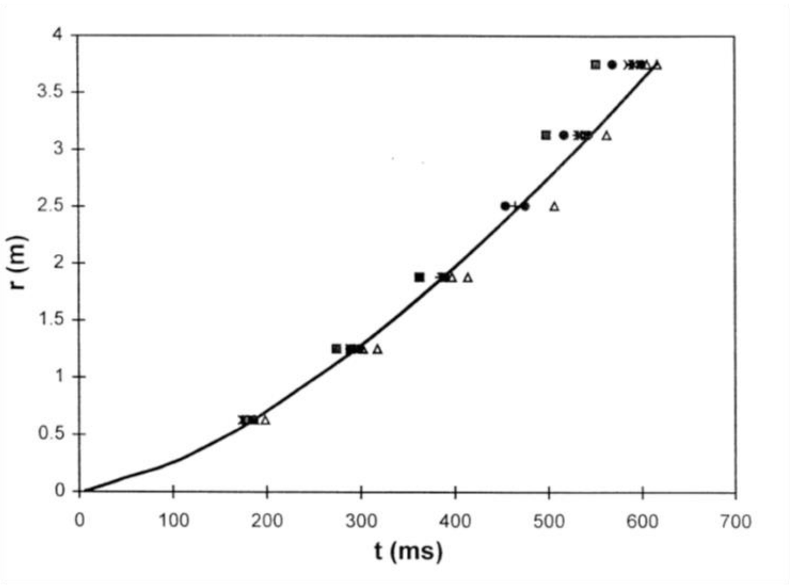
Laminar burning velocity



Flame instabilities

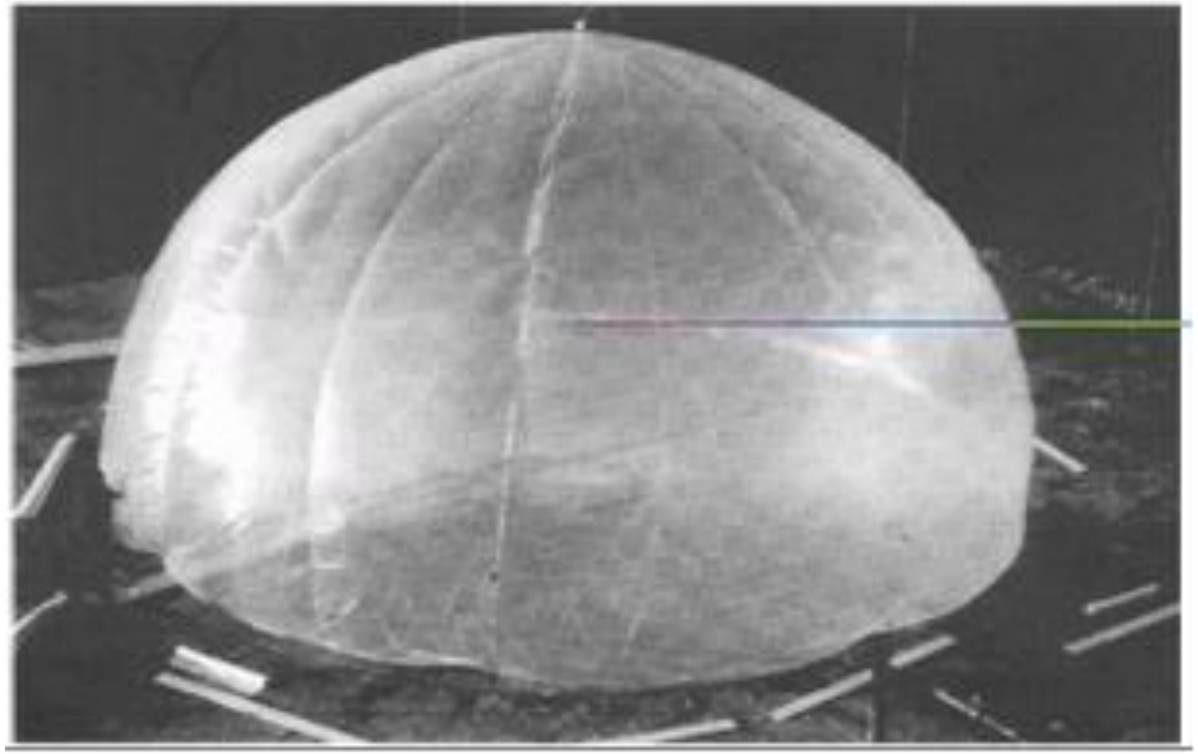
- Flame instabilities will cause laminar flames to accelerate, especially due to increase of flame area
- Example:
  - Intrinsic instability





Methane-air

Intrinsic flame instabilities: DDT?



Ignition of optimal hydrogen-air mixture in 20m diameter balloon (Fh-ICT, 1982) resulted in max. 60 mbar overpressure

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Turbulent combustion

- Turbulence causes an increase of burning velocities due to mixing of combustion products and reactants and due to an increase of the flame surface area
- Flame speeds (expansion + combustion) can vary from 5-600 m/s

Explosion generated turbulence

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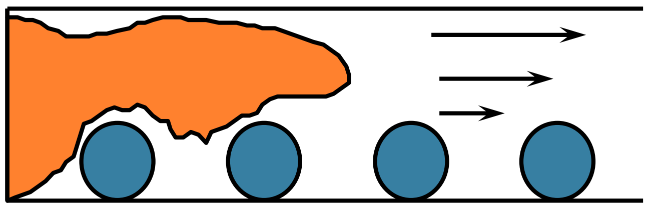
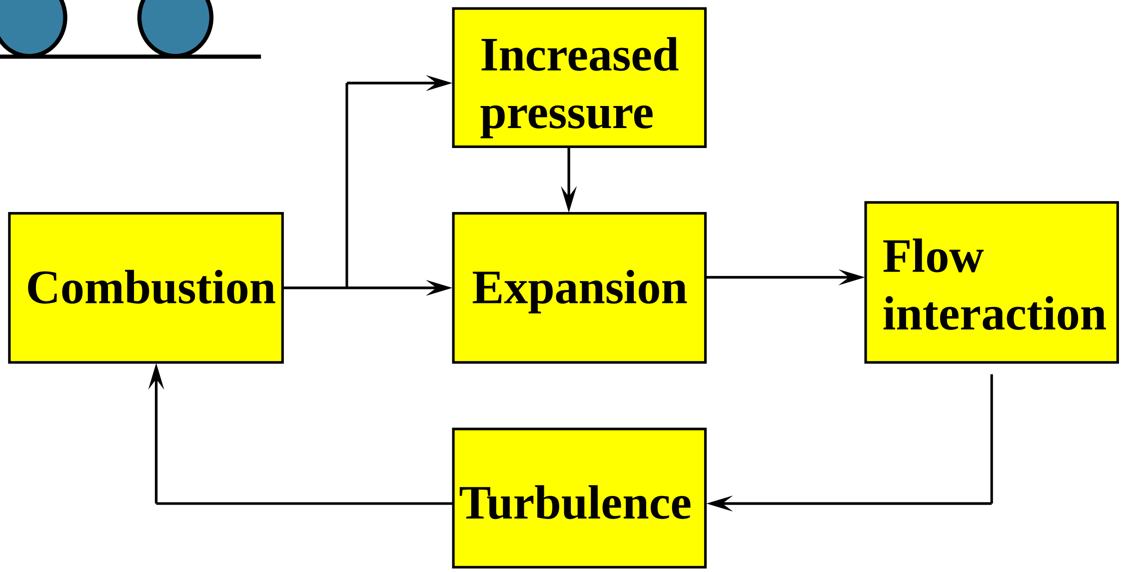
- Positive feedback mechanism of explosion generated flow and combustion

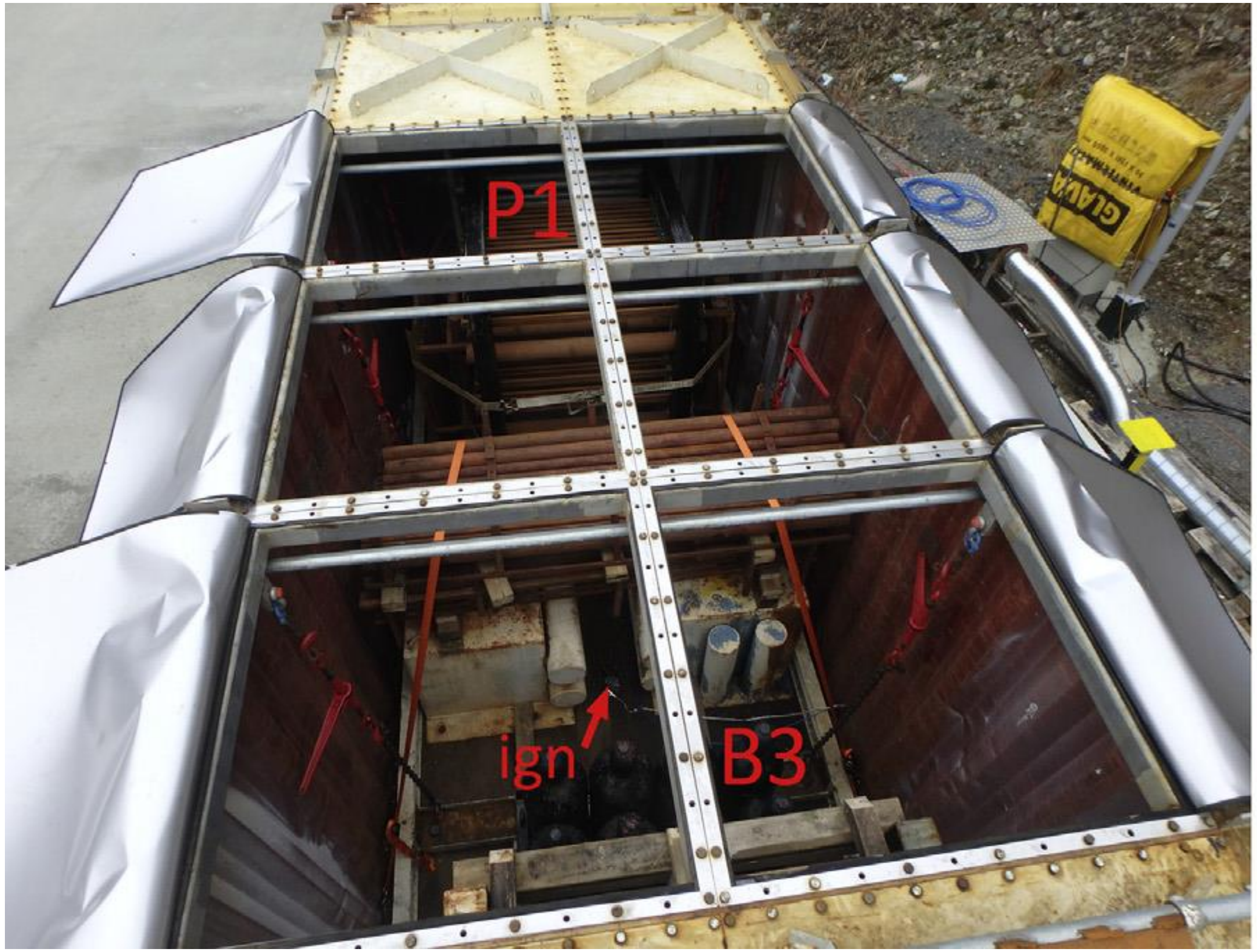


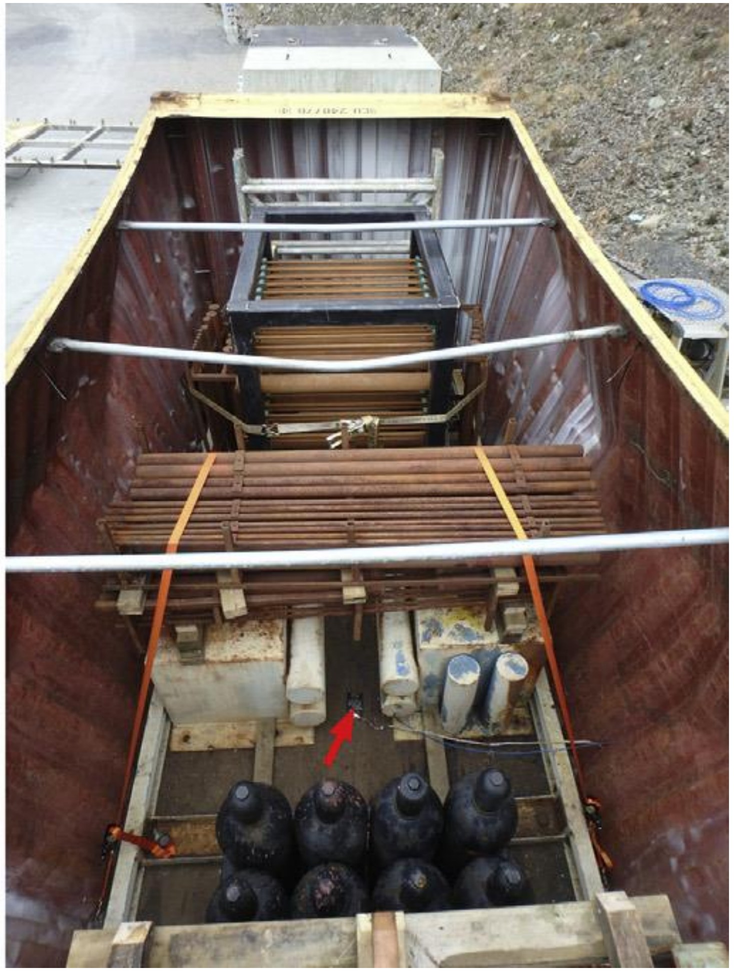


Explosion generated turbulence

- Positive feedback mechanism of explosion generated flow and combustion

High congestion inside module





12 vol.% hydrogen, high congestion

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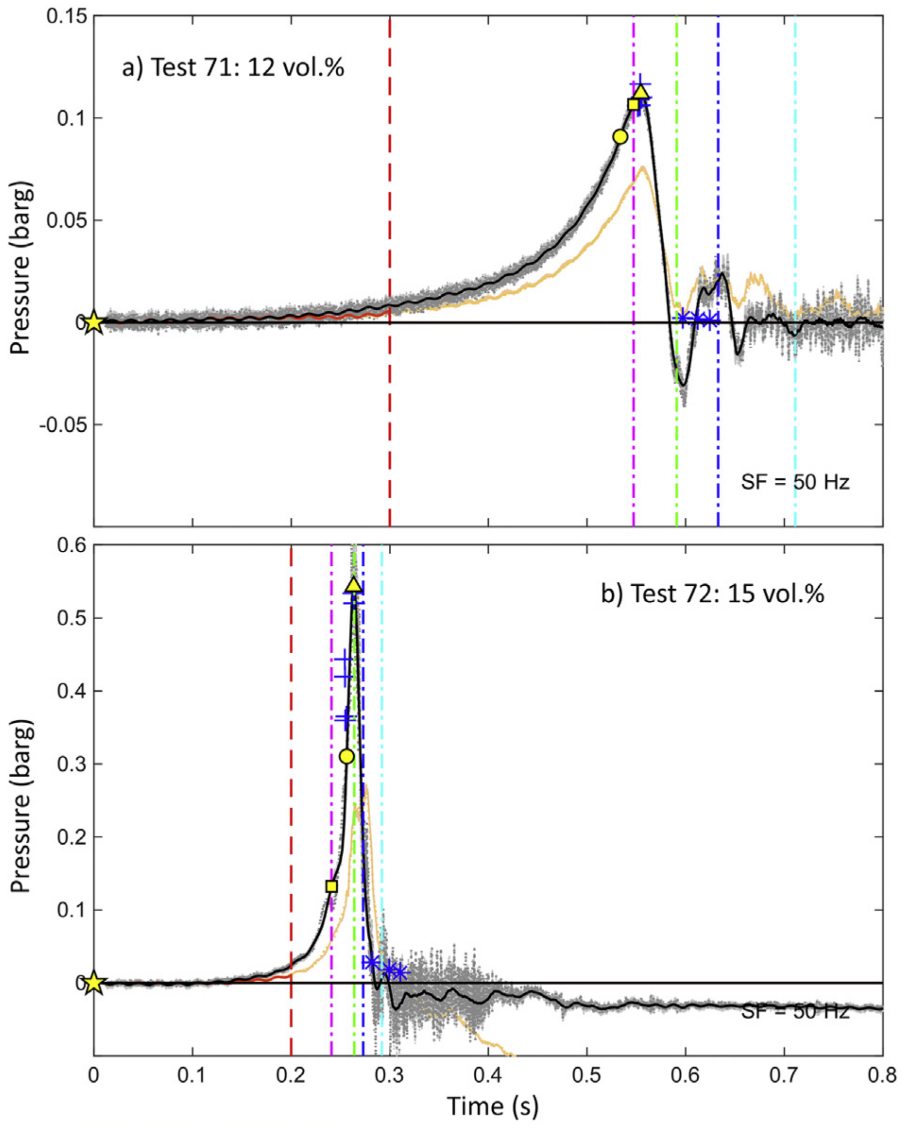
15 vol.% hydrogen, high congestion

Comparison pressure-time histories



Ignition sources

- Electrostatics
- Frictional heat and sparks
- Spontaneous ignition

Different electrostatic discharges

- Electrostatic sparks
- Corona discharge
- Brush discharge

Electrostatic sparks

- Discharge occurs between two electrically conducting materials
- ”All” available energy is discharged
- Yield sparks having high energy-content
- Energy can be calculated from capacitance and potential difference ($E = \frac{1}{2} CV^2$), in practice max 1 J
- Can be avoided by grounding and bonding of equipment to same electrical potential

Theoretical spark energy

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$E = \frac{1}{2} CV^2$

C = capacitance and V = voltage

Object	Capacitance (pF)	$1/2\ CV^2$ (mJ) at various voltages		
		10 kV	20 kV	30 kV
Single screw	1	0.05	0.2	0.45
Flange (100 mm nominal size)	10	0.5	2	4.5
Shovel	20	1	4	9
Small container (bucket, 50 litres drum)	10-100	0.5-5	2-20	4.5-45
Funnel	10-100	0.5-5	2-20	4.5-45
Drum (~200 litres)	100-300	5-15	20-60	45-135
Person	***100-300***	***5-15***	***20-60***	***45-135***
Major plant items (large containers, reaction vessels)	100-1000	5-50	20-200	45-450
Road tanker	1000	50	200	450

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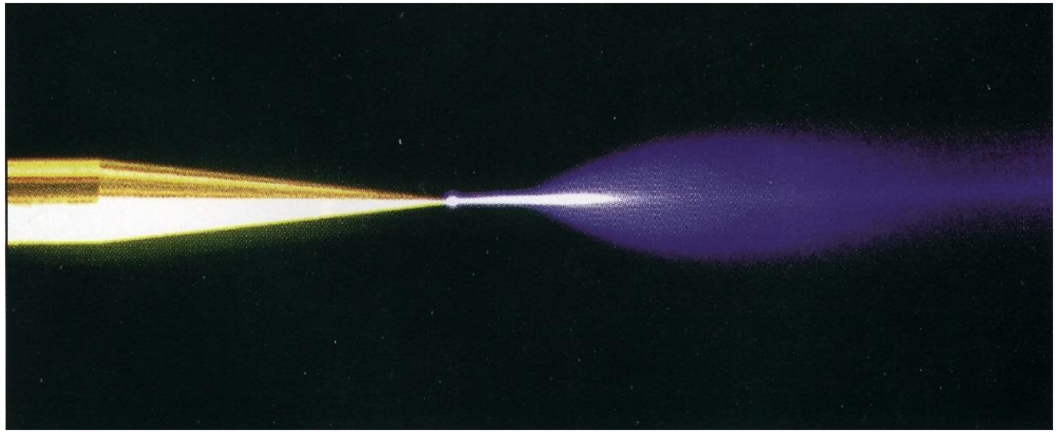
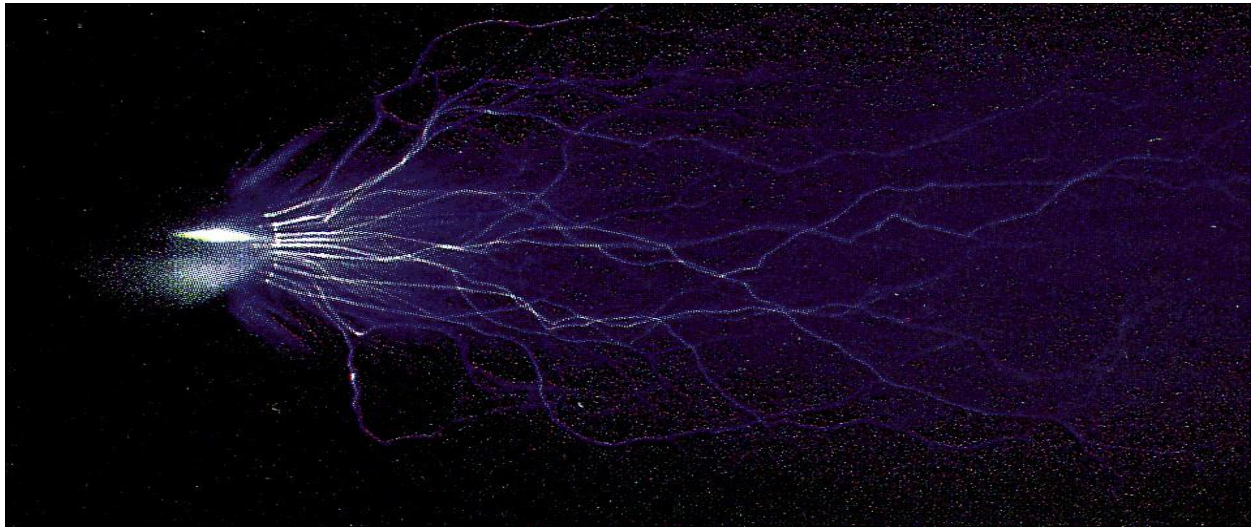
Corona discharge

- Occur when sharp/pointed conducting materials approach charged non-conducting materials
- Low energy-content
- Can lead to ignition of very ignition-sensitive gases like acetylene and hydrogen
- NOT able to ignite methane/propane



Brush discharge

- Usually occurs when rounded conducting materials approach charged non-conducting materials
- Only a limited part of the available energy is discharged
- Energy-content < 4 mJ
- Can ignite hydrocarbon gases and vapours



Electrostatic discharges, summary

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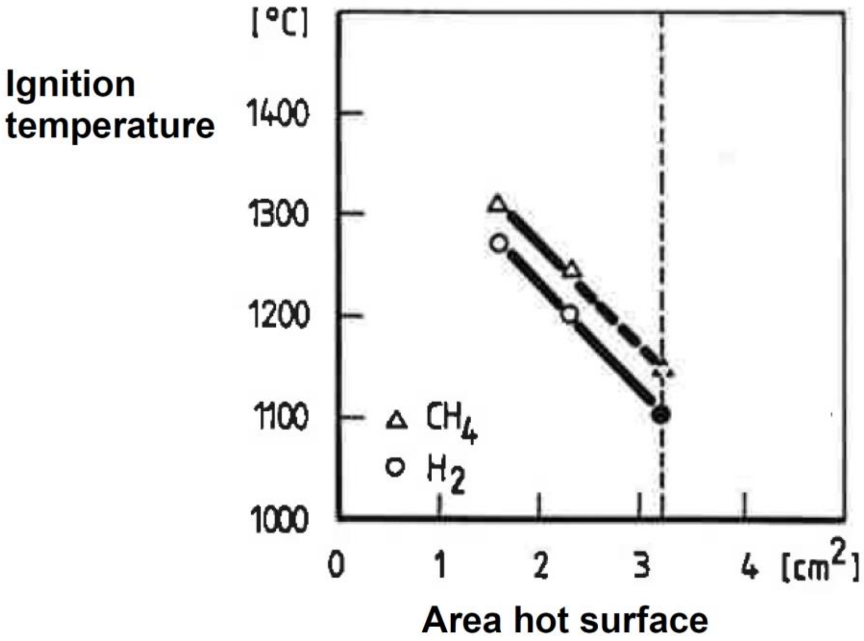
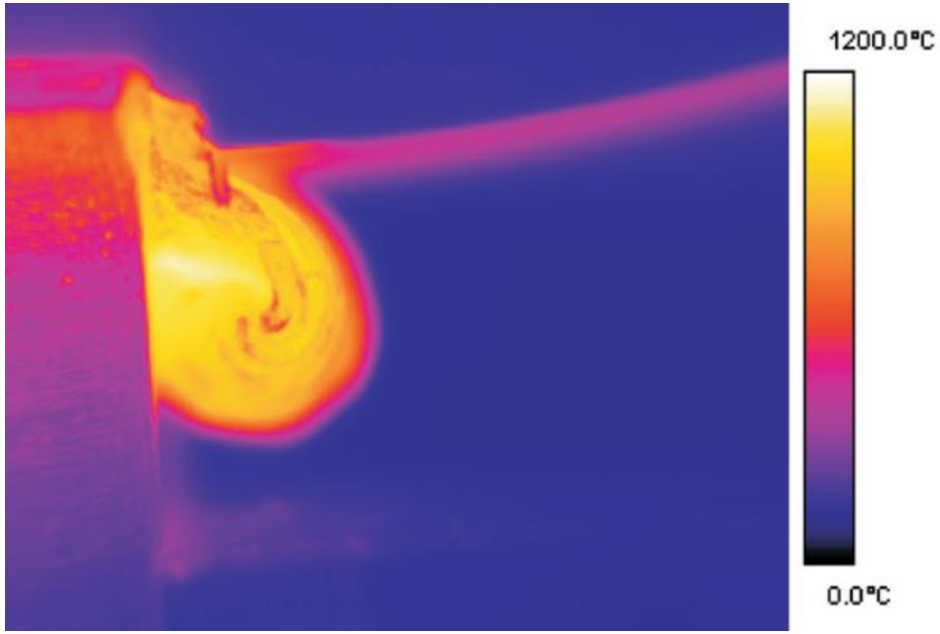
Type of discharge	***Incendivity***	
	Hydrogen MIE = 0.017 mJ	Solvents, hydrocarbon gases MIE > 0.025 mJ
Electrostatic spark	+	+
Brush discharge	+	+
Corona discharge	+	-

Ignition temperature of hot surfaces: influence of geometry (surface area)

- Large surface area and high temperature is more dangerous than a small surface with lower temperature





Hot burr formed on the trailing edge of a contact zone

Phenomenology

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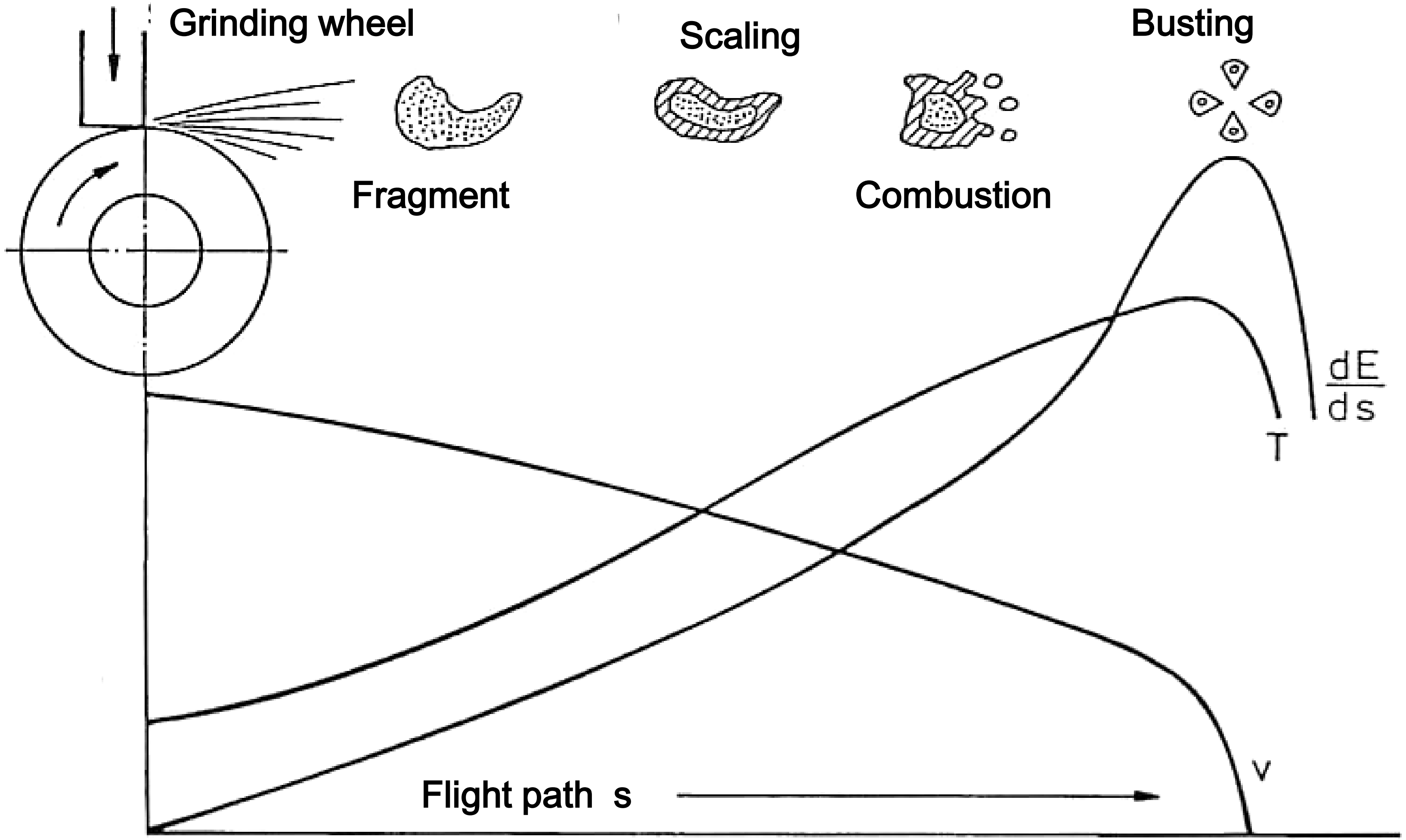
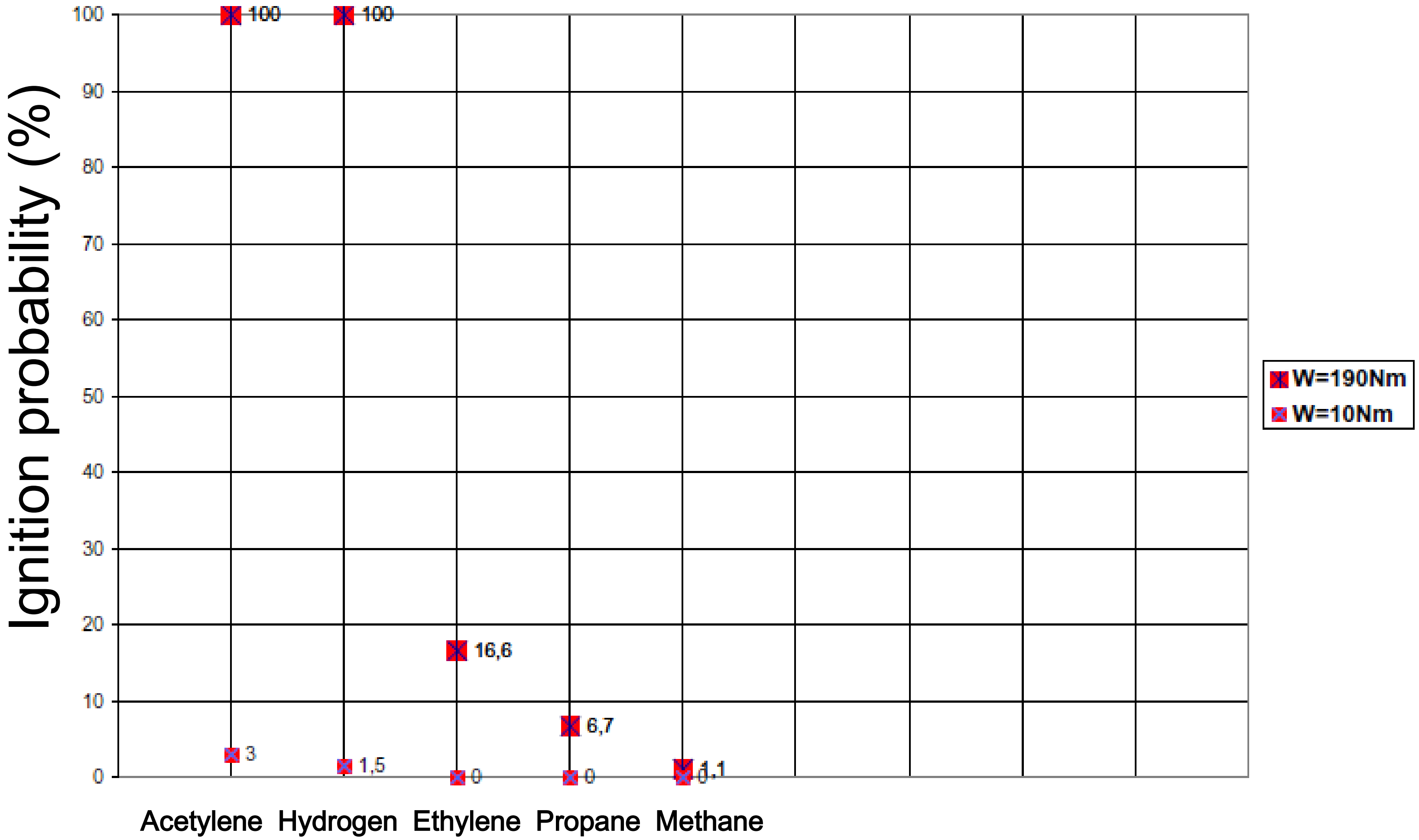
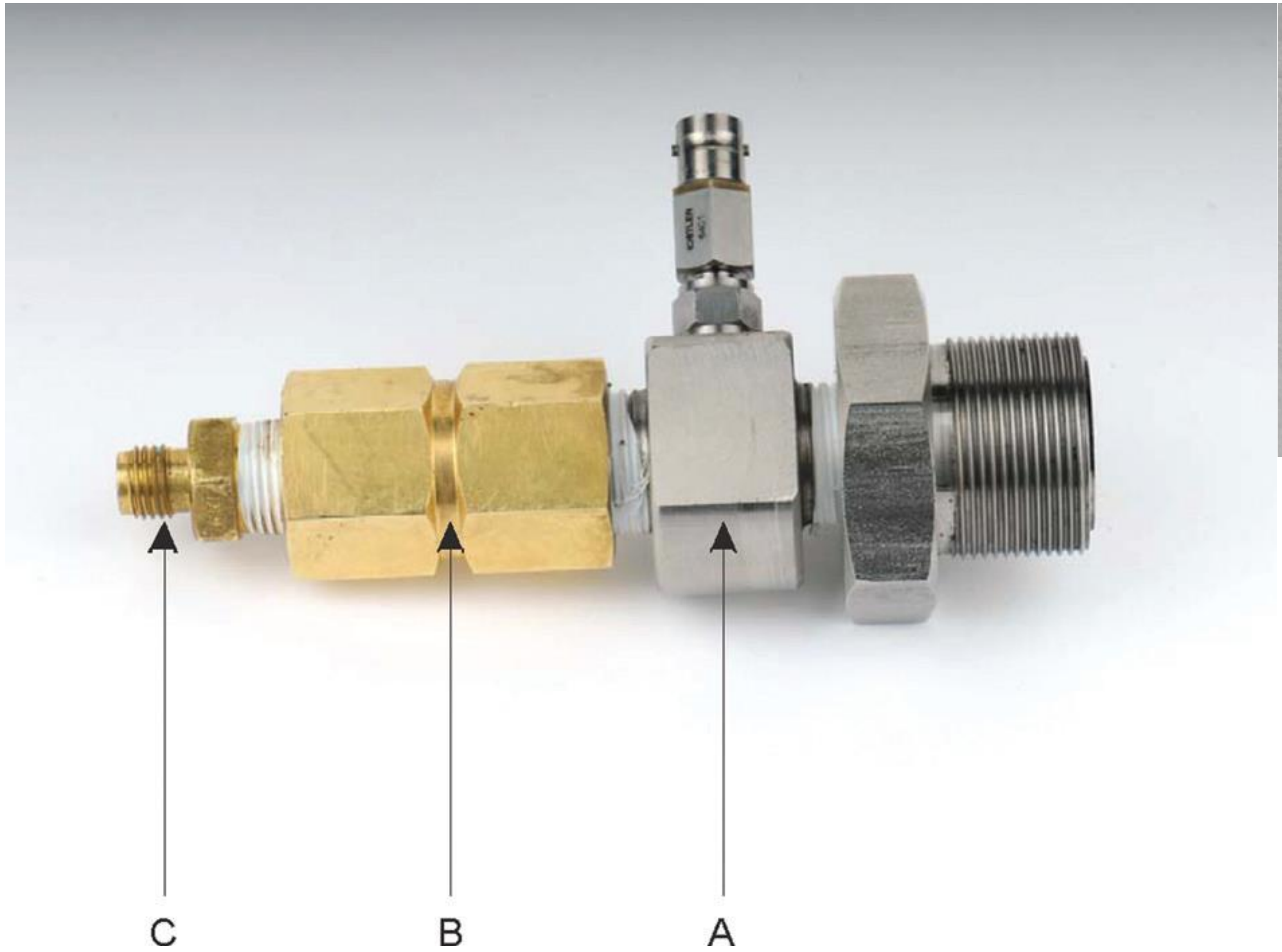


Incendivity single impact sparks (steel-steel)

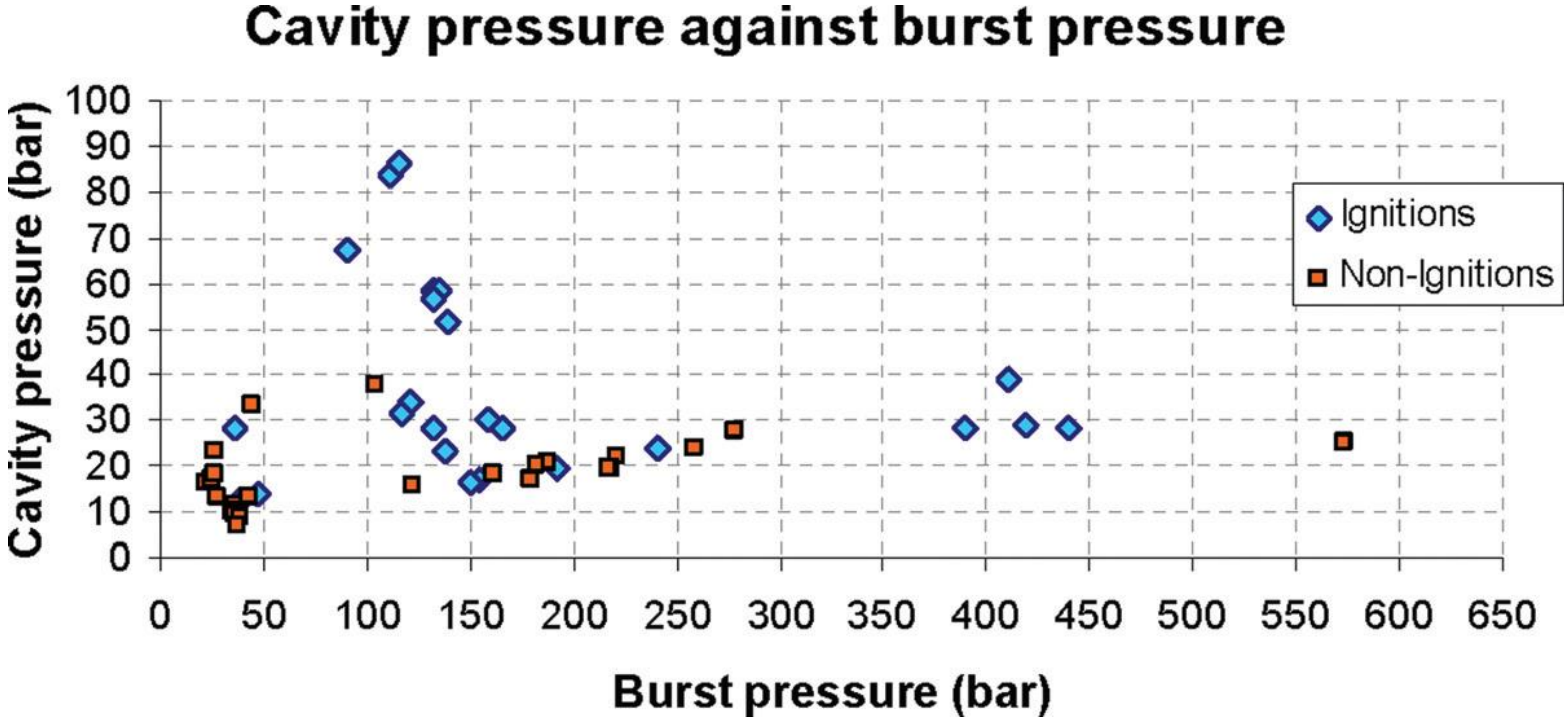


Spontaneous ignition: Experiments by HSL (Hooker et al., 2011)

ID = 18.3 mm
Length > 300 mm



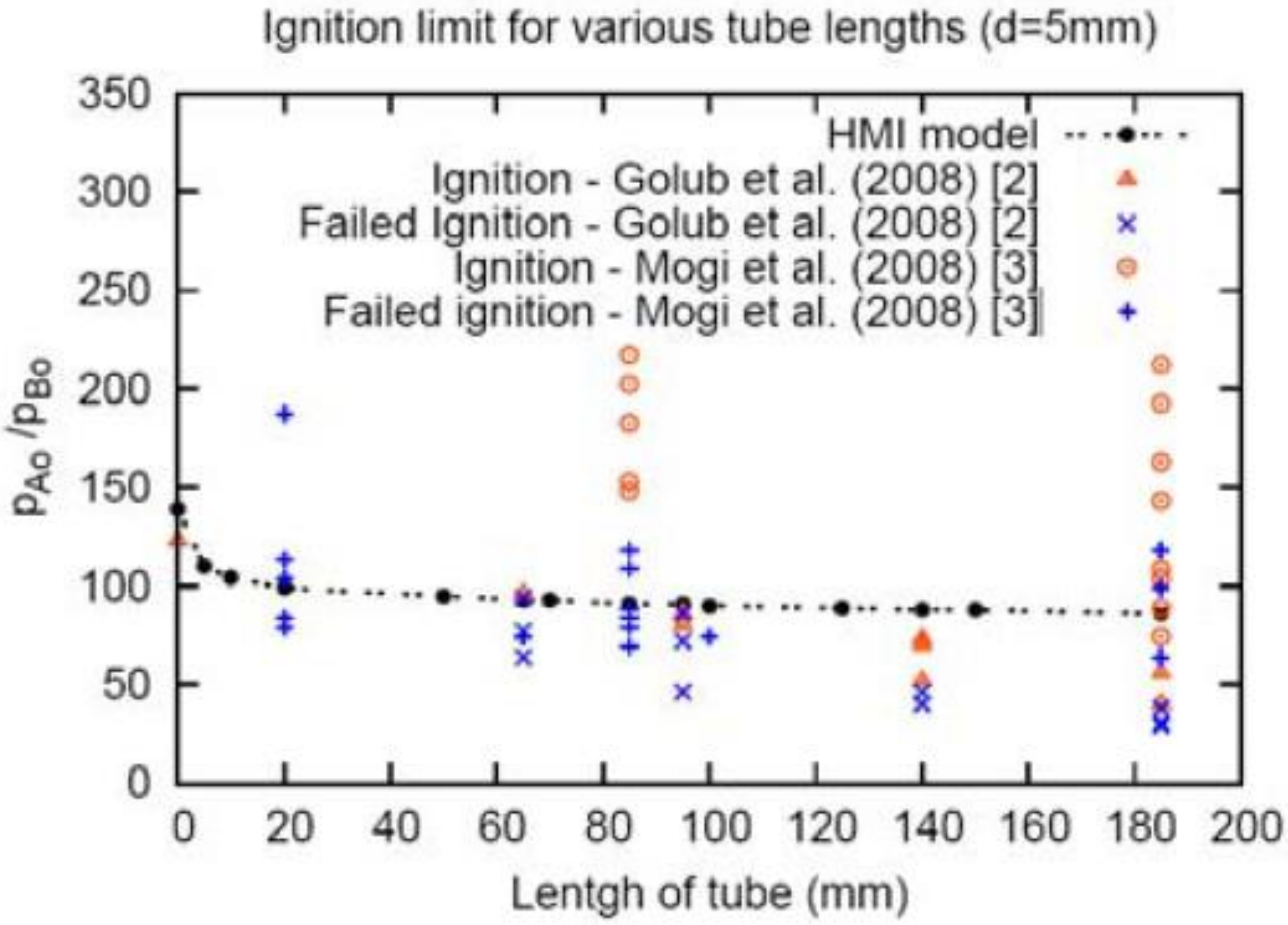
Conditions resulting in ignition/no ignition



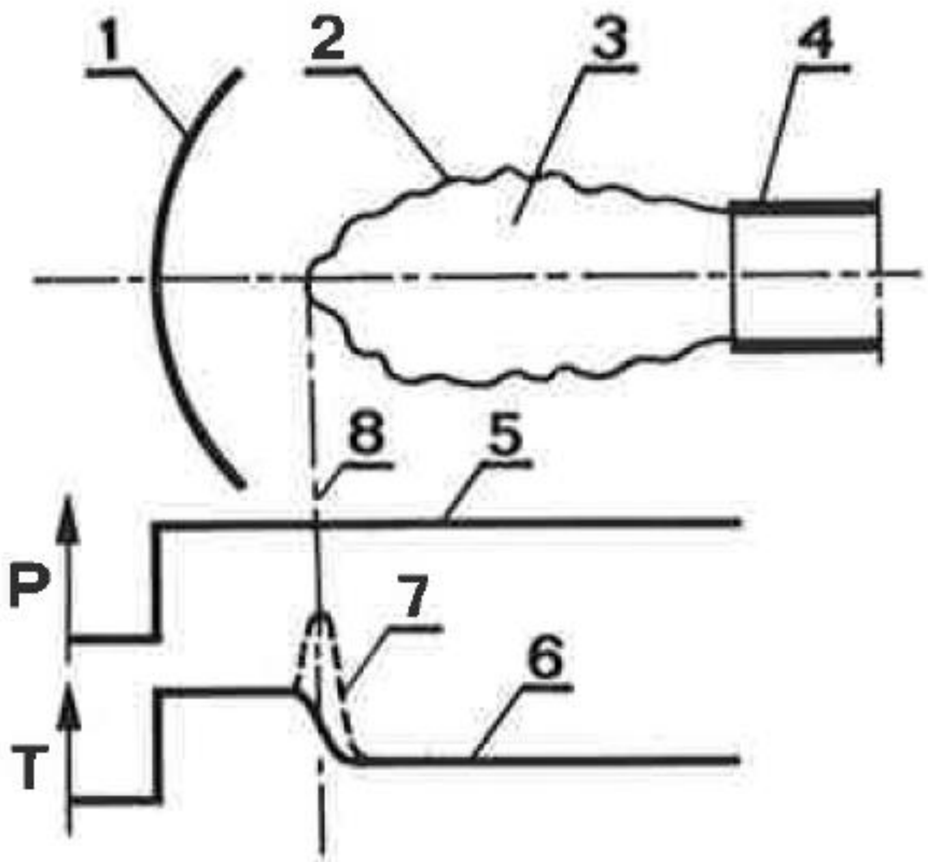
Findings

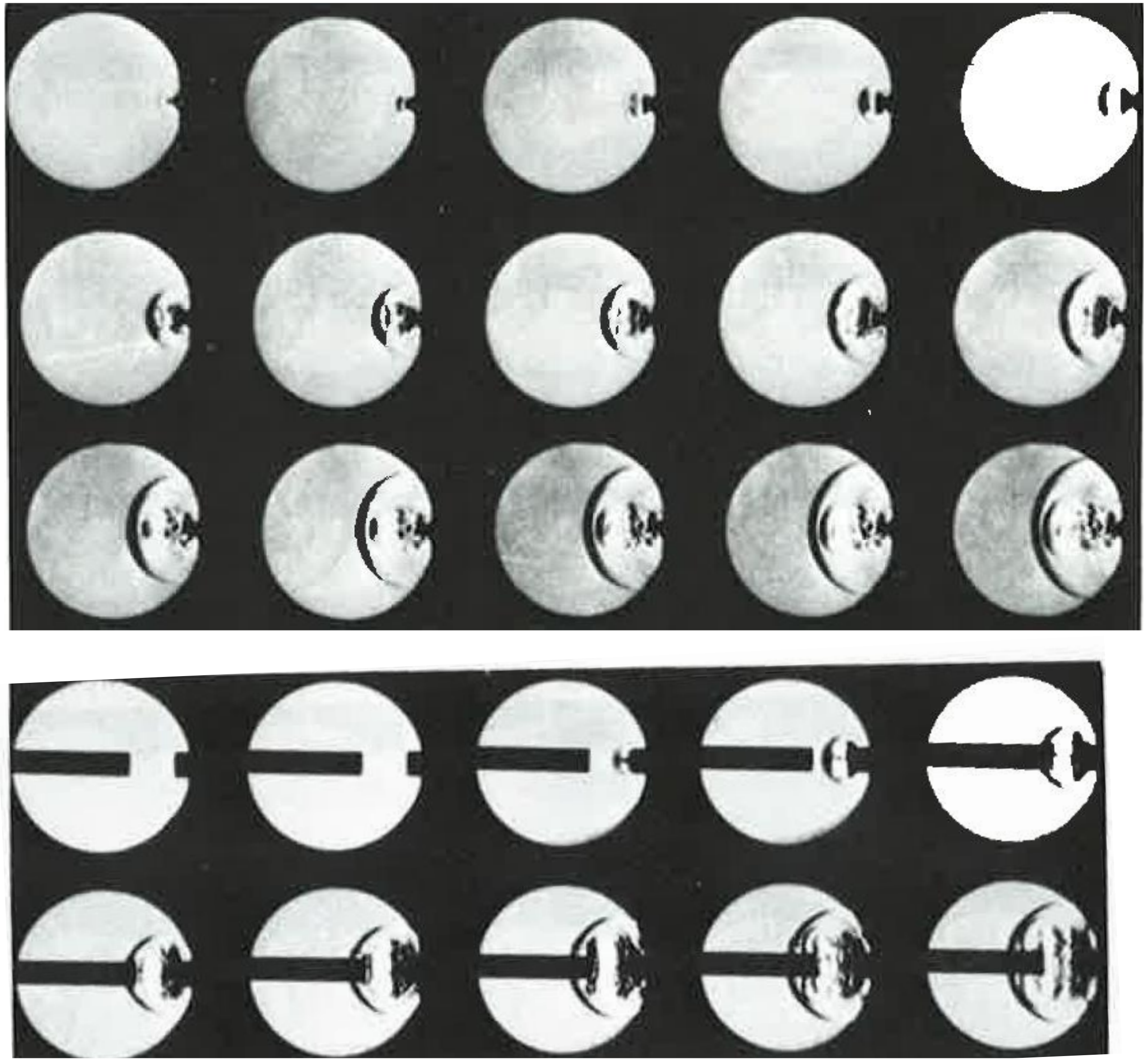
- With no fittings to restrict or reflect the flow, there was no ignition up to 831 barg
- The lowest disc burst pressure at which an ignition was obtained was 35.5 bar

Maxwell, 2009



Wolanski, 1972





Conclusions

- Light gas: reducing likelihood of generating large gas clouds in the open (unless liquified)
- Wide explosive range
- High reaction rate
- Easy to ignite by electrostatic sparks/discharges
- Relatively easy to ignite by mechancial sparks
- Less easy to ignite by hot surfaces
- «Spontaneous ignition» only possible in case of presence of obstructions in vicinity of leak position

Thank you very much for your attention

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