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SAFETY OF HYDROGEN IN ENERGY TRANSITION

safera

B. TRUCHOT

Hydrogen is not new

More than 50 millions tons of hydrogen used each year since 2000

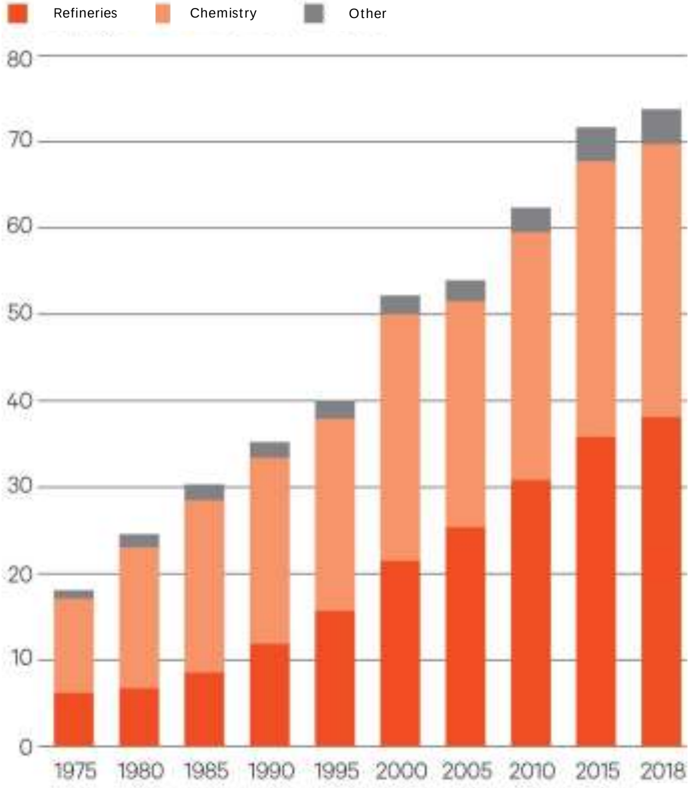
For space applications

- From the 40’s for military purpose and in the 60’s and 70s for rockets
- Use of large amount of cryogenic hydrogen
- Many research on hydrogen safety for that purpose

For industrial purposes

- Hydrocarbons desulfurization
- Heavy chemistry (ammonia, oxygen peroxide production, …)

World hydrogen consumption
in million tons of H_2 (source ADEME)



With victories and drama

But we face off a new deal

Individual Transports

Collective transports

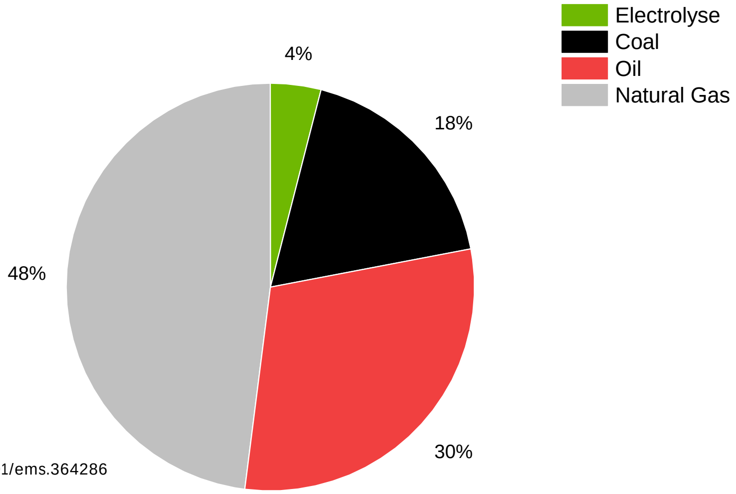
Domestic applications

Hydrogen production should increase

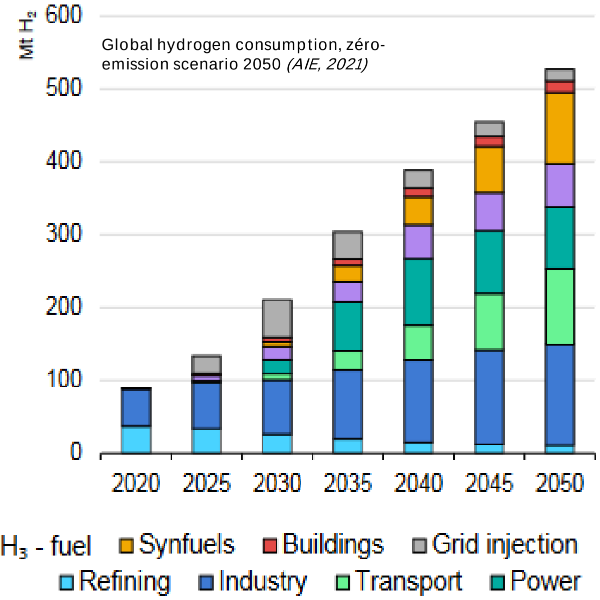
Due to the development of hydrogen applications

- Expected hydrogen quantity would be 6 times the current quantity
- Quantity for transportation in 2050 would be higher than the whole current quantity

But



Adapted from Doi: 10.26701/ems.364286

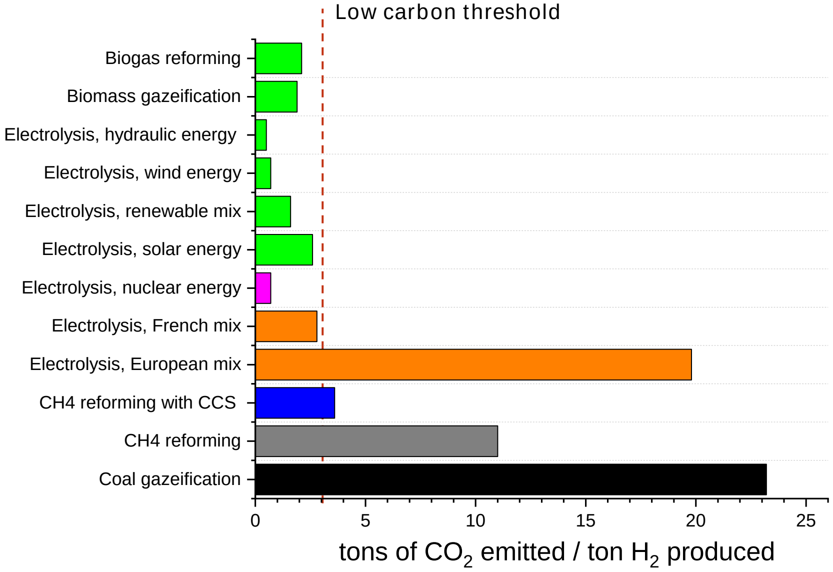

Global hydrogen consumption, zéro-emission scenario 2050 *(AIE, 2021)*

Production methods should evolved

Most of the current hydrogen produced is not decarbonized

- The major part comes from methane reforming
  - 1 ton of hydrogen produces 11 t of CO_2
  - Burning 1 ton of fuel produces 3 tons of CO_2 (only combustion), up to about 20 t when considering the whole chain

- Electrolyze could be a solution
  - But the energetic mix used for production should be considered
  - Large-scale electrolysers should be developed in safe conditions



Adapted from *Base Carbone ADEME / PPE 2019 / JRC – Etude WTT 2021*

With innovative issues for risk management

Assuming that we need hydrogen to reduce our carbon footprint

- Hydrogen massive deployment should be safe
- Any major accident could be dramatic for the development strategy

To meet such an objective

- A reinforced knowledge in hydrogen properties is the basis
- Defining hydrogen systems safe by design to prevent any event is a key
- Having planned the worst case and its consequence is mandatory

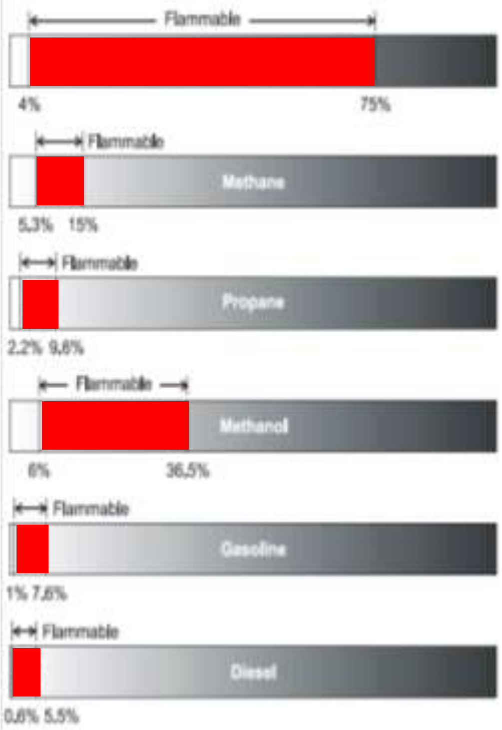
GPL, Venissieux, France, 1999

H_2 - Norway - 2019

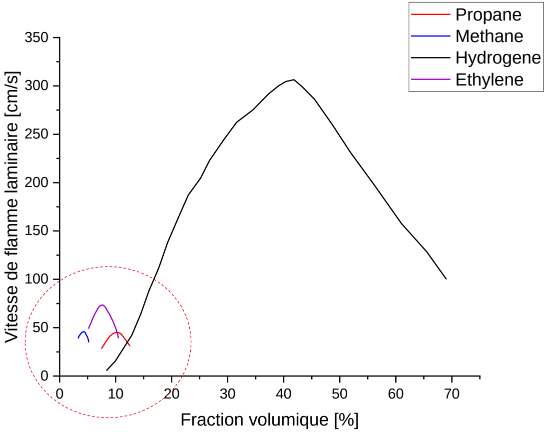
The basic: hydrogen properties

Main properties are well known

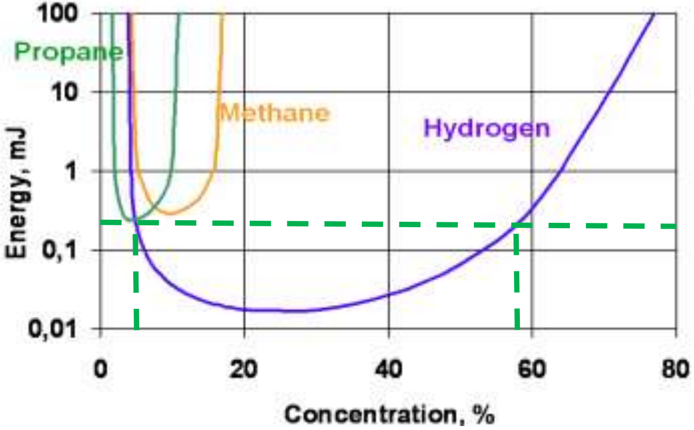
- 14 lighter than the air in gaseous form
- Odorless, colorless, non-toxic, non-corrosive
- Could interact with metals
- Could be liquified under 33 K
- Highly energetic : 120 MJ/kg vs ~40 MJ/kg for hydrocarbons,
  but only 11 MJ/m^3 in ambient conditions vs 33750 MJ/m^3 for gasoline
- One of the largest flammability range
- One of the largest fundamental flame velocity
- One of the smallest minimum ignition energy



With safety issues

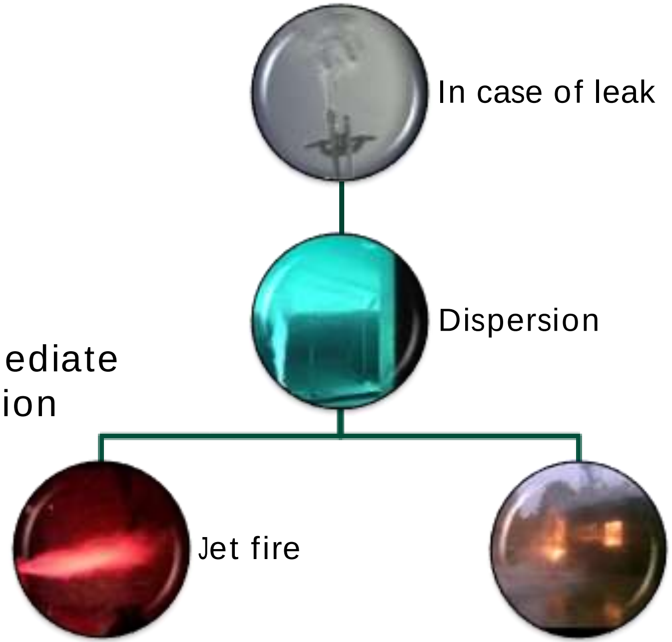


Laminar flame velocity



The Minimum Ignition Energy,
10 times lower than HC ones

Dangerous phenomena are known



In case of leak

Dispersion

Immediate ignition

Late ignition

Jet fire

Vapor cloud Explosion

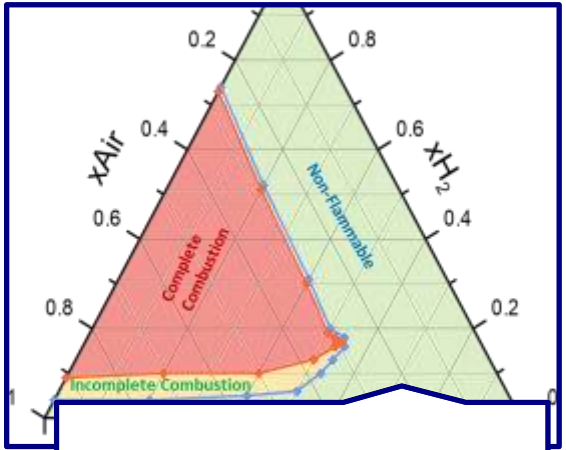
Without leak

Tank burst

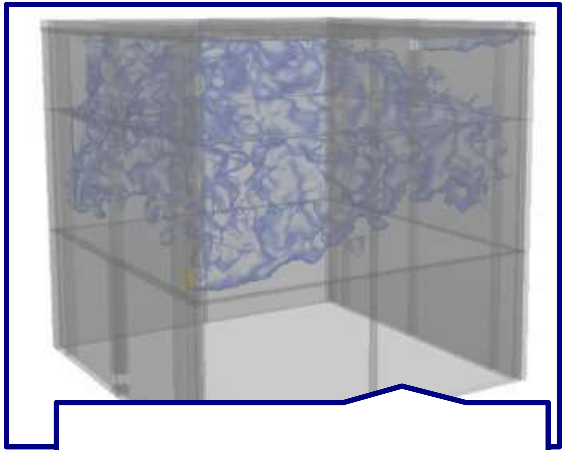
Breakthroughs are needed

≠

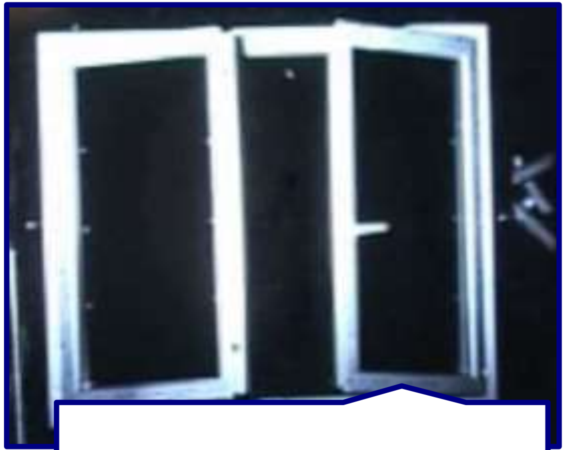
In several fields



Fundamentals



Modelling



Consequences

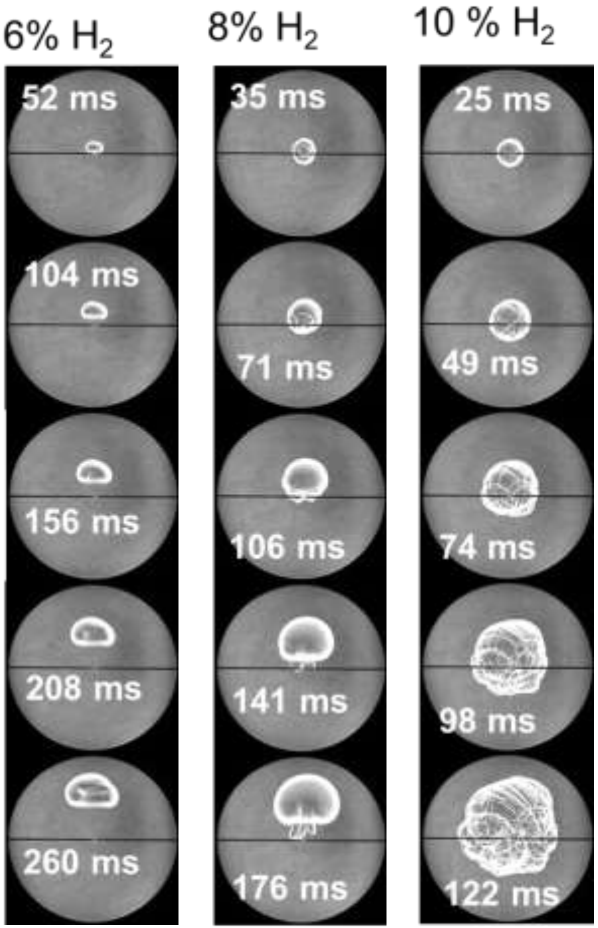
Lower Flammability Limit (LFL)

4% is based on standard approaches

- Measured using current international standards

But in a 4% hydrogen mixture, flame do not propagate

- No jet fire establishment
- No pressure effects
- Only a hot gases volume



From Cheikhravat, H., Chaumeix, N. , Bentaib, A., Paillard, C.-E., Flammability limits of hydrogen-Air mixtures, Nuclear Technology 178 (1), 2012, p. 5-16

Flame acceleration

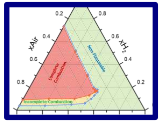
Two important physical aspects to understand

- Flame velocity is not combustion velocity
  - More important wrinkling is, more important combustion velocity is
  - Several parameters govern the flame acceleration
    - Instabilities, turbulence, burnt gas dilation, …
- The pressure effects depend on the combustion velocity, 2 main regimes
  - Subsonic combustion propagation : deflagration ➔ potential high consequences
  - Supersonic combustion propagation : detonation ➔ Strongly increase consequences

In a nutshell

- High fundamental flame velocity
- Sensitive to instabilities
- …

} DDT should be considered



The characteristic leak size

The 60079-10-1 proposes standard leaks

- For ATEX applications
- Not relevant for major scenarios

For major scenarios

- Some tools are available, typically HyRAM

But based on very few data

- Mainly for hydrogen energy applications
- Databases should be enriched
  - Through accidents, but we cannot wait to have some
  - Through experiments (Multhy-fuel project)

But not only consequences

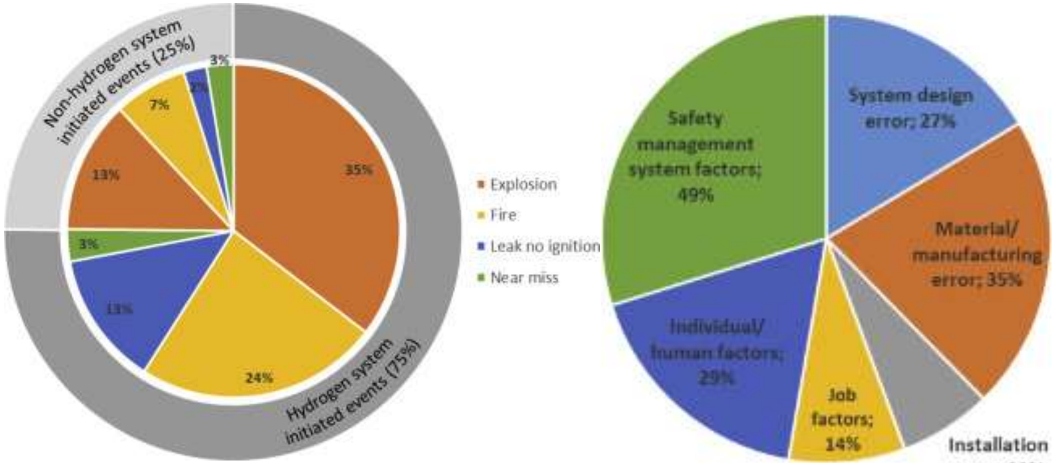
Risk evaluation requires evaluating consequences but also probability

- Probability of the main events means
  - Probability of the initial failure
  - Safety system failure probabilities

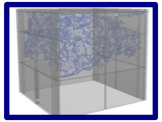
Defining probabilities implies data

- Hydrogen energy is quite new
- Data should be collected
  - Some on-going project
  - Few data available yet

Some results exist, but more data are needed to make it reliable



From https://doi.org/10.1016/j.ijhydene.2022.03.170

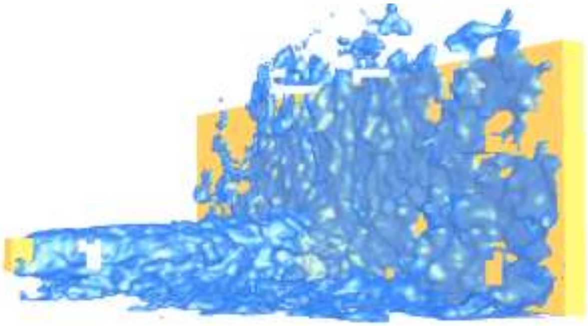


Leak dispersion

The beginning of many phenomena

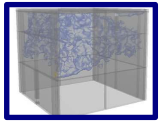
Modelling leak dispersion, in free field configuration is not a problem

- Algebraic relevant models exist
- CFD codes are able to forecast such a situation
- Experimental data are available for validation



But free field is not a common situation

- The standard approach for impinging jet consists in multiplying the flammable mass by 10
- Is this relevant for hydrogen energy applications?
- CFD simulations can be performed, but experimental data are needed



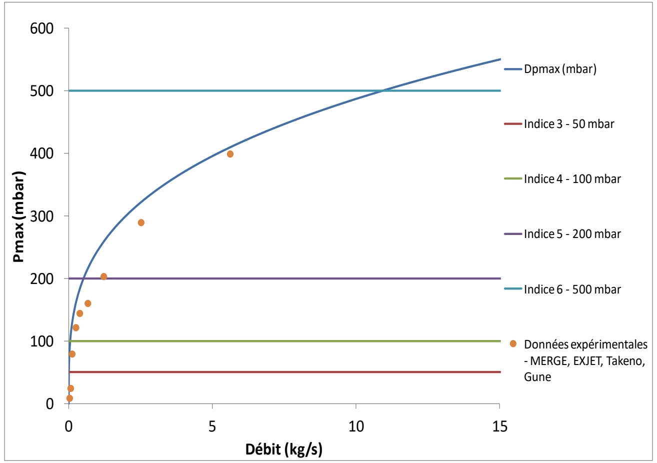
Vapour cloud explosion

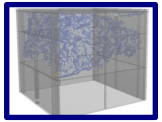
This could appear quite simple

- Evaluation of the flammable mass ➔ available energy
- Use of standard methods (Multi-energy) to get pressure effects

But reality is not so simple

- The mass that participates to the explosion is not the whole mass
  - Only the half-sphere inscribed in the flammable volume does
- The explosion violence depends on the ‘available time’ for flame acceleration
  - Empirical data are available for some configurations
  - CFD models could be used, but still under improvements / developments





Tank behavior in fire situation

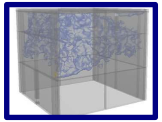
In case of surrounding fire, a tank burst is

- Delayed but sudden
- Violent with
  - Pressure waves
  - Fireball
  - Projection

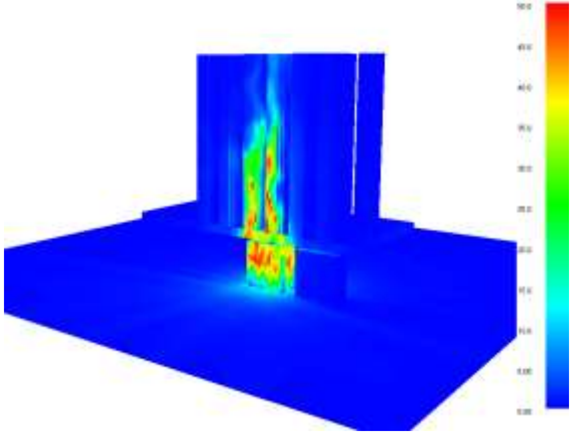
Major issues consist in

- Predicting whether or not burst could happen based on fire properties
- Predicting the corresponding delay before burst, some seconds, minutes, more …
- Defining safety system to **<u>prevent</u>** the tank burst


19 l – 700 bars



From data to model



Data for tank behavior exist

- For some types (I, II, III, IV) of bottles
- In some situations

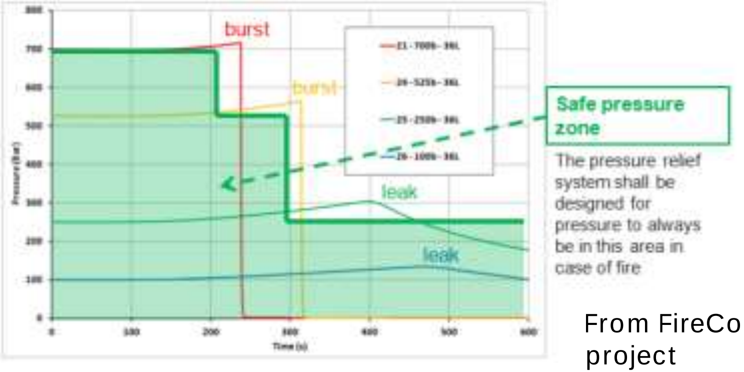
Several fire models are available

- Computing net heat flux on tank is possible

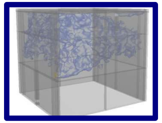
But many configurations exist

- Size and pressure of the tank (100% charge or not)
- Orientation of the tank ...

➔ A generic approach is needed



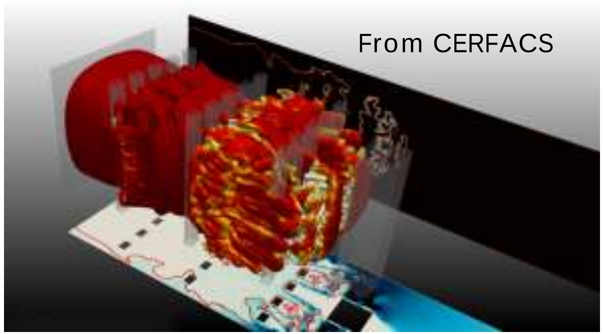
From FireComp project



And always, the validation

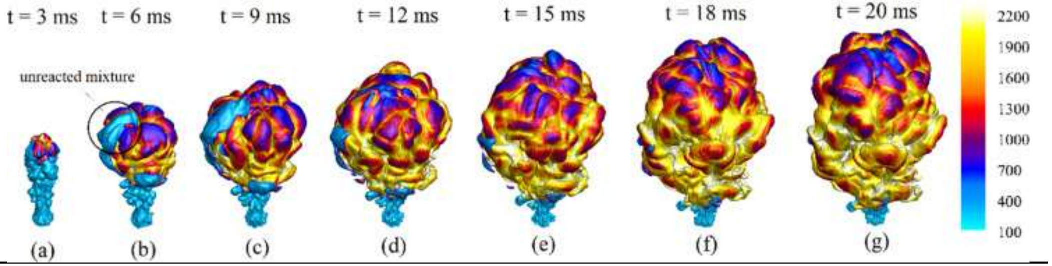
As usual, numerous codes appear

- From simple correlations
  - https://elab.hysafer.ulster.ac.uk/
- Through integral / empirical correlation
  - HyRAM, Phast, …
- To 3D model based on CFD (Computation Fluid Dynamics)
  - HyFOAM, AVBP, …

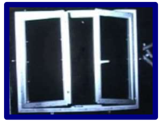


From CERFACS

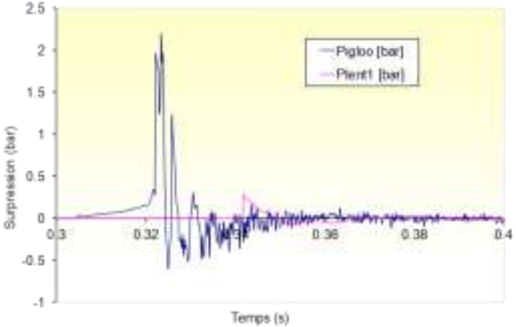
➔ Defining the application field
and validating the model is essential

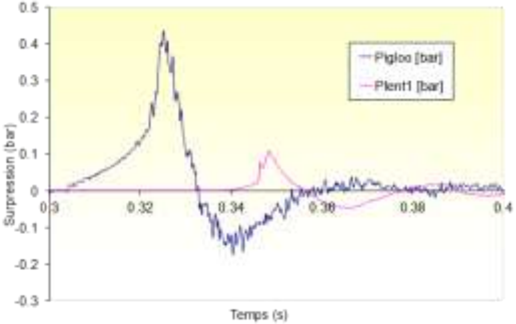


From https://doi.org/10.1016/j.ijhydene.2022.06.230



Evaluation of the impact on structures





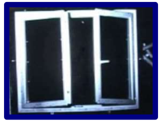
Overpressure thresholds for structure are commonly based on the pressure peak

- The application time and loading shape is also important
- For the same overpressure, the structure response will vary

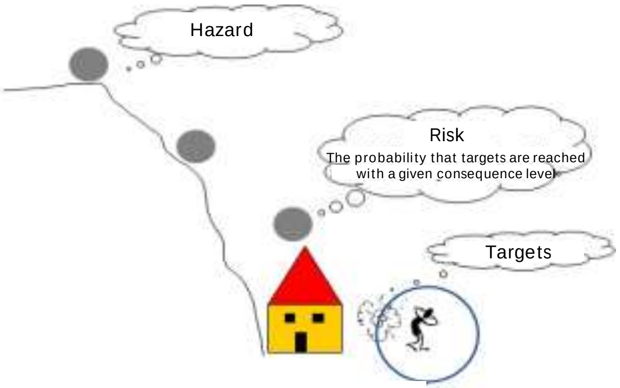
Also important for protection system definition

- For venting systems
- For structure design, including pressure absorption systems

From HySea project



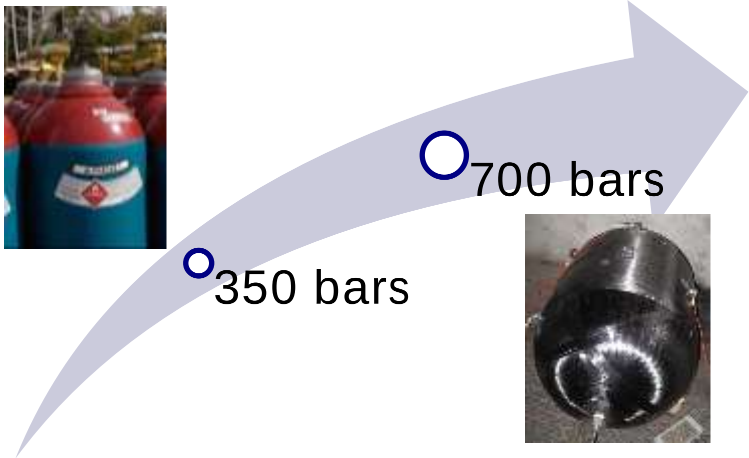
But also on human beings



Consequences are based on some thresholds

- Overpressure:
  - 50 mbar, 140 mbar, 200 mbars …
  - Overpressure is one part of the problem; application time is the second
- Thermal
  - 3 kW/m², 5 kW/m², 8 kW/m² …
  - But radiation is not the only topic
    - Ex : 900 bar, 2 mm
    - Flame temperature: up to 1800°C
    - Radiation is low for hydrogen flames
    - But what about the temperature some meters behind the flame

And the future is coming



350 bars

700 bars

Most of current hydrogen applications are based on compressed hydrogen

- 350 to 700 bar
- Tomorrow, 1000 bars?

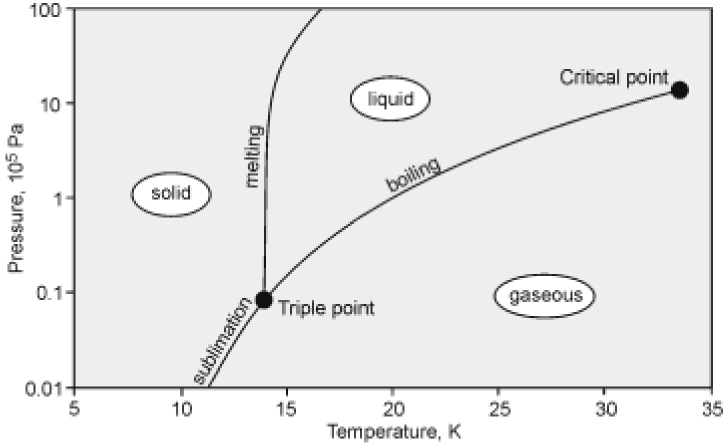
But still not enough, improving the density of energy remains crucial for some applications

Mercedes

Airbus

Kawasaki

With new topics



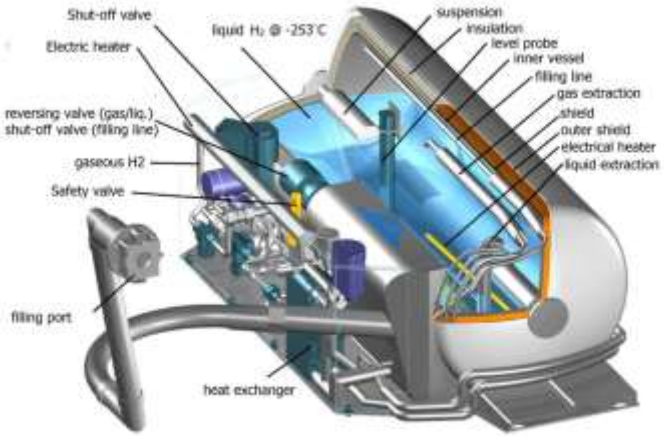
Cryogenic hydrogen let appear highly specific conditions

- Temperature about 20 K (–253°C) at atmospheric pressure
- For pressure in the range 1 to 10 bars

Thermal insulation should be strongly controlled

- For economic reasons: heating the tank means losing hydrogen
- For safety reasons: a quick temperature rise could induce important leak, up to the tank burst

A new field of scientific investigations



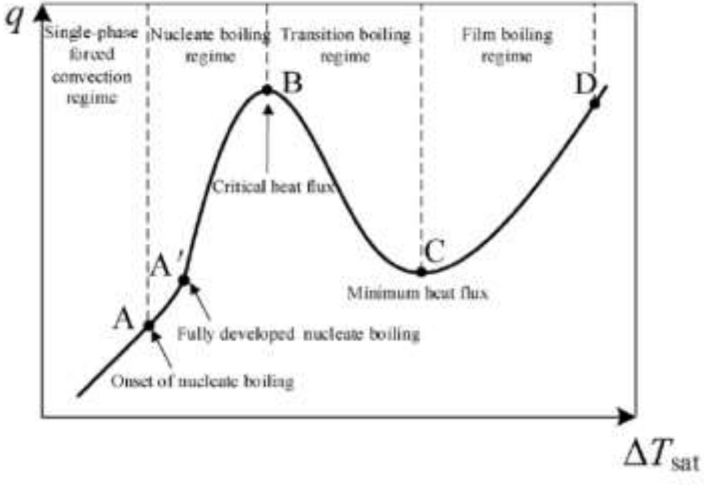
Including very fundamental questions

Liturgical hydrogen is one of the coolest liquid : 20 K at ambient pressure

- Development of dedicated tanks
  - Double wall, void insulation, specific insulation layer (MLI – Multi Layer Insulation)
- Boiling regime transition specific to hydrogen

Very few data relative to cryogenic tank in fire

- Some tests made with Helium
- Determining the thermal exchange coefficients is an issue to build a relevant model
  - Addressed is the on going French ESKHYMO project



Cryogenic hydrogen is challenging

From PRESLHY Deliverable 6.2

Release is colder than the air liquefaction temperature

- Oxygen and nitrogen will be liquefied / solidified in case of LH2 leak

What about the flashing

- A small volume of LH2 means
  a large volume of GH2 and
  an enormous flammable volume
- With potential 'auto-ignition'
  - If all conditions are met (concentrations, presence of particles, …)

Several European and National on-going projects on that topic

From SH2IFT final report

Key messages in a nutshell

Hydrogen is used for many years

- ➔ We should not forget lessons learns
- ➔ A strong evolution is required

Using hydrogen as new energy carrier let offer new challenges

- ➔ Citizen will be in the heart of the hydrogen development
- ➔ Improvement needed for risk evaluation, fundamentals properties, modelling and consequence evaluation
- ➔ We should ensure a safe and efficient development

And be ready for the in coming future

- ➔ Knowledge development for cryogenic systems

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