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Hydrogen safety aspects

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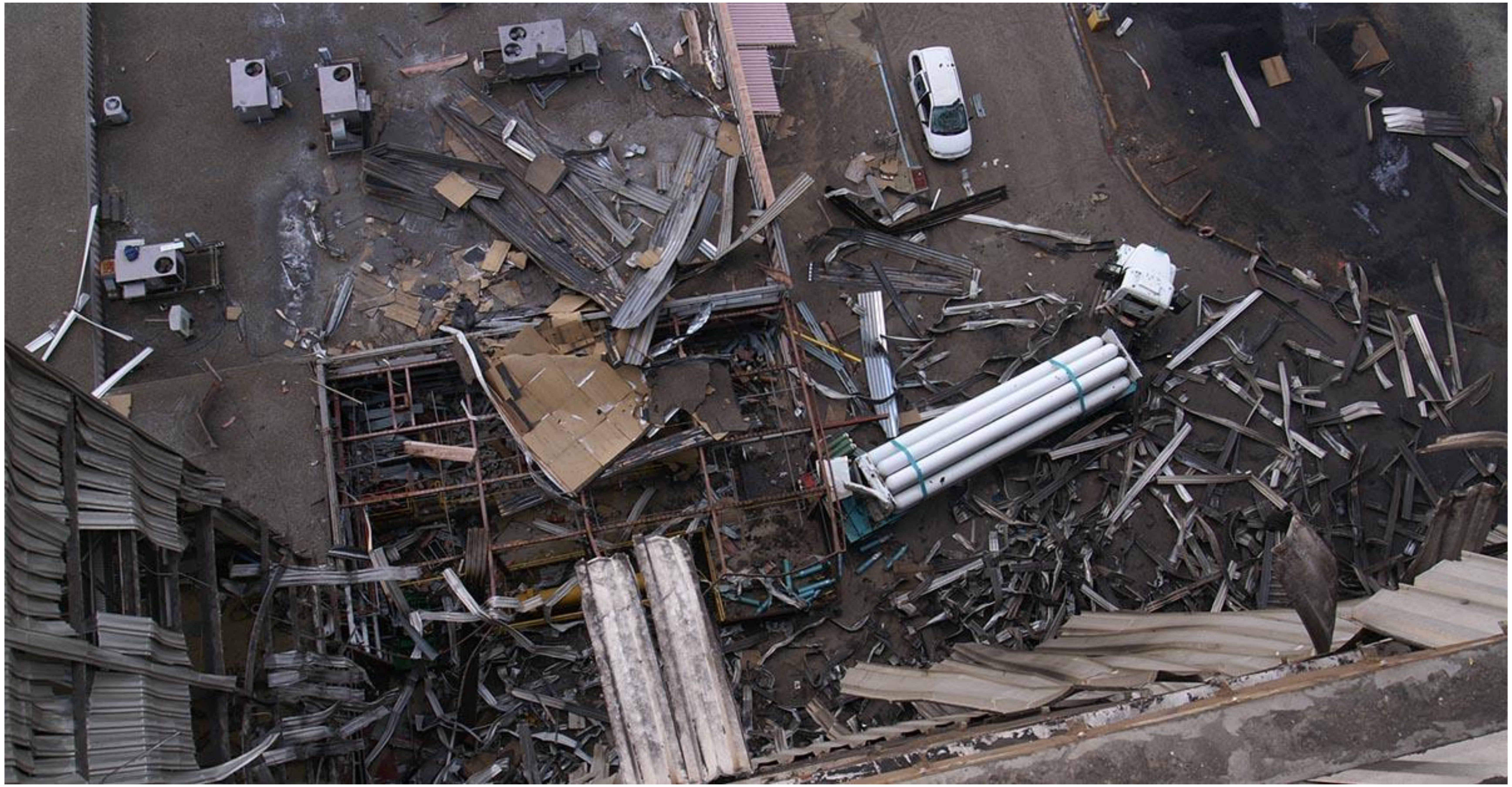
Contents

Introduction/ learning from accidents

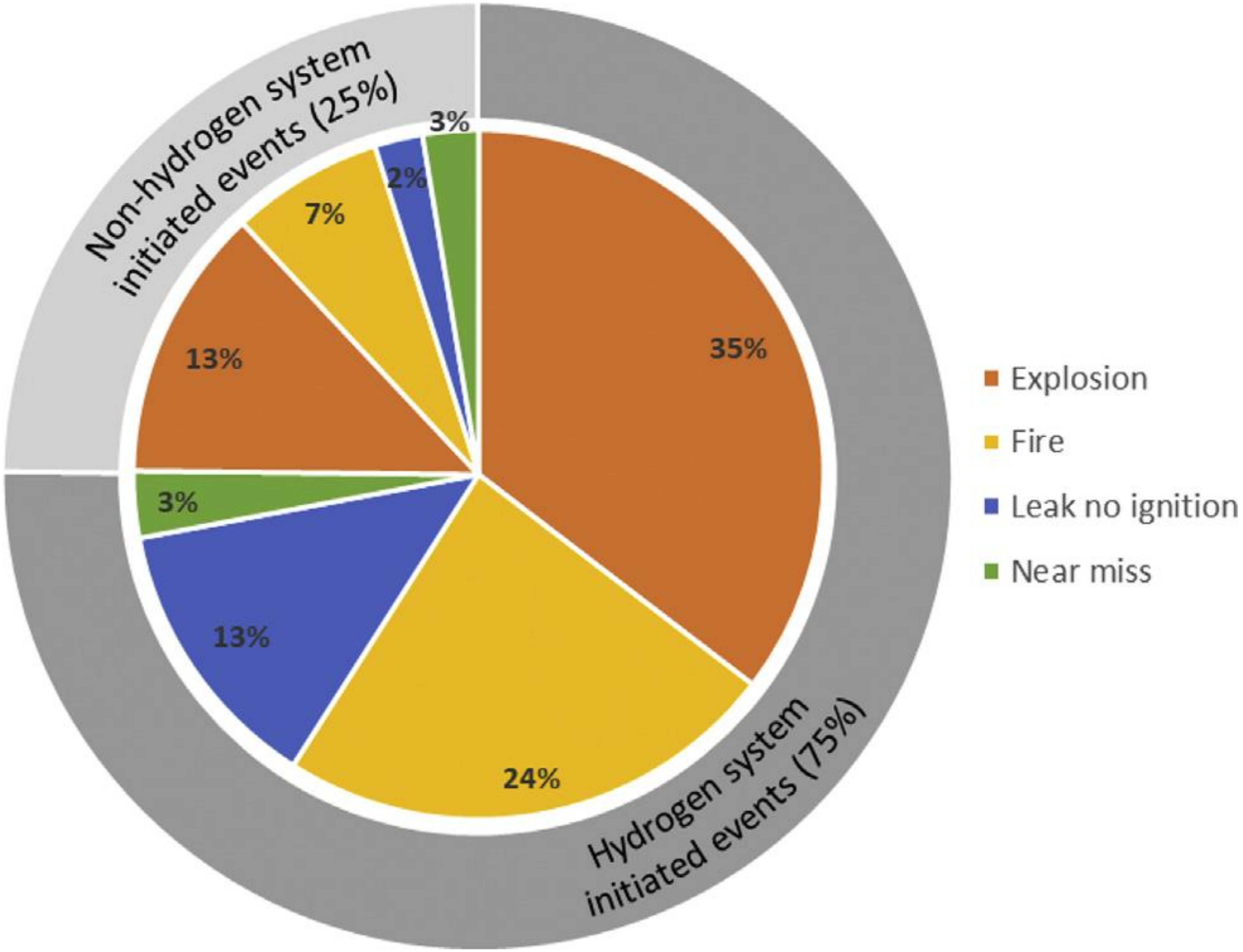
Explosion ammonia production facility, Herøya, Norway, 1985

Explosion American Electric Power, Ohio, USA, 2007



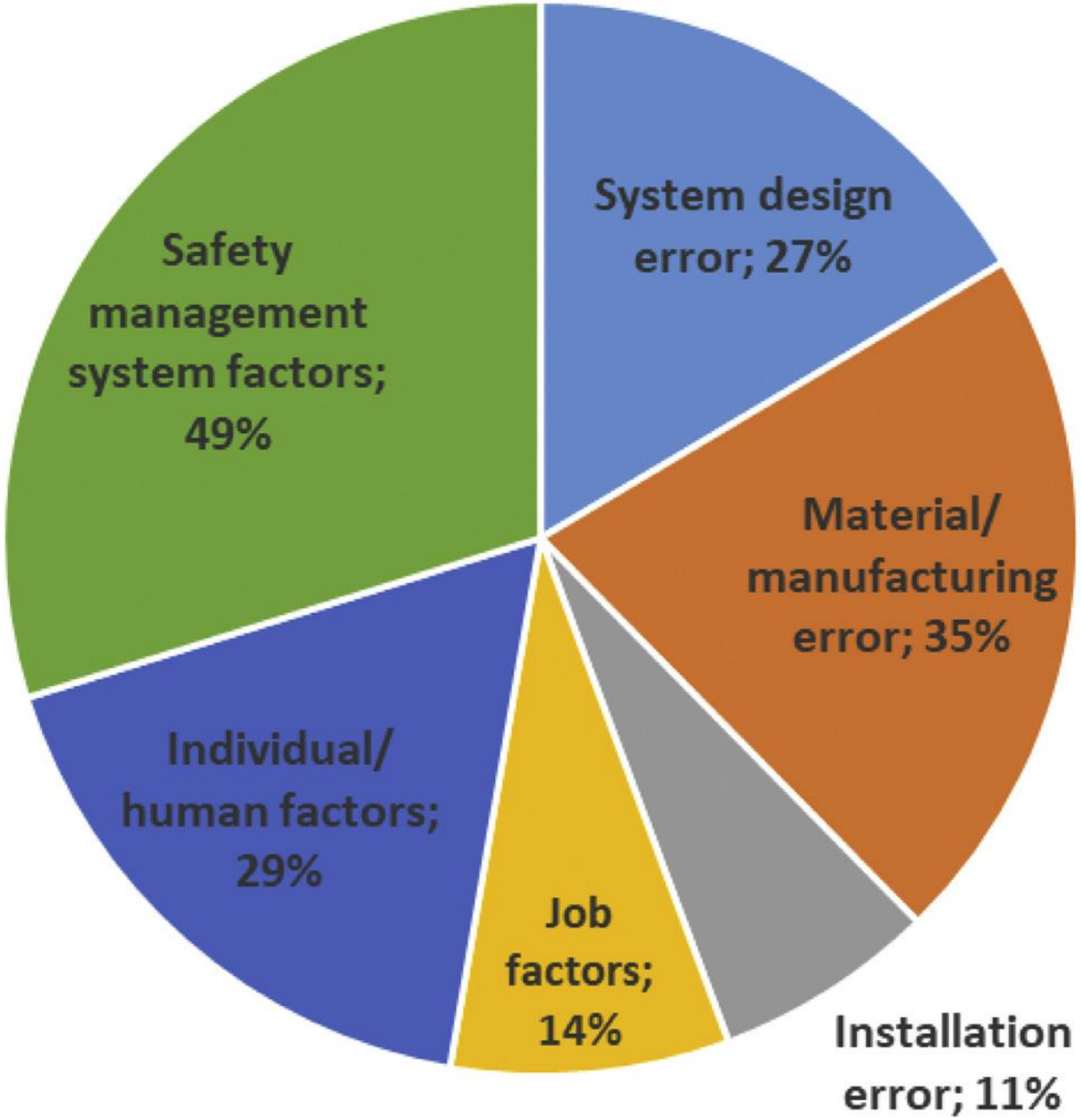
Explosion hydrogen fuelling station, Kjørbo , Norway, 2019

Safety: hydrogen incidents, HIAD 2.0 database



Wen, 2022

Safety: hydrogen incidents, HIAD 2.0 database



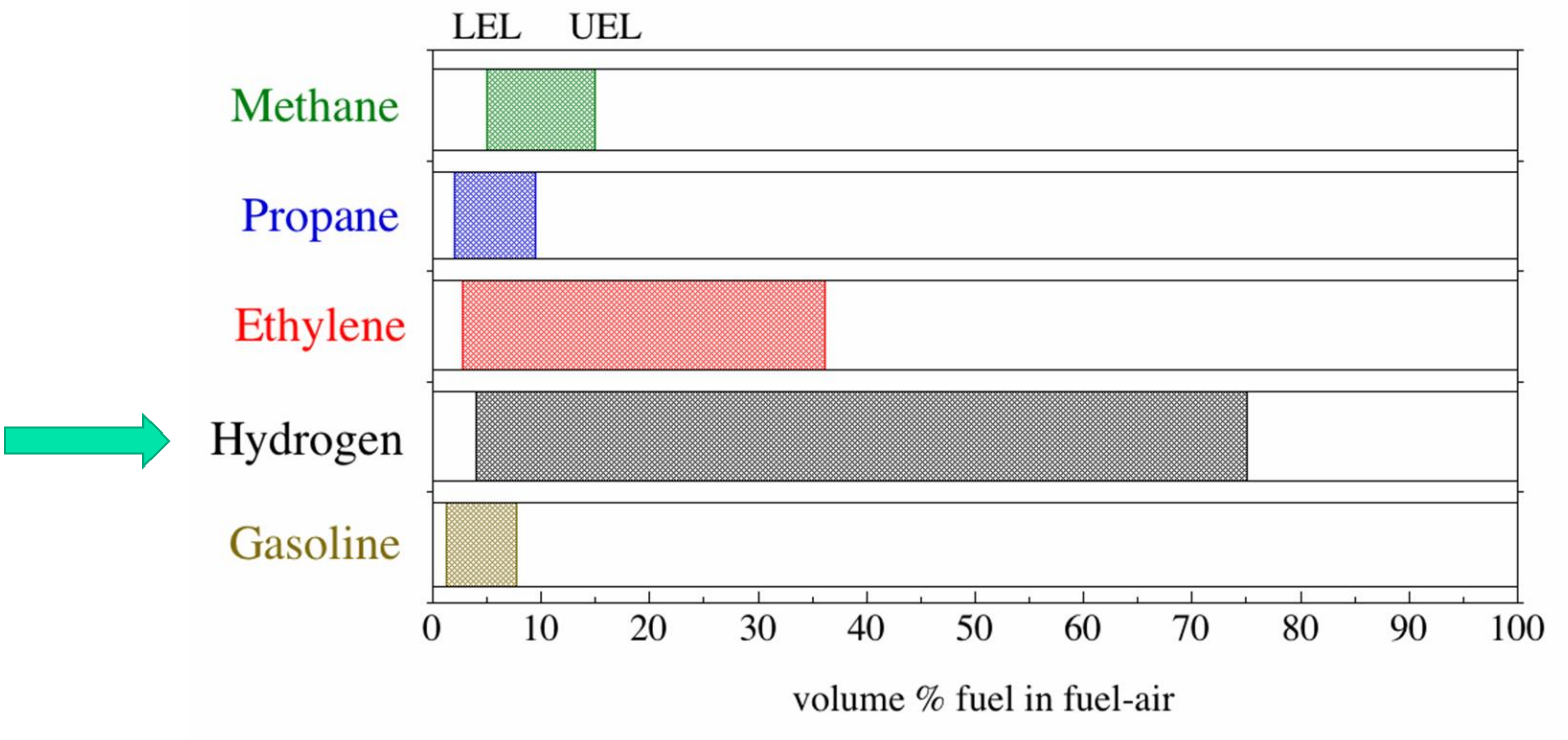
Wen, 2022

Hydrogen properties

- Density: 0.082 kg/m^3 compared to 1.23 kg/m^3 for air and 0.68 kg/m^3 for natural gas
- Hydrogen is colourless, odourless and tasteless gas
- Burns in clean atmosphere with “invisible” flame
- Combustion energy: 141.8 MJ/kg (286 kJ/mol) compared to methane with 55.5 MJ/kg (890 kJ/mol)

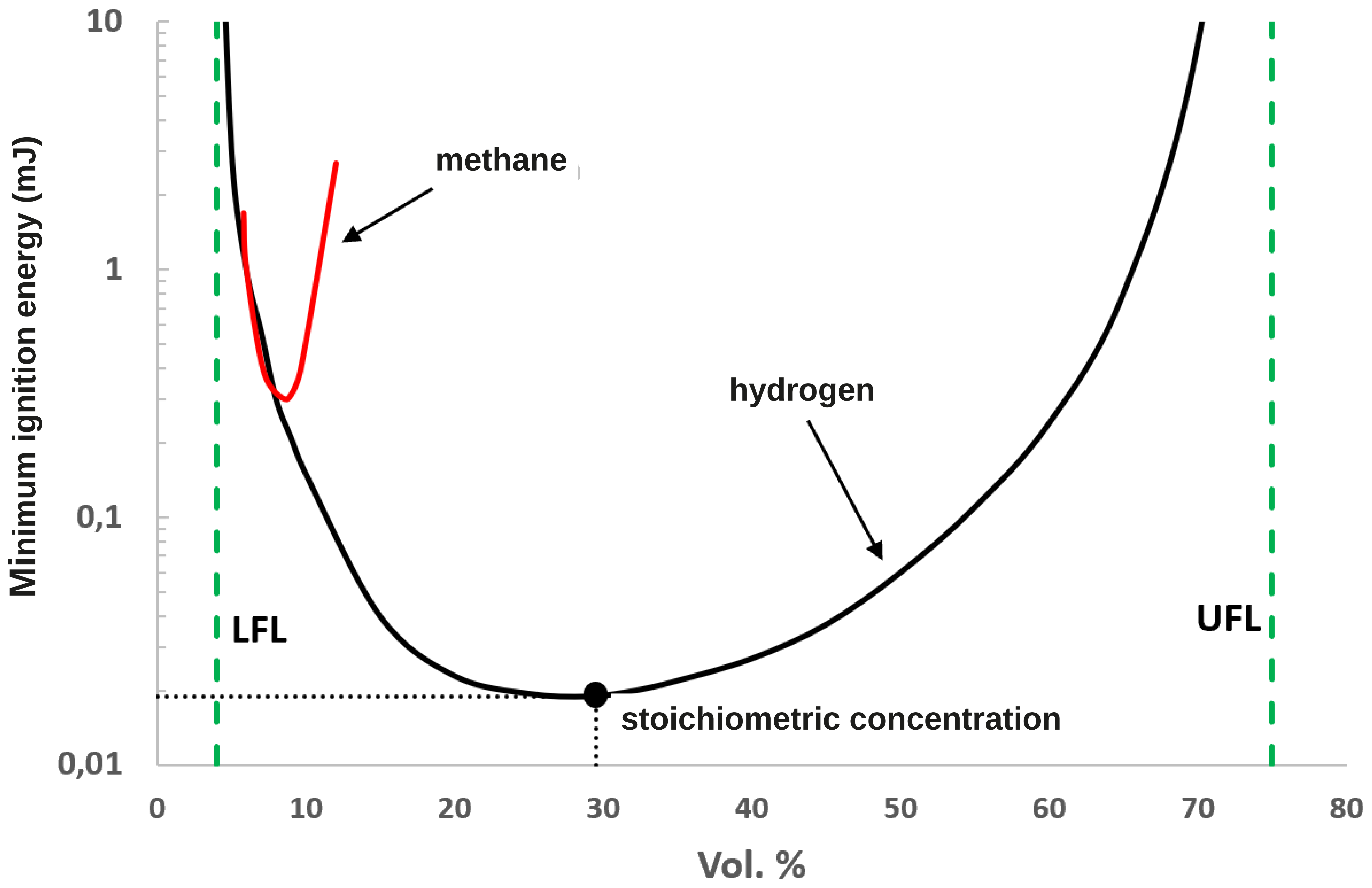
- Very reactive gas: laminar burning velocity 2.9 m/s compared to methane 0.36 m/s
- More prone to deflagration-to-detonation transition compared to most of flammable gases

Explosive part of cloud



Minimum ignition energy and explosion limits: hydrogen vs methane

Minimum energy of an electrical spark able to start combustion



Minimum ignition energy
Methane: 0.28 mJ
Hydrogen: 0.017 mJ

Hydrogen safety philosophy

- Prevention of releases of hydrogen
- Limitation of build-up of dangerous gas clouds
- Avoidance of ignition sources
- Limitation of consequences of jet fires and explosions
- Limitation of other hydrogen hazards

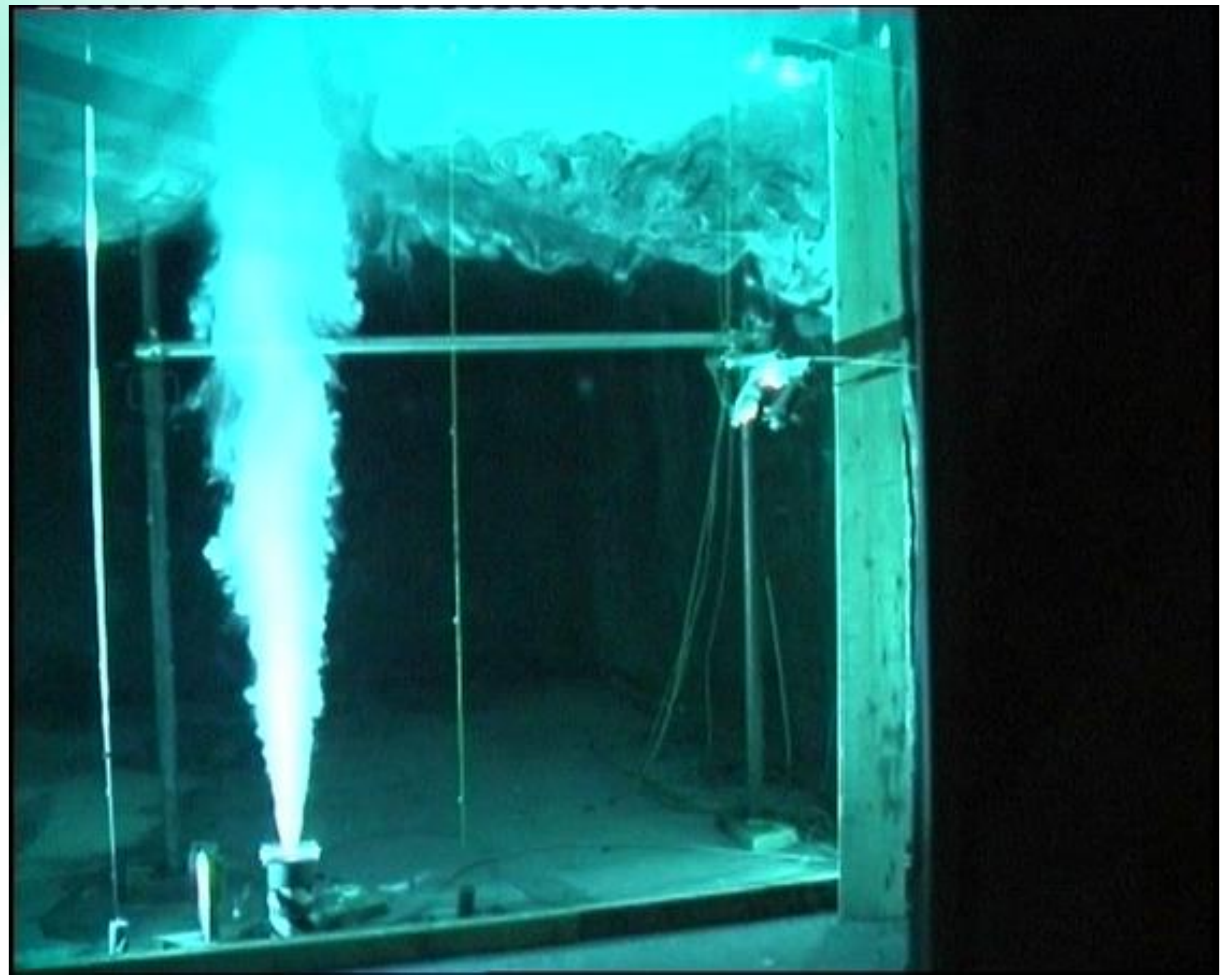
- **Training of people!**

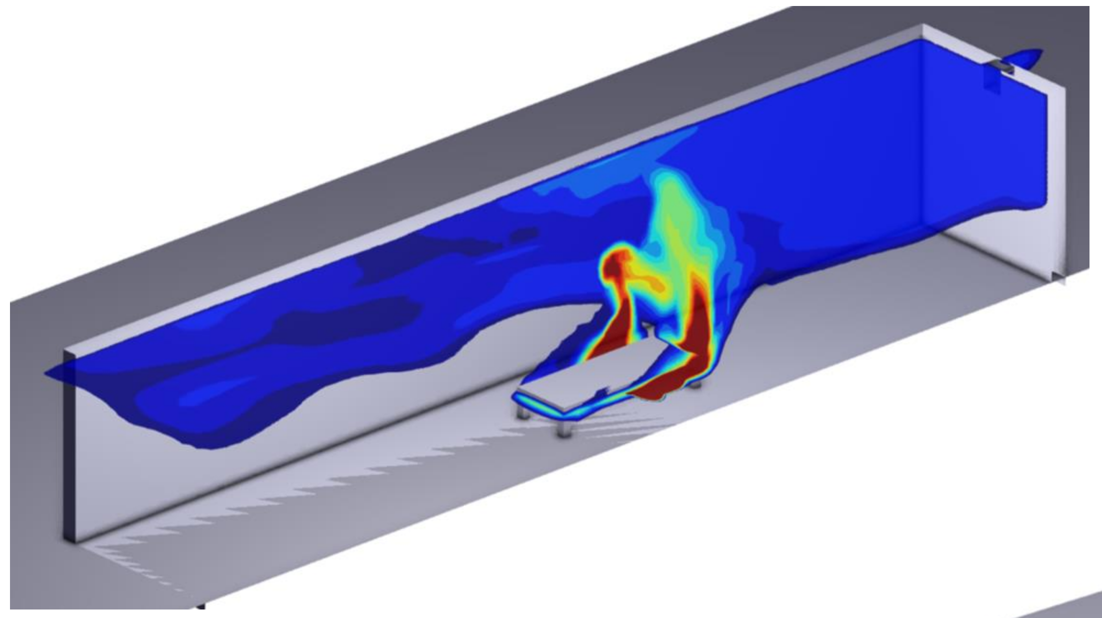
Prevention of releases

- Design: choice of materials is important: some metals are susceptible to a process called hydrogen embrittlement causing the metal to lose its ductility and tensile strength
- Design: liquified hydrogen: Equipment in direct contact with liquid hydrogen must be designed and manufactured to withstand the extremely low temperature (-253 °C)
- Design: limit the sources of possible releases: joints in piping and tubing shall be mainly made by welding or brazing.
- Everyday and maintenance operations by trained personnel

Prevention of build-up of dangerous gas clouds

- Make use of the low density of hydrogen compared to air: allow for “escape” of hydrogen from congested areas
- Ventilation: avoidance of build-up of hydrogen in rooms
- Design using CFD





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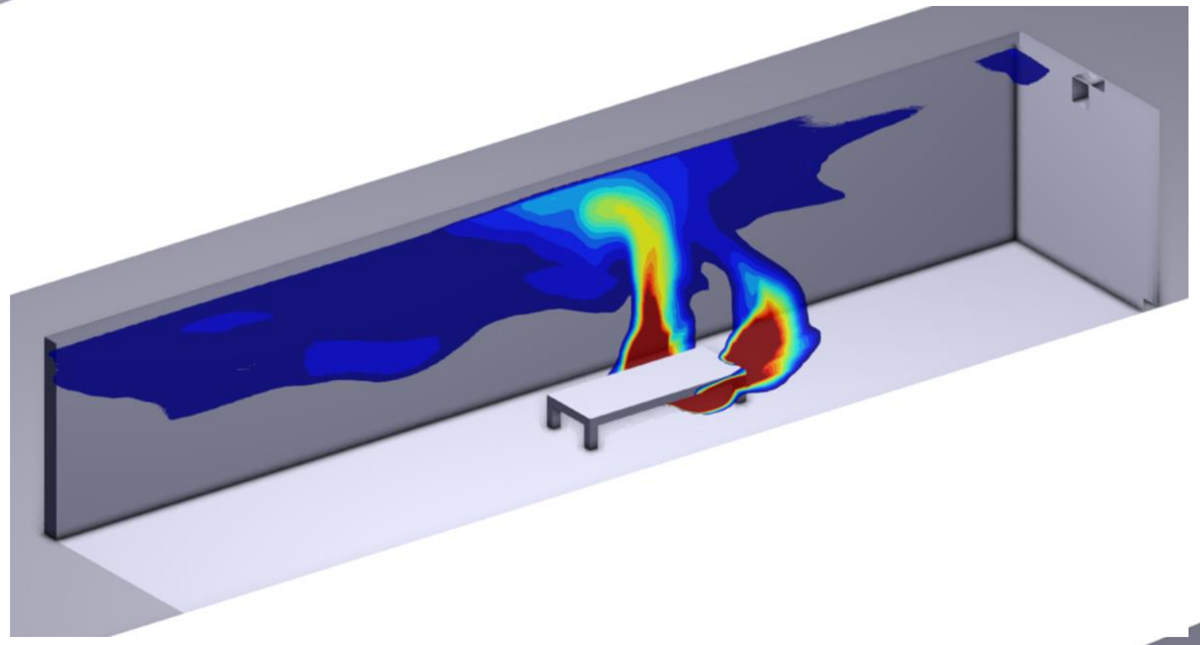
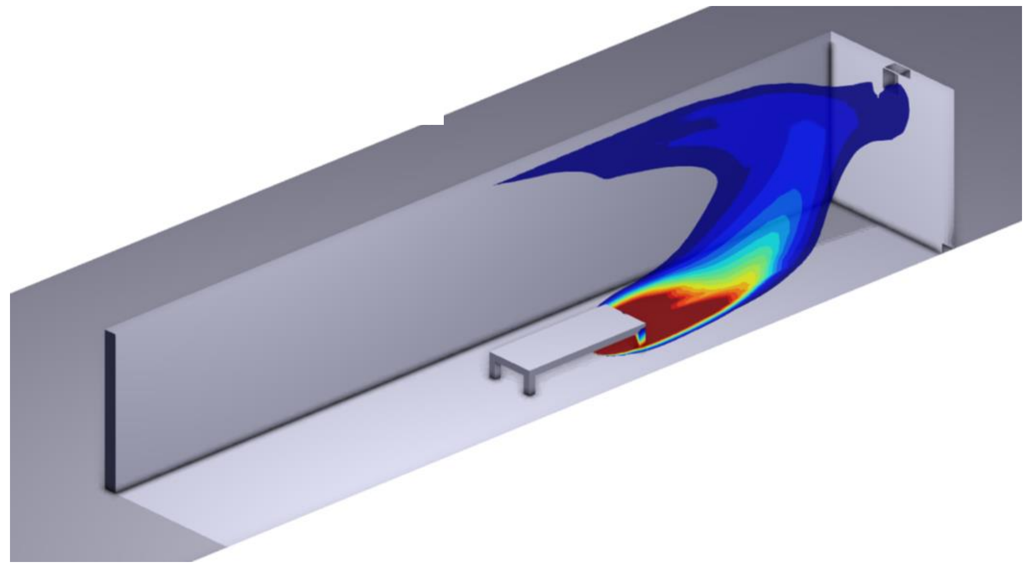


15 ACH



40 ACH

Avoidance of ignition sources, in combination with hazardous area classification

13 possible types of ignition sources (Source: EN-1127-1)

- Hot surfaces
- Flames and hot gases
- Mechanical sparks
- Electrical equipment
- Static electricity
- Lightning
- Exothermic reactions & self-ignition
- Radio frequency waves
- Electromagnetic waves
- Ionizing radiation
- Ultrasonics
- Adiabatic compression
- Stray electric currents

Electric equipment

- Potential ignition sources:
  - Electric sparks
  - Hot surfaces
- Ignition can be prevented if the equipment is correctly designed, constructed, installed and maintained in accordance with relevant standards (IEC 60079 series) for hydrogen
- Use explosion safe equipment first of all in classified areas (hazardous area classification) but consider also using them beyond these areas

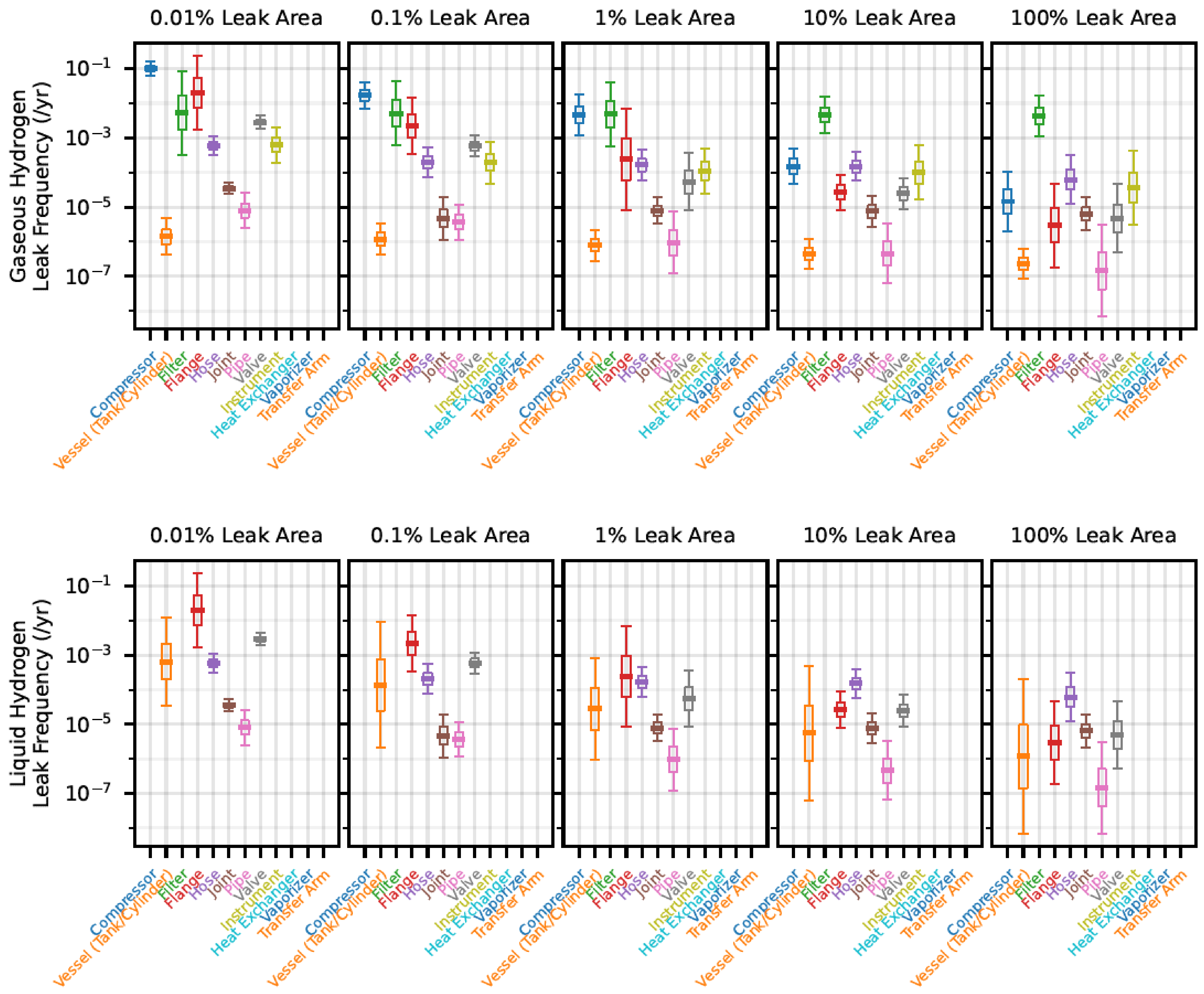
Non-electric equipment

- Use explosion safe equipment first of all in classified areas (hazardous area classification) but consider also using them beyond these areas
- Frictional heat, mechanical sparks, electrostatics

Limitation of consequences if risks are unacceptable

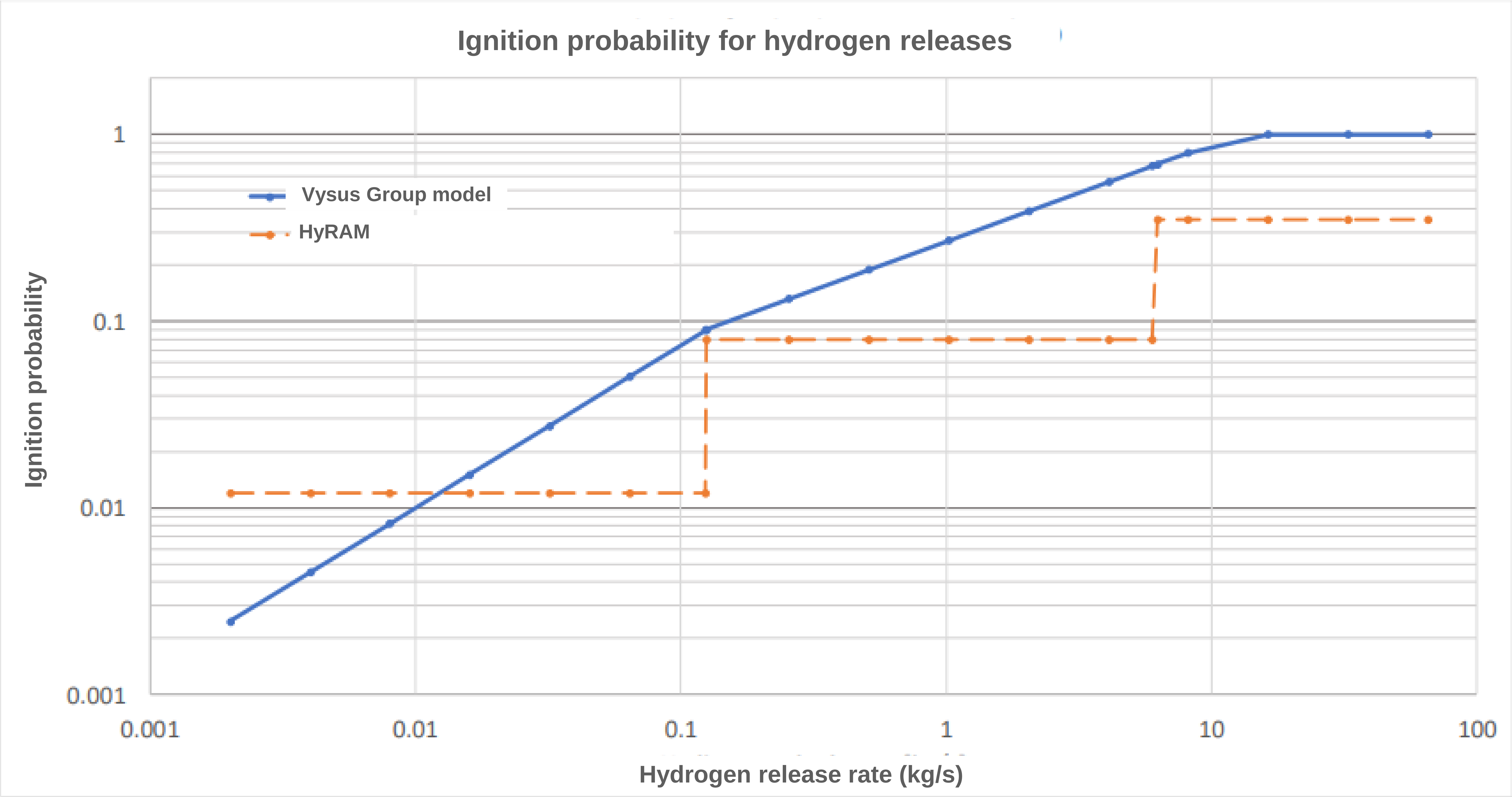
- Prediction of consequences of hydrogen releases (fire and explosion) in combination with probability of occurrence (QRA)
- Comparison to acceptance criteria
- Where risk is unacceptable design of consequence limiting measures

Probability of hydrogen leakages



Source HyRAM+ version 4.1

Probability of ignition



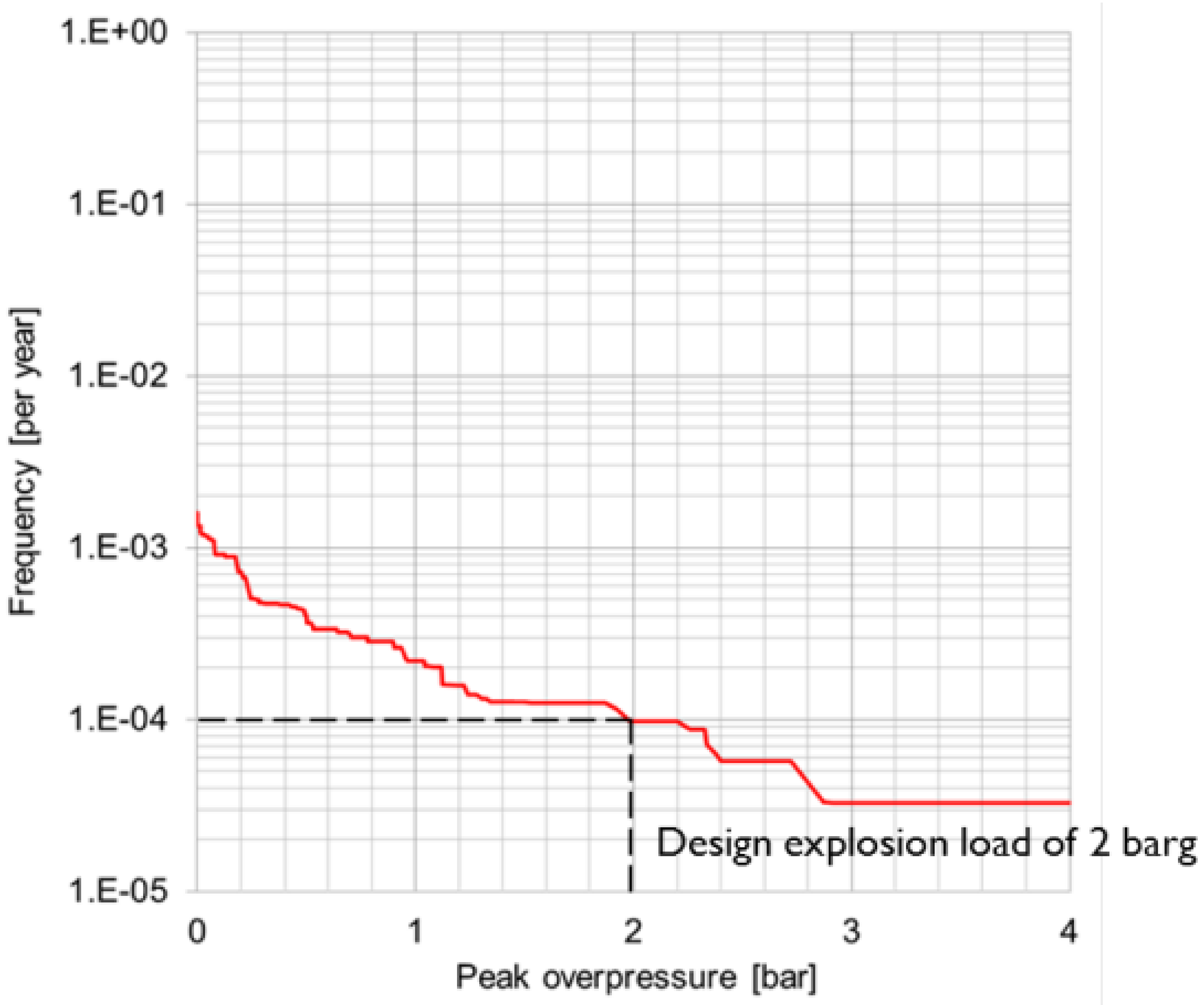
Consequences: H_2 jet fire load on H_2 storage vessels, effect of protecting walls

Simulation result of jet fire impinging on storage vessel

Consequences: H_2 explosion load on walls vented container

Explosion pressure inside vented structure caused by ignition of hydrogen cloud developed from realistic release

Design on basis of probabilistic consequence analysis



Other hazards

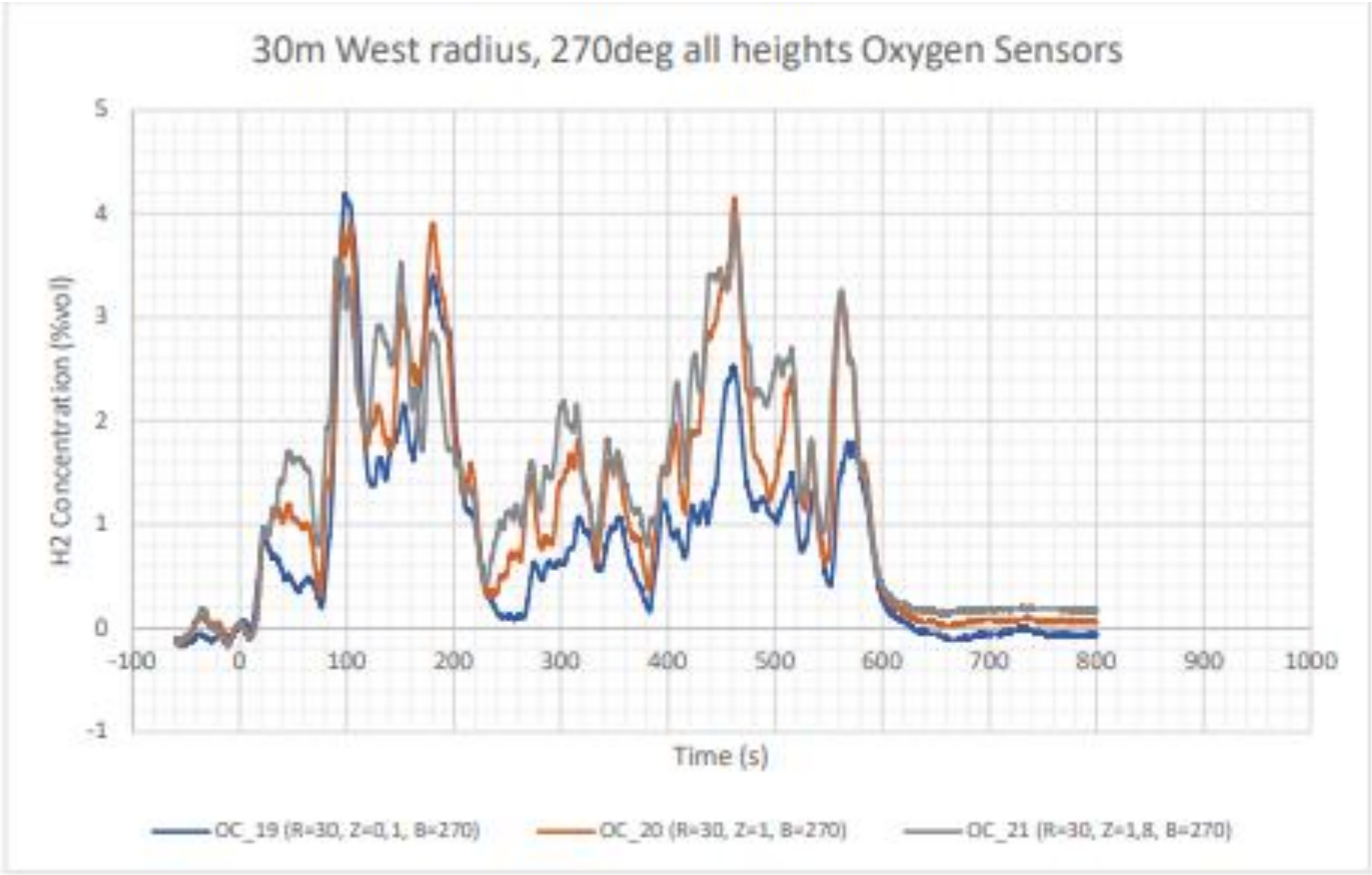
- BLEVE
- Rapid phase transition (RPT)

Recent research: reducing uncertainties

- Recent findings regarding:
  - Build-up of dangerous gas clouds
  - Ignition sources
  - Consequences of jet fires and explosions
  - Consequences of other hazards

Build-up of dangerous clouds

Releases of liquified hydrogen and subsequent dispersion



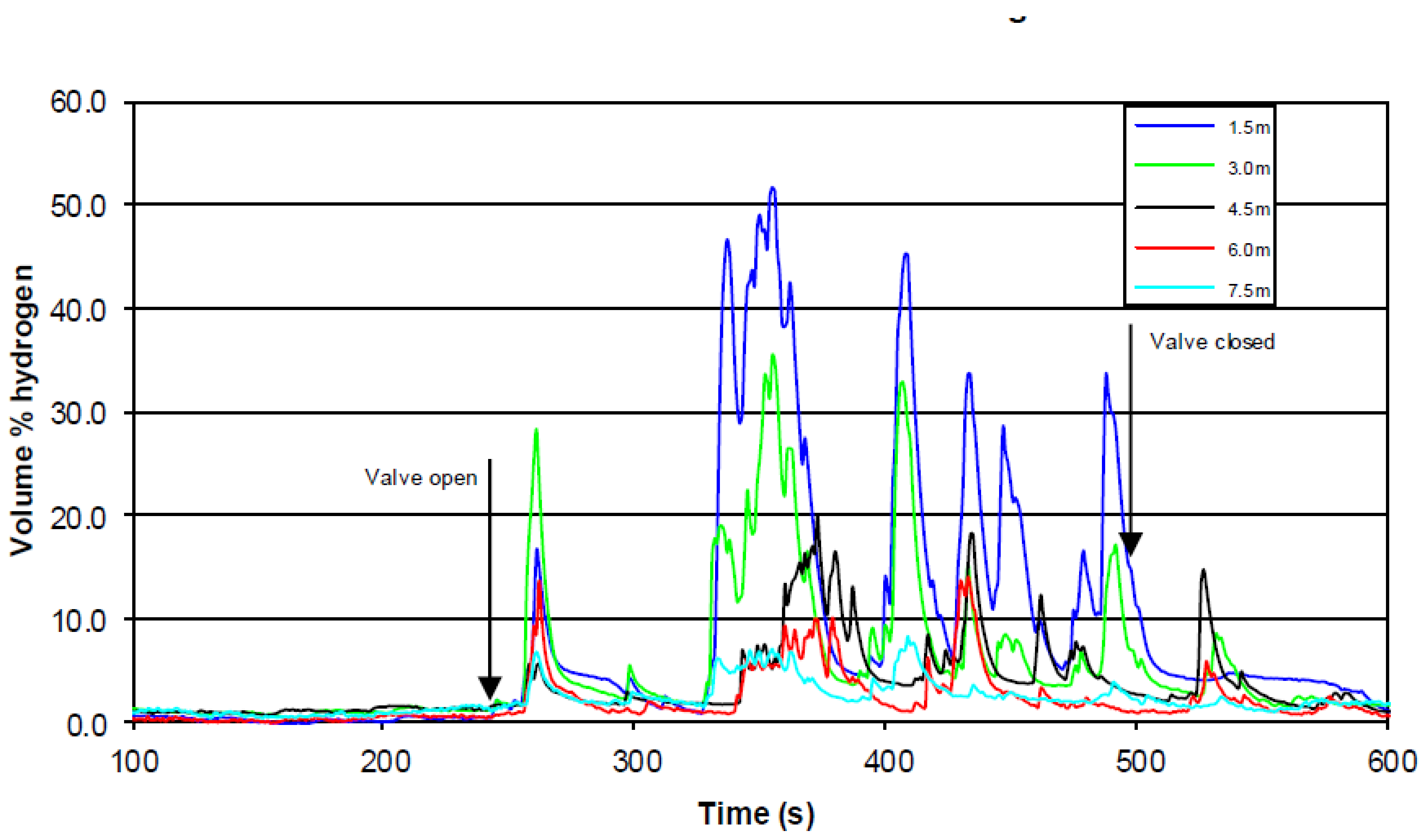
Allison_2021

Explosion/fire

Overpressure 15-30 mbar

Radiation fire: 90 kW/m^2.at 5 m

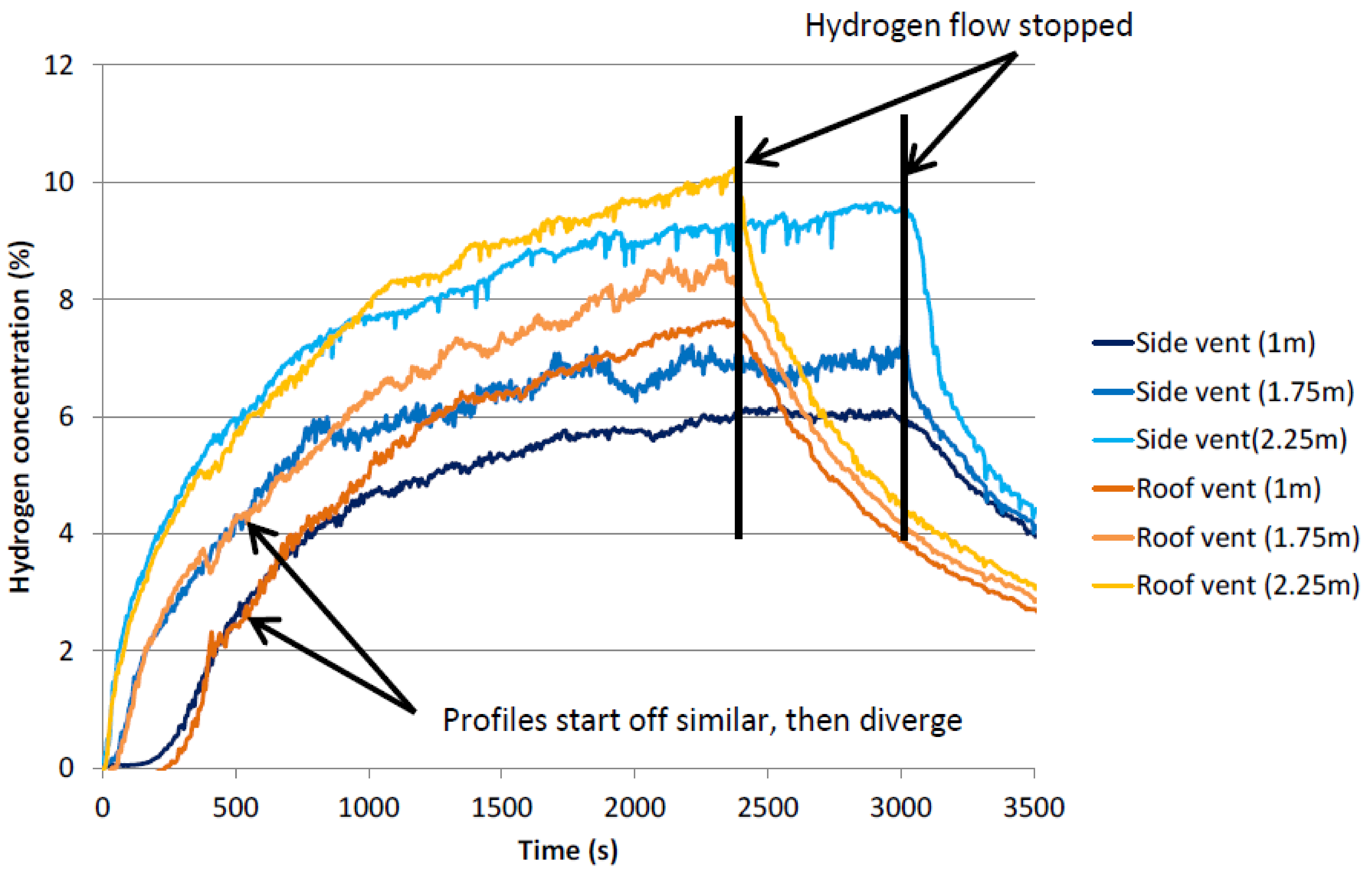
Releases of liquified hydrogen and subsequent dispersion



Royle_2014

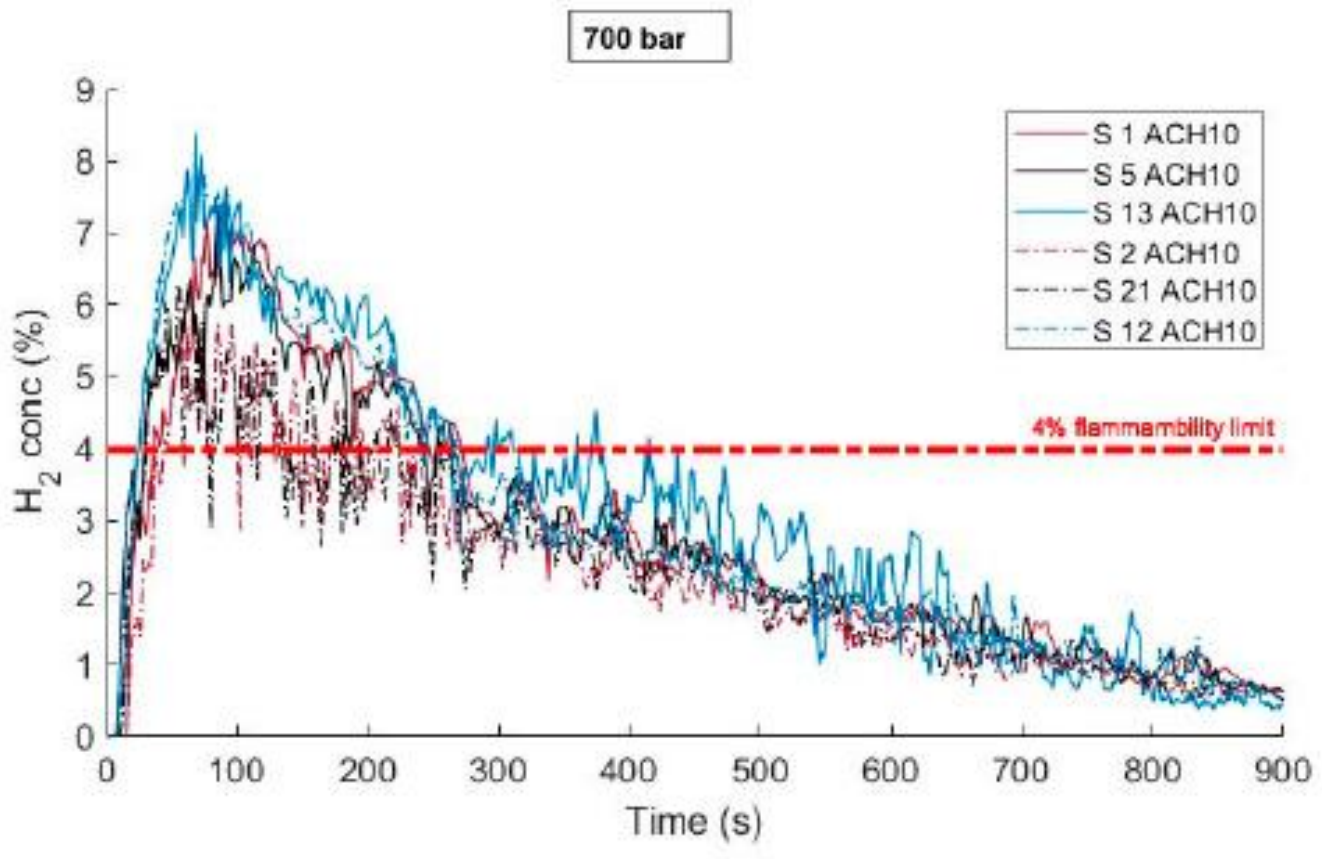
Ignited releases give maximum heat flux of 75 kW/m^2, Hall_2014

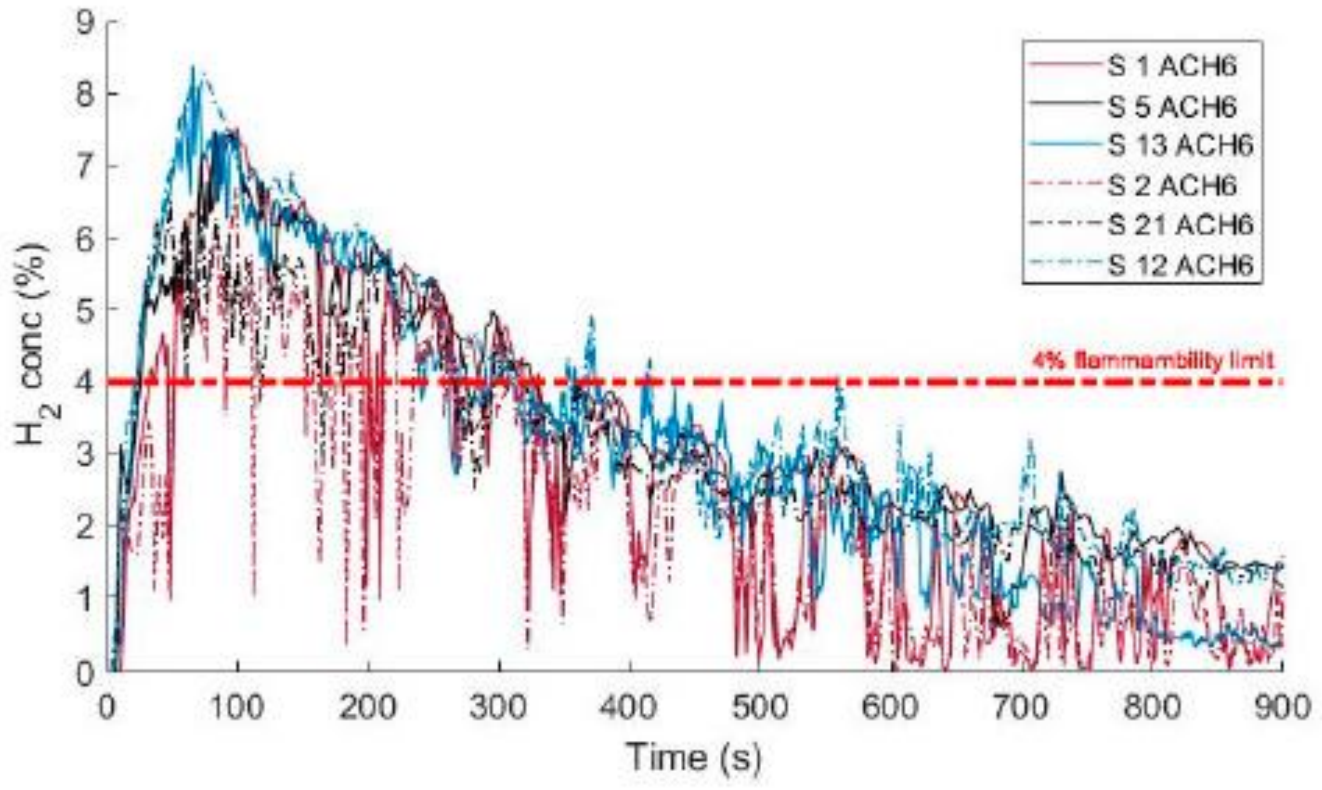
Hydrogen releases in rooms with passive vents

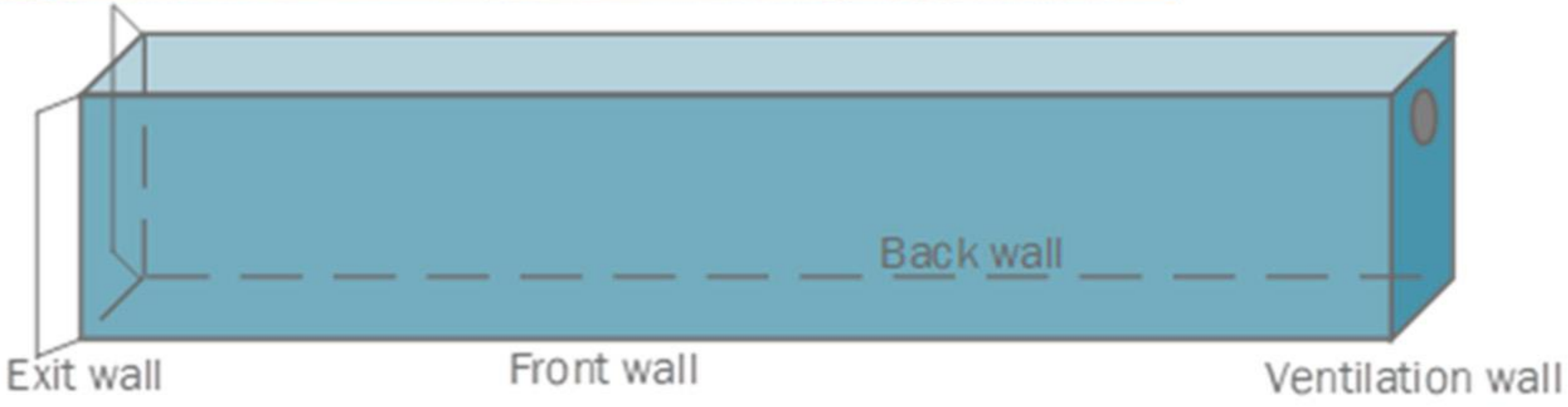


Hooker_2014

Hydrogen releases in room with forced ventilation

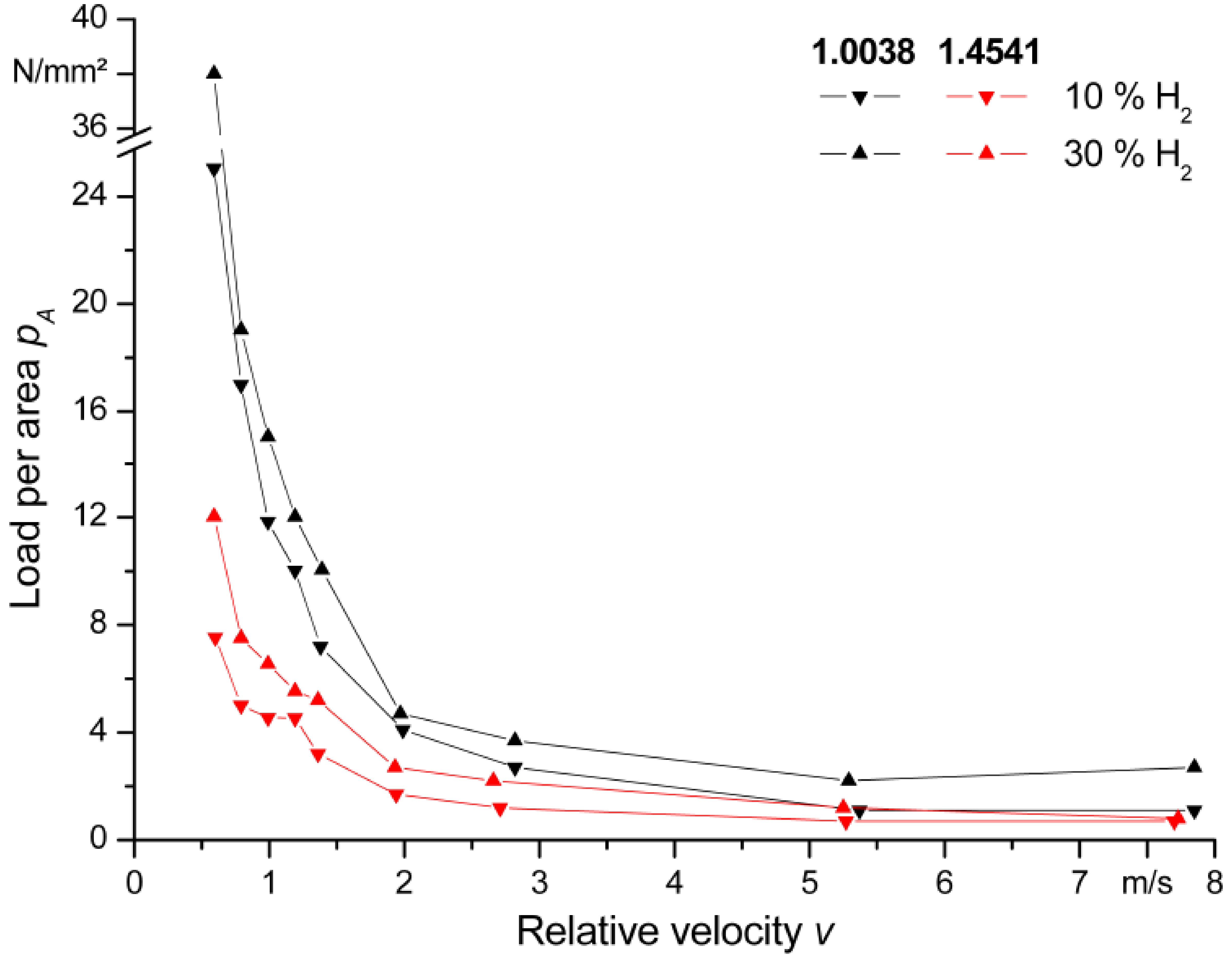






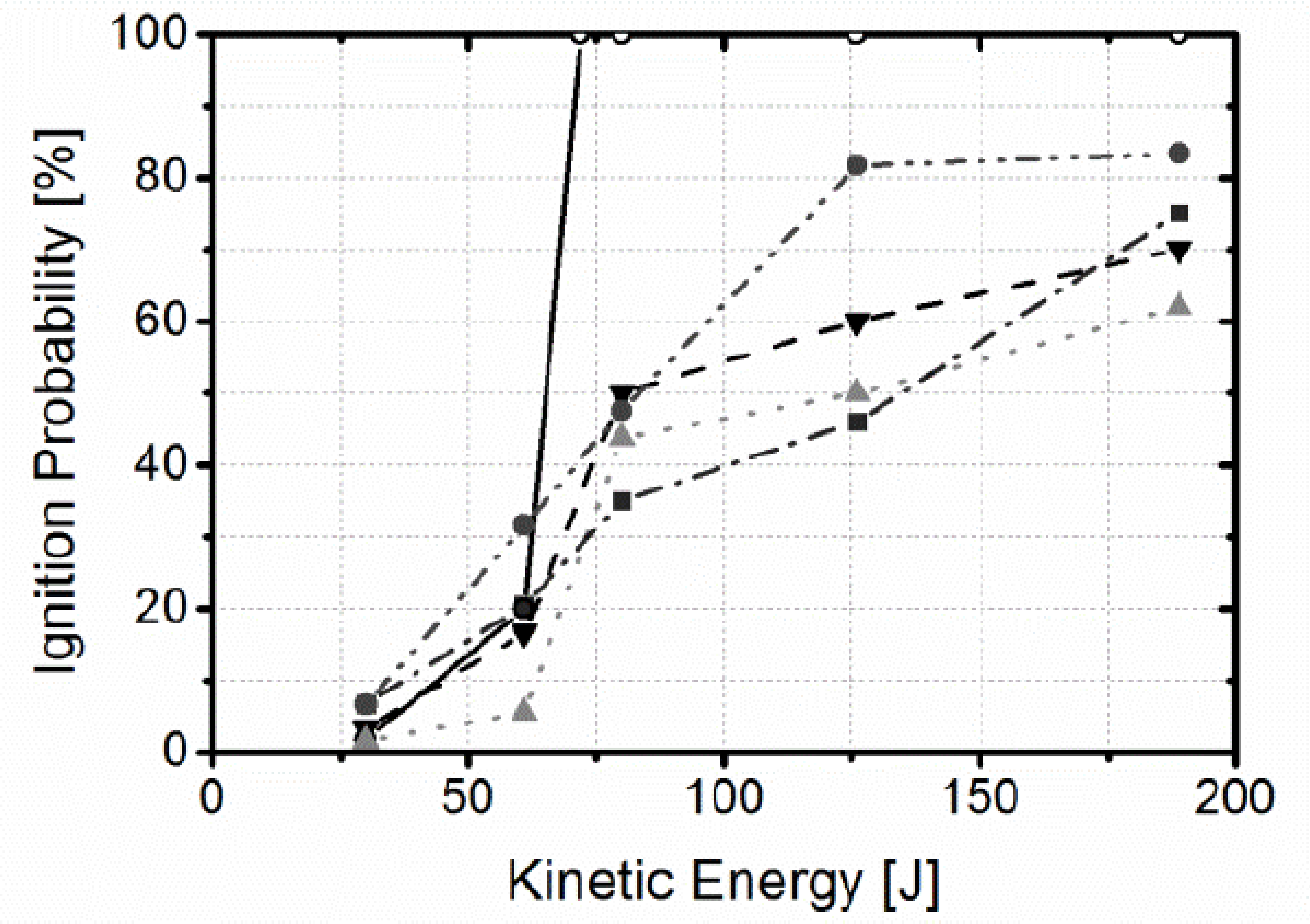
Ignition sources

Non-electrical equipment: ignition of hydrogen-air mixtures by mechanical friction



10% H_2, mild steel: always spark ignition
30 % H_2, mild steel: always hot surface ignition
Stainless steel: always hot surface ignition

Ignition of 10 % hydrogen-air by single impact

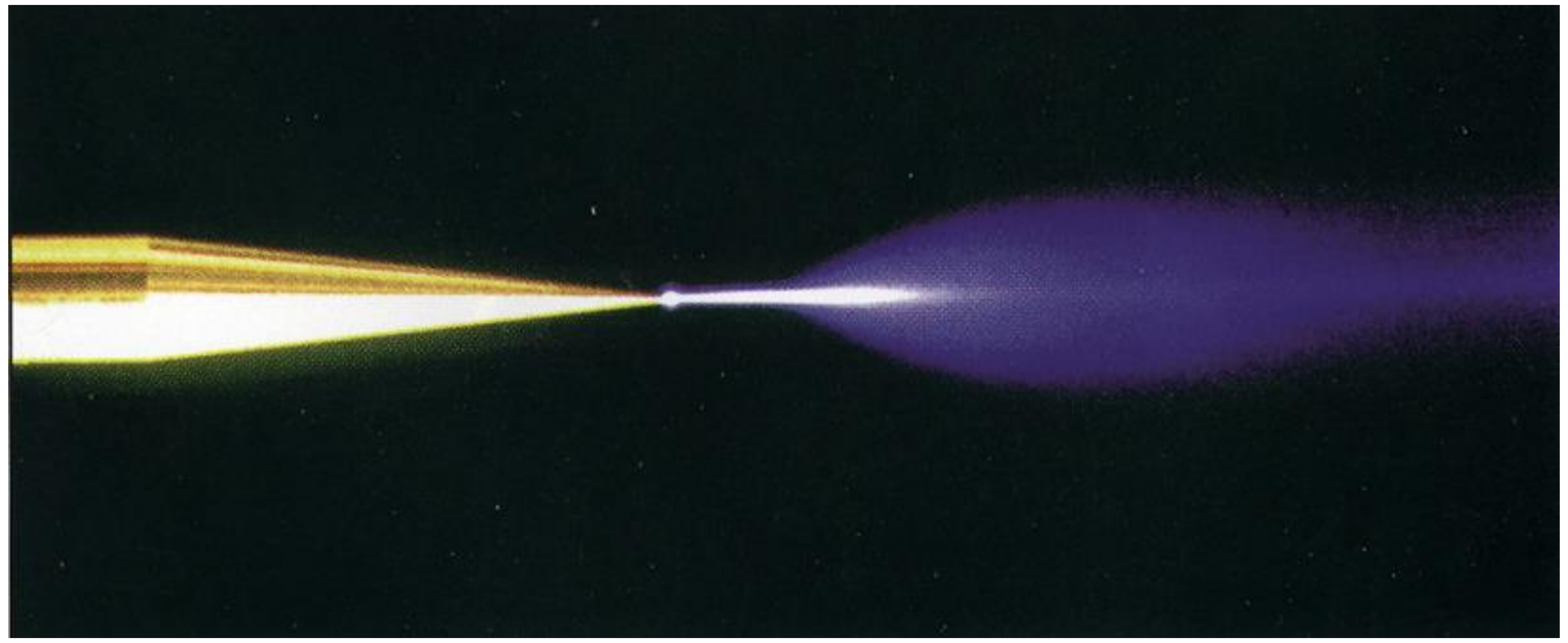


Stainless steel 1.4307 (▼)
1.4313 (▲)
1.4462 (●)
1.4541 (■)
Mild steel 1.0570 (○)

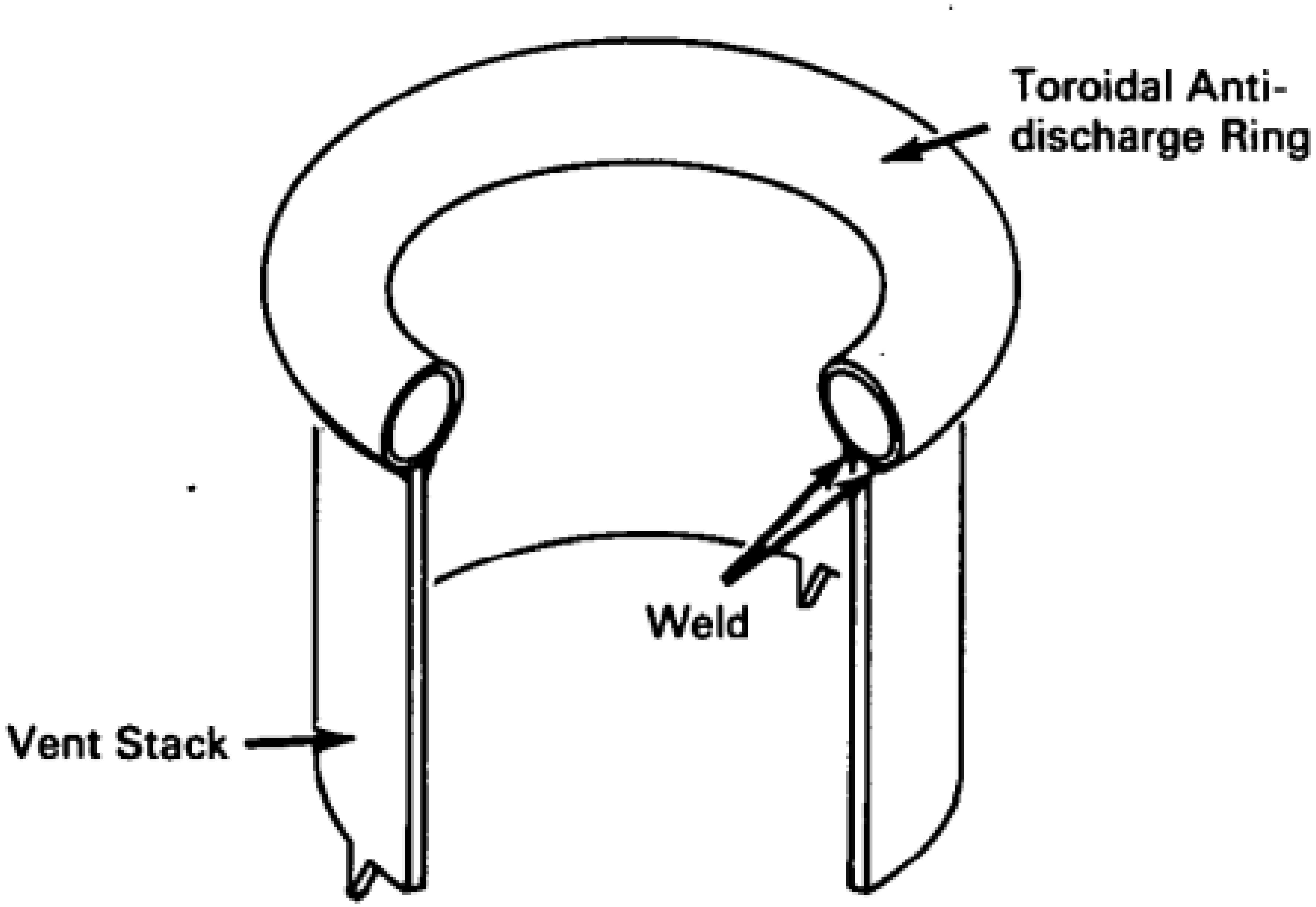
Holländer_2016

Electrostatic discharges: corona discharge

- Occurs at sharp/pointed conducting materials in electric fields, e.g. when approaching charged non-conducting materials
- Low energy-content
- Can lead to ignition of very ignition-sensitive gases like acetylene and hydrogen

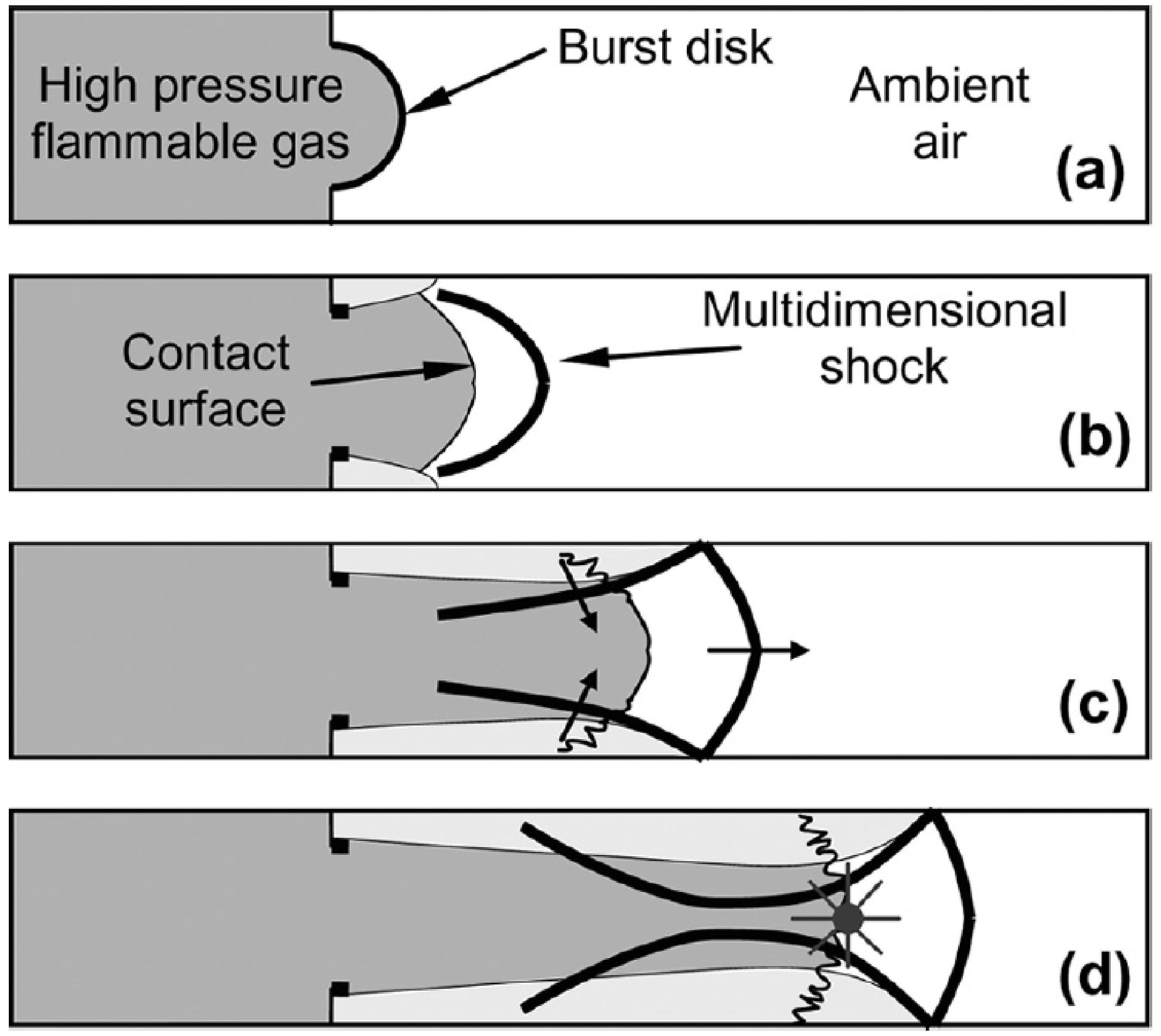


Ring on top of vent stack to prevent corona discharges (NASA)



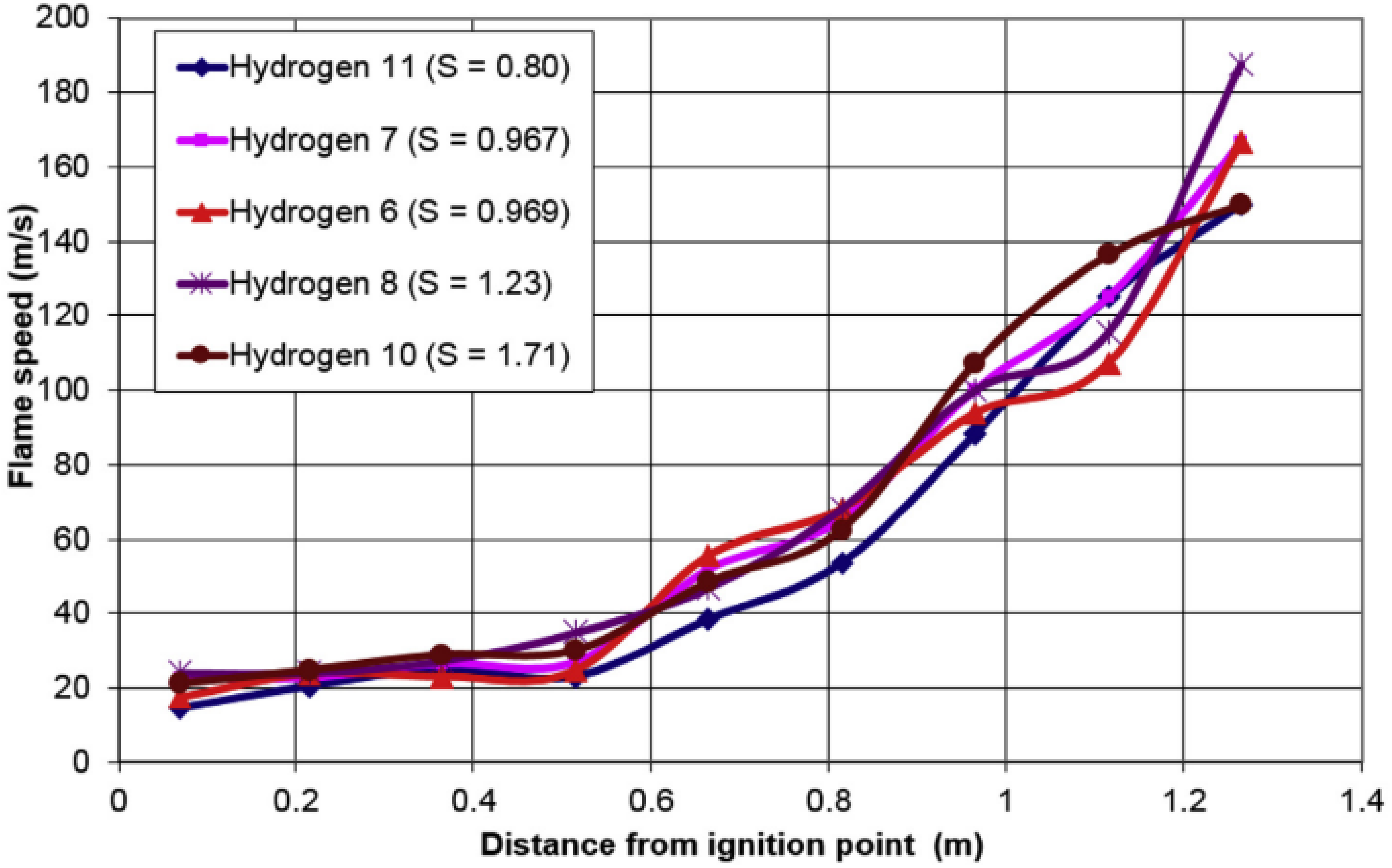
Spontaneous ignition

- Ignition of hydrogen upon sudden release from high pressure chamber connected to a venting line
- Most probable cause are shock wave reflections igniting the hydrogen at the interface between hydrogen and air where due to diffusion a flammable mixture has arisen
- Spontaneous ignition seems to occur predominantly in thin vent line connected to a high-pressure chamber protected by a bursting disk
- Up to a certain length increase of the length of the vent line promotes ignition



Explosions and jet fires

Hydrogen explosions in congested 3-D geometry

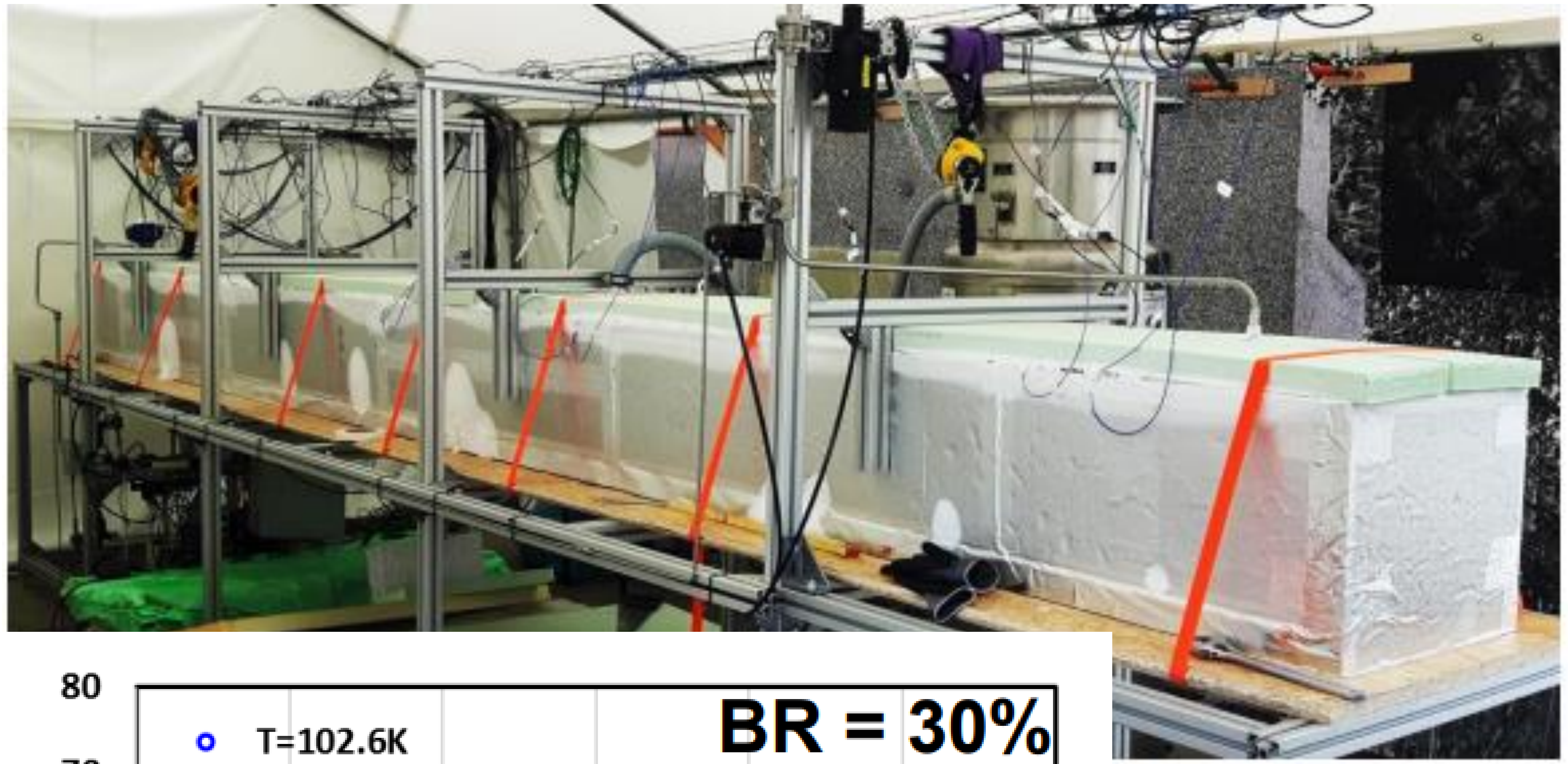


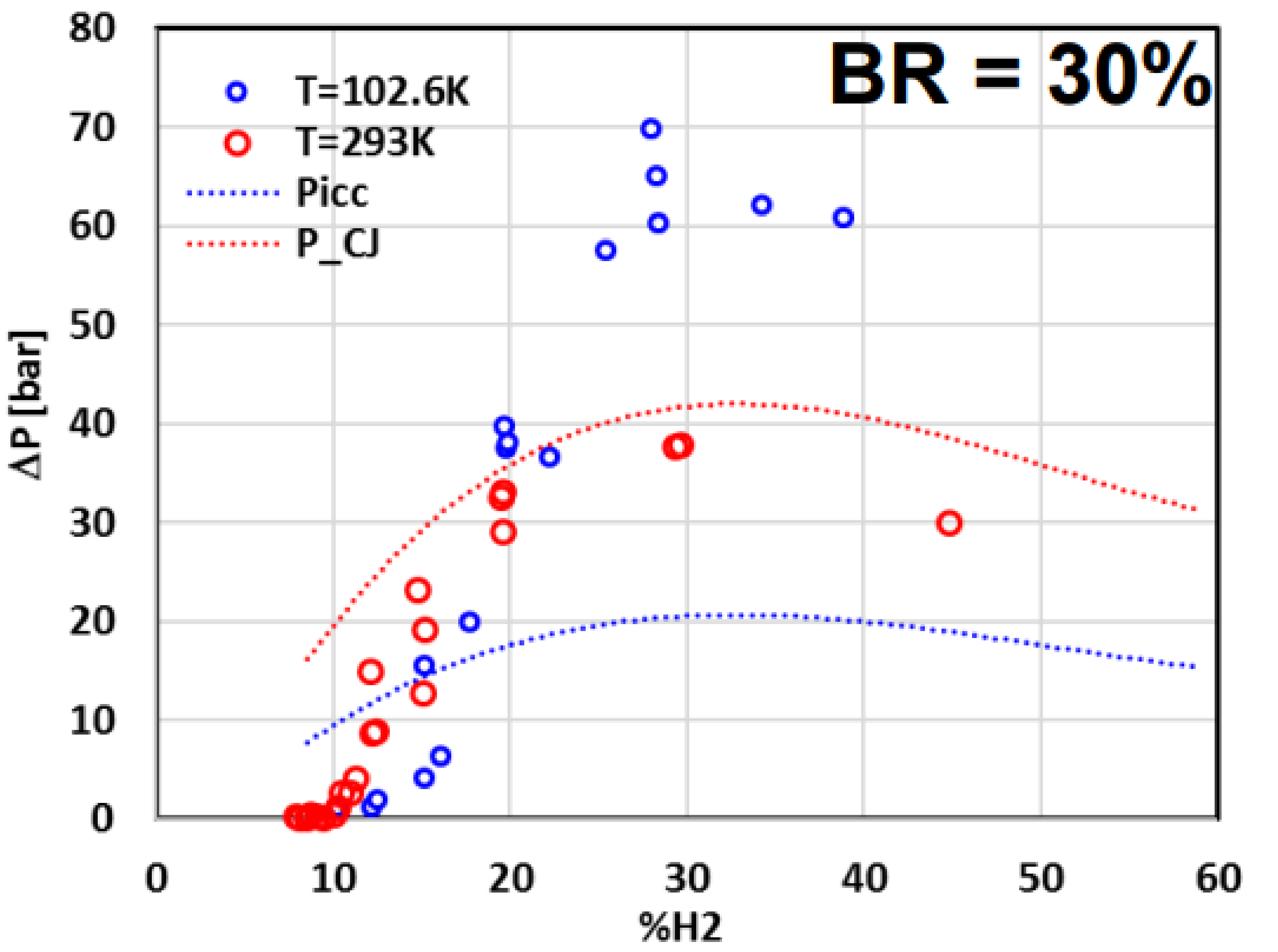
Shirvill_2018

Flame propagation at cryogenic temperature (100 K)

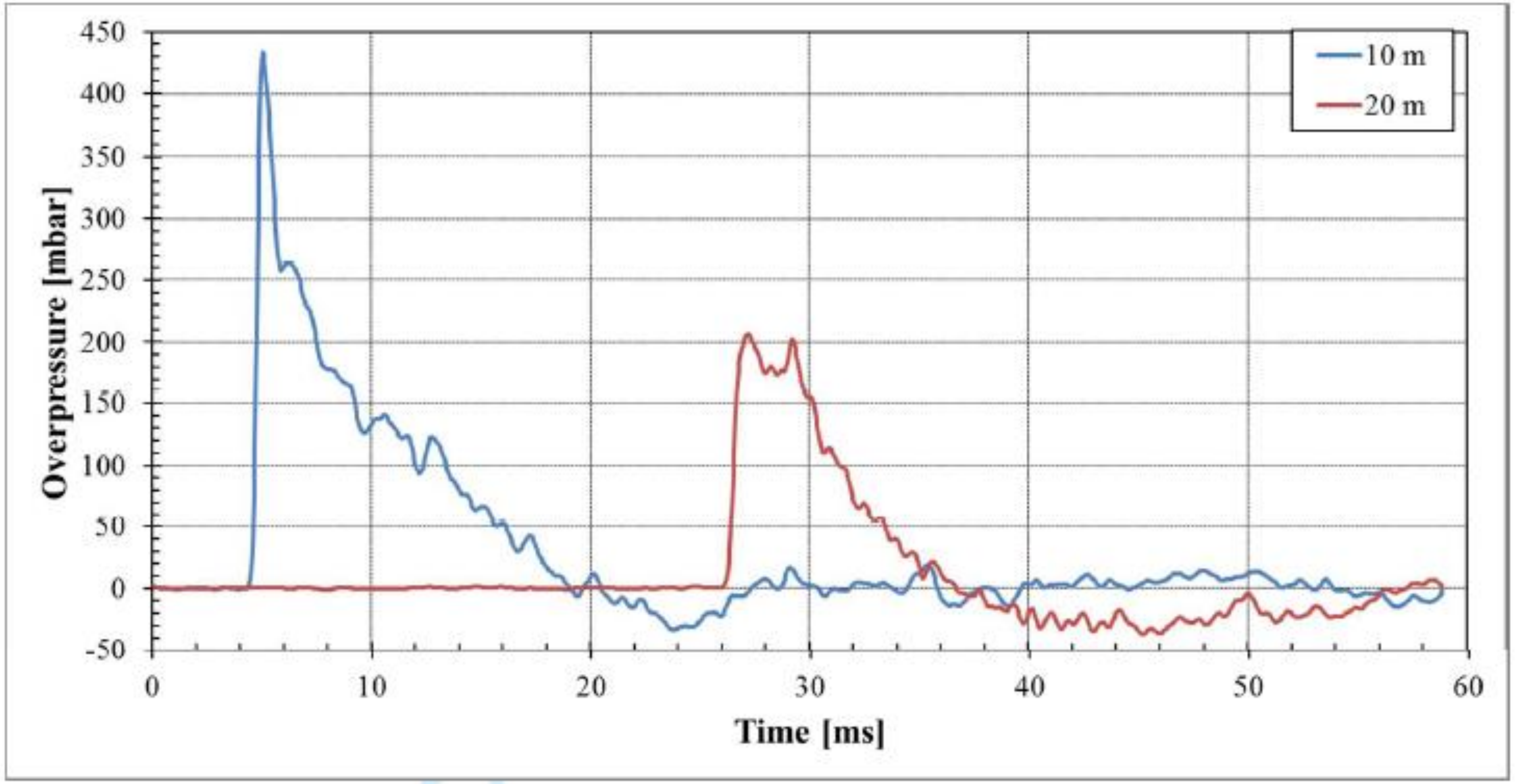
- Experiments in obstructed channel
- Run-up distance to detonation reduced by factor of two
- Wider range of choked combustion
- Considerably higher pressures

Kuznetsov_2021





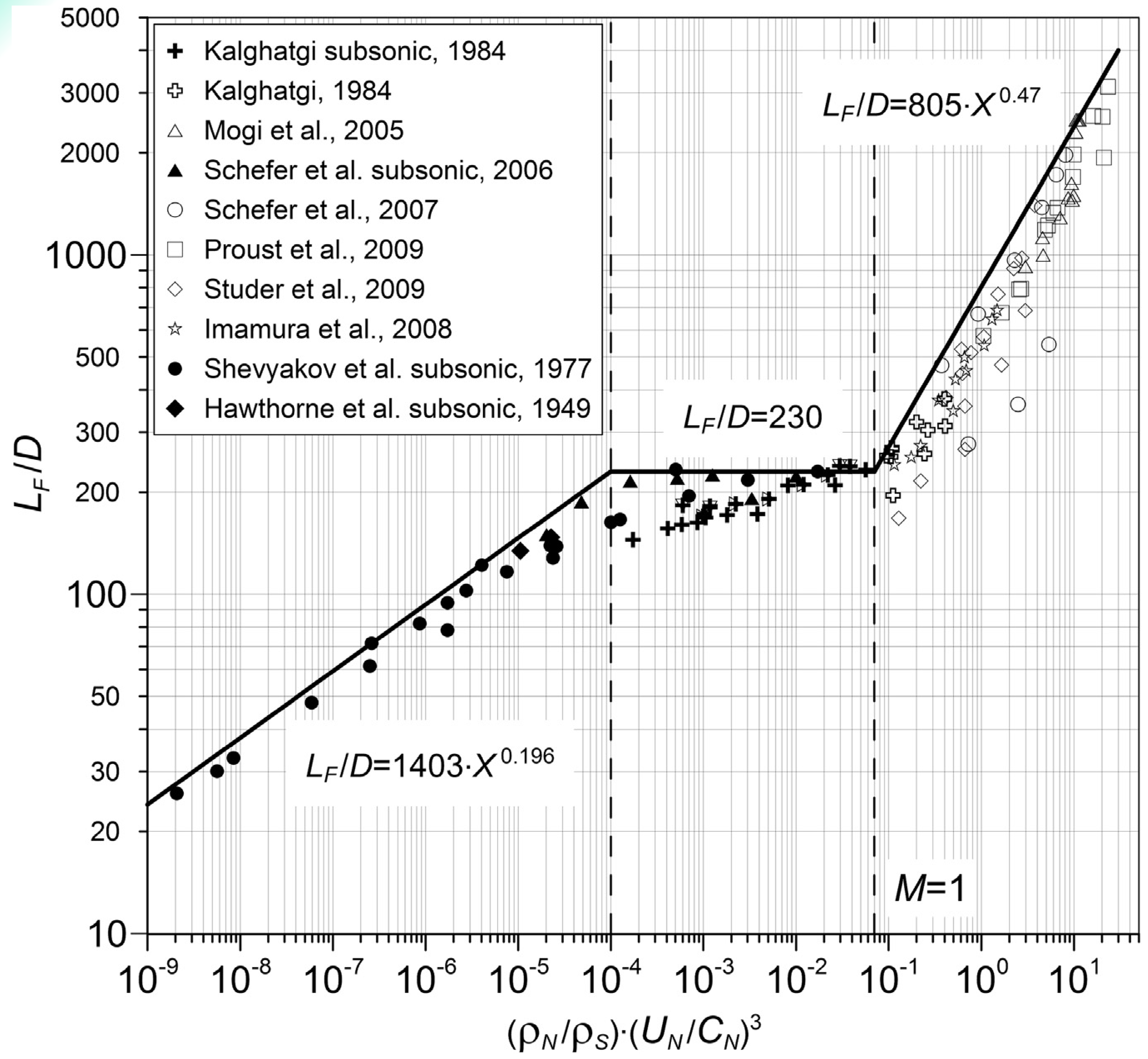
Hydrogen jet explosion

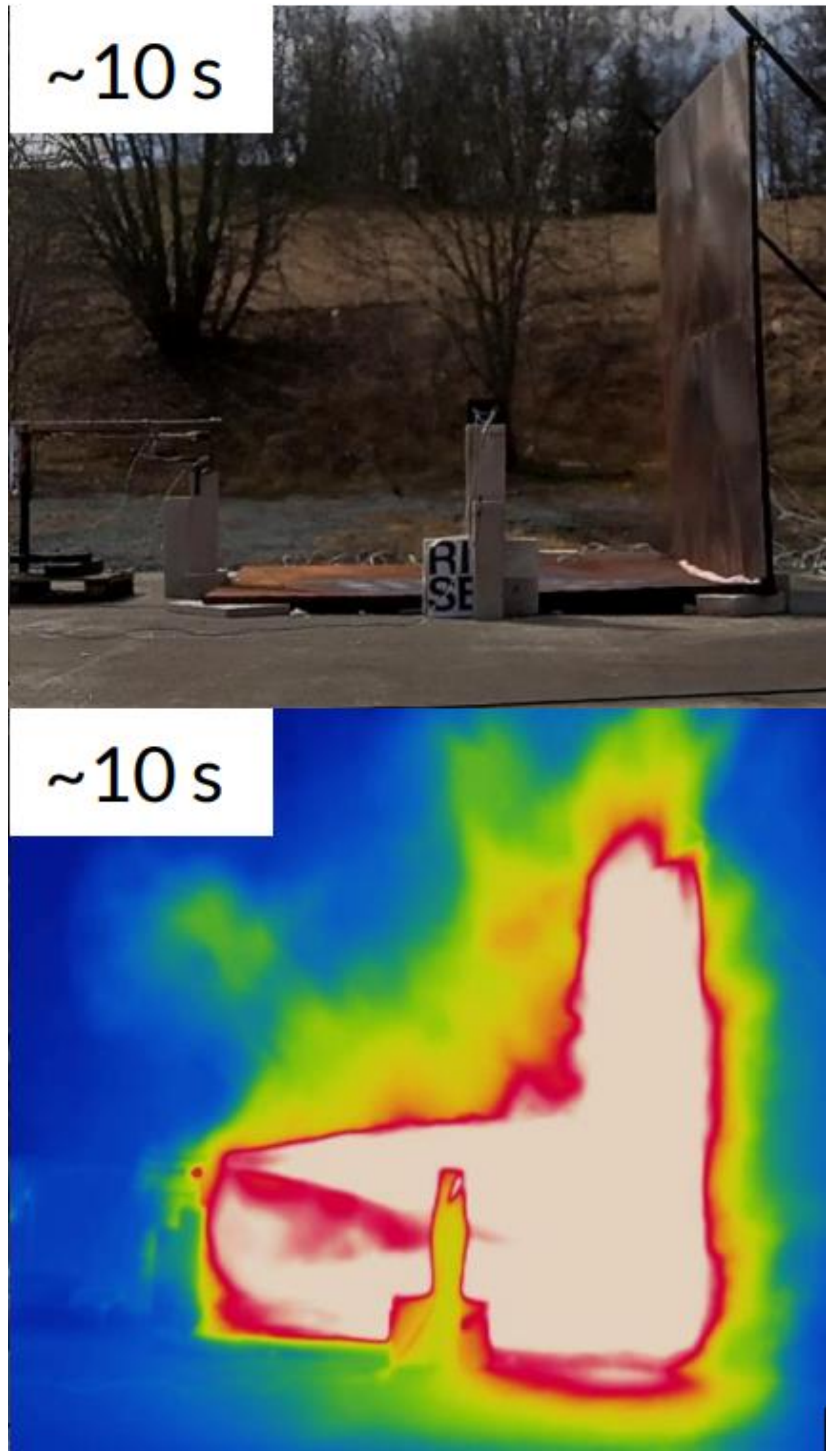


Jallais_2018

2 inch release, 60 bar
8 kg/s

Hydrogen jet fire





Impacting jets

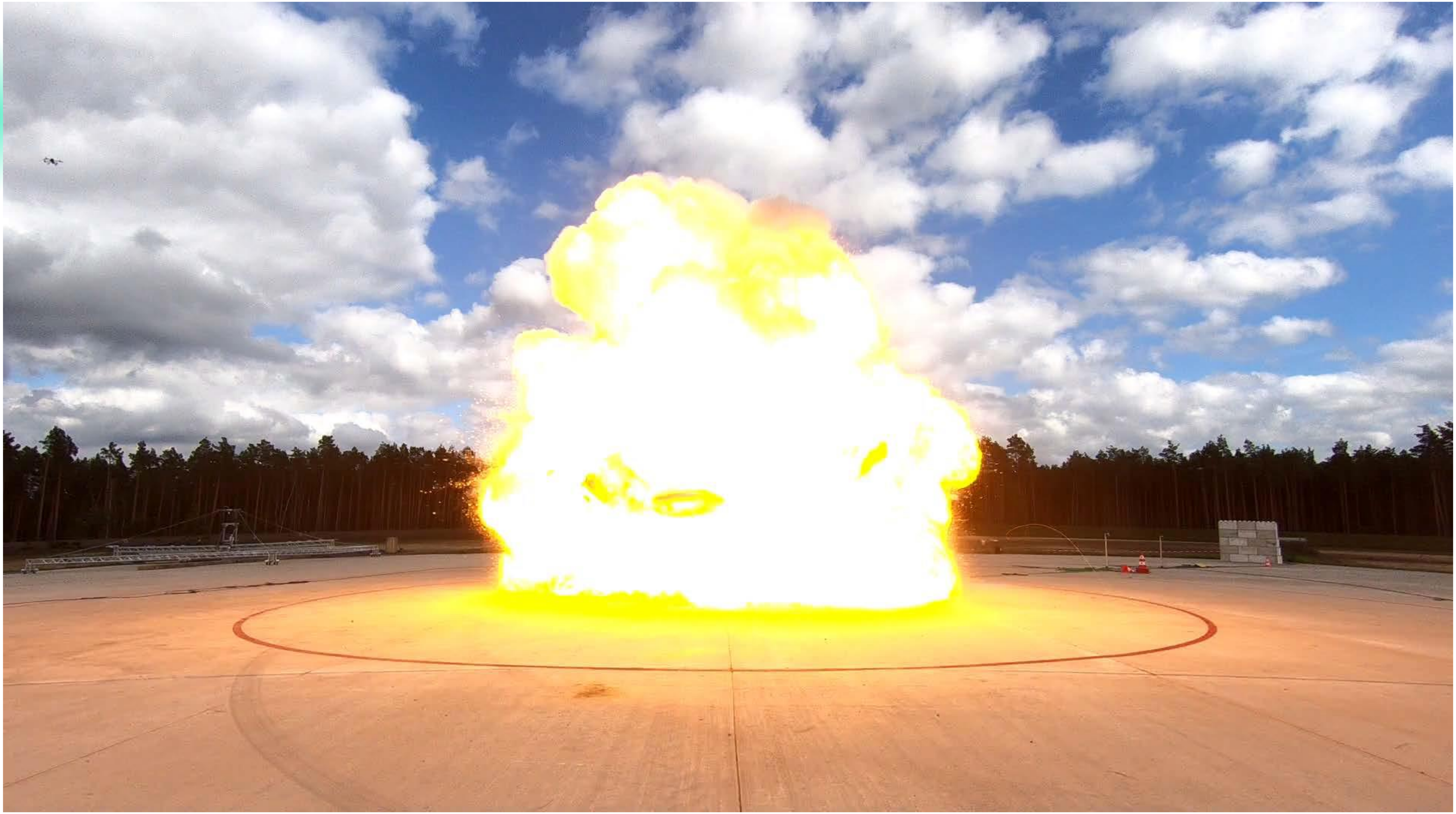
- **Very high heat flux levels where the jet impacts (over 700 kW/m²)**
- **Lower heat flux on surfaces outside the jet flame (< 125 kW/m²)**

Stølen_2021

Molkov, 2013: **relationship flame length for free jets**

BLEVEs

BLEVE of Liquid hydrogen storage vessel



BLEVE

- One out of three 1 m^3 doubled-walled vacuum insulated pressure vessels with disabled pressure-relief valve caused BLEVE after exposure to propane fire
- The event caused a fireball (maximum emissive power of 60 kW/m^2) fragmentation of the vessel 70 kg part at 170 m) and blast waves

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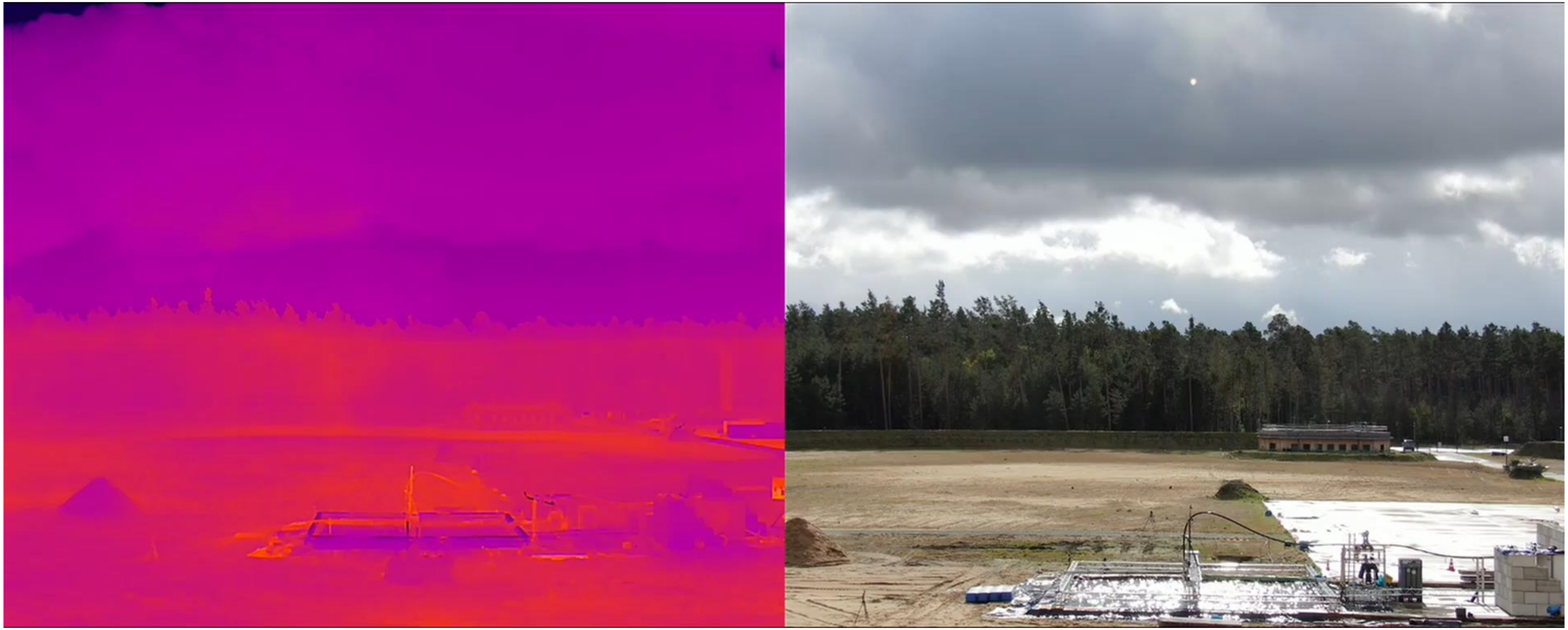
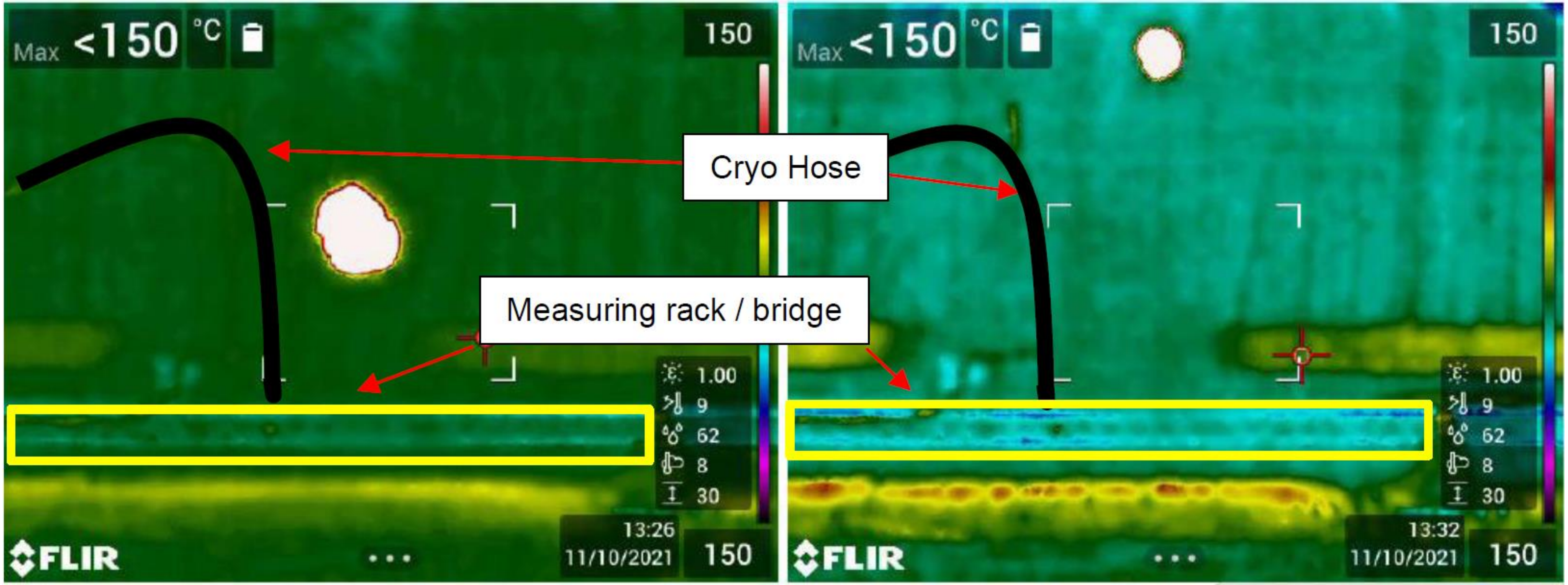
Rapid Phase Transition

Releases of liquified hydrogen onto and under water



Interaction of hydrogen jet with water

Ignition location



Overall cases of ignition

Type of release	Total number of releases	Total Number of observed ignitions	Percent of releases with ignition
Above water pointing downwards	31	21	68
Under water pointing downwards	34	32	94
Under water pointing horizontal	10	7	70

RPTs

- The evaporation mechanism differs from that described for LNG and water. An RPT, in the traditional sense as seen for e.g. LNG, does not occur. Pressure waves due to release of high momentum LH2 jets into water are in the range of several 10 mbar
- The majority of the releases showed an ignition of the generated gas cloud followed by an explosion producing overpressures of up to several 100 mbar in air and up to several bars under water
- The ignition source is unknown and further research is needed to clarify

Van Wingerden, 2022

Conclusions

- Hydrogen is currently enjoying unprecedented political and business momentum as a viable, low-carbon energy source for industrial and transportation uses
- Hydrogen is however highly flammable and accidents have happened. Safety shall have a high attention to avoid accidents from becoming a showstopper
- Safe handling of hydrogen is fully possible with an acceptable residual risk by combination of proper design of the facility and training of personnel operating and maintaining the facilities
- Proper design includes prevention of leaks, limitation of the generation of dangerous clouds, avoidance of ignition sources and limitation of potential consequences (fires and explosions)
- Recent and ongoing research increases our level of understanding of safety aspects associated with the handling of hydrogen and contributes to an even better basis for proper safe design of hydrogen facilities and reducing uncertainties

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Thank you