Engineering correlations and tools for cryogenic hydrogen hazards assessment

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Pre-normative REsearch for Safe use of Liquid HYdrogen

Pre-normative REsearch for Safe use of Liquid Hydrogen (PRESLHY)

Project Deliverable

D6.5 Detailed description of novel engineering correlations and tools for LH2 safety, version 2

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Outline

- Introduction
- List of engineering correlations and tools
- Engineering correlations and tools for:
  - Release and mixing
  - Ignition
  - Combustion
- Conclusions

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Introduction

- Experiments available in the literature or performed within PRESLHY project were used to build semi-empirical and empirical correlations, or to validate theoretical models.
- The engineering correlations and tools aim at characterising the phenomena associated with cryogenic hydrogen and liquid hydrogen safety, and assessing the hazards and consequences from likely incidents.
- The engineering correlations and tools are gathered in D6.5 “Detailed description of novel engineering correlations and tools for LH2 safety, version 2”.
- The objectives were the following:
  - Present the engineering correlations developed and validated within PRESLHY project to close the relevant knowledge gaps. The engineering correlations contributes to Recommendations for RCS and the novel guidelines for safe design and operation of LH_2 systems and infrastructure
  - Provide the description of the engineering correlations and tools according to a unified template for future implementation into existing and/or future integrated platforms for hazards and risks assessment, e.g. the e-Laboratory developed within project NET-Tools.

List of correlations and tools

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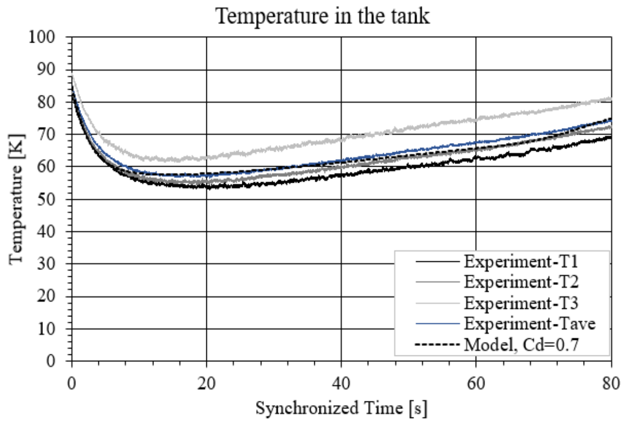
Group	N.	WP	Correlation title	Leading partner
Release & mixing	**1**	3	The non-adiabatic blowdown model for a hydrogen storage tank	UU
	2	3	Steady state single / two-phase choked / expanded flow through a discharge line with variable cross section with account of friction and extra resistances	NCSRD
	3	3	The similarity law for concentration decay in momentum jets	UU
	4	3	Method for calculating the final state when mixing liquid hydrogen and moist in the air	HSE
	5	3	Extent of cryogenic pools - HyPond	INERIS
Ignition	**6**	4	Ignition Energy for hydrogen-air mixtures	UU
	7	4	Electrostatic field-up generated during hydrogen releases	PS
Combustion	**8**	5	Laminar burning velocity and expansion ratios for hydrogen-air mixtures	INERIS
	9	5	Flame length correlation and hazard distances for jet fires	UU
	10	5	Thermal load from hydrogen jet fires	UU
	11	5	Maximum pressure load from delayed ignition of turbulent hydrogen jets	UU
	12	5	Flame acceleration and detonation transition for cryogenic hydrogen-air mixtures	KIT
	13	5	Fireball size after liquid hydrogen spill combustion	UU, KIT

Releases

The non-adiabatic blowdown model for a cryogenic hydrogen storage tank (UU)

Aim: accurately predict the temperature and pressure dynamics in cryogenic hydrogen storages during blowdown, the parameters at the nozzle and release rate by taking into account:

- Non-ideal behaviour of hydrogen gas;
- Heat transfer through a tank wall;
- Heat transfer through the discharge pipe wall.



P_{in}=200 bar, T_{in}=80Km d=1 mm

Steady state single / two-phase choked / expanded flow through a discharge line with variable cross section with account of friction and extra resistances (NCSRD)

Aim: predict the choked mass flow rate and distribution of all relevant physical quantities along the discharge line by taking into account:

- Discharge line friction and extra resistances;
- Transition to two-phase state.

Dispersion and mixing

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The similarity law for expanded and under-expanded jets (UU)

Aim: calculate the axial hydrogen concentration decay in cryogenic momentum-controlled jets.

$$C_{ax} = 5.4 \sqrt{\frac{\rho_N}{\rho_s}} \frac{d}{x}$$

where ρ_N is the density of hydrogen at the nozzle, ρ_s is the density of the surrounding air, *d* is the nozzle diameter and *x* is the distance from the release point.

Method for calculating the final state when mixing LH_2 and moist air (HSE)

Aim: determine the final thermodynamic state when LH_2 is mixed with ambient air. The final state is defined by: temperature, hydrogen volume fraction, density.

- The method allows estimation of gas concentrations from measured temperature, if the humidity and temperature of ambient air are known.
- The primary use of such an analysis is to support experiments on dispersing clouds of cold hydrogen in circumstances where there is minimal exchange of heat except with entrained air.

Liquid hydrogen pools

Extent of cryogenic pools – HyPond (INERIS)

Aim: estimate the maximum extent of a liquid pool likely to spread on the ground following a low pressure spillage of liquid hydrogen. The model addresses continuous spillages, which can be caused by a hose rupturing or disconnection, etc.

$$r_{pond} = \sqrt{\frac{Q_m \cdot L_{vap} \cdot \sqrt{\pi \cdot a_{diff}}}{k \cdot \pi \cdot \left(T_{ground} - T_{eb}\right)}} \cdot t^{1/4}$$

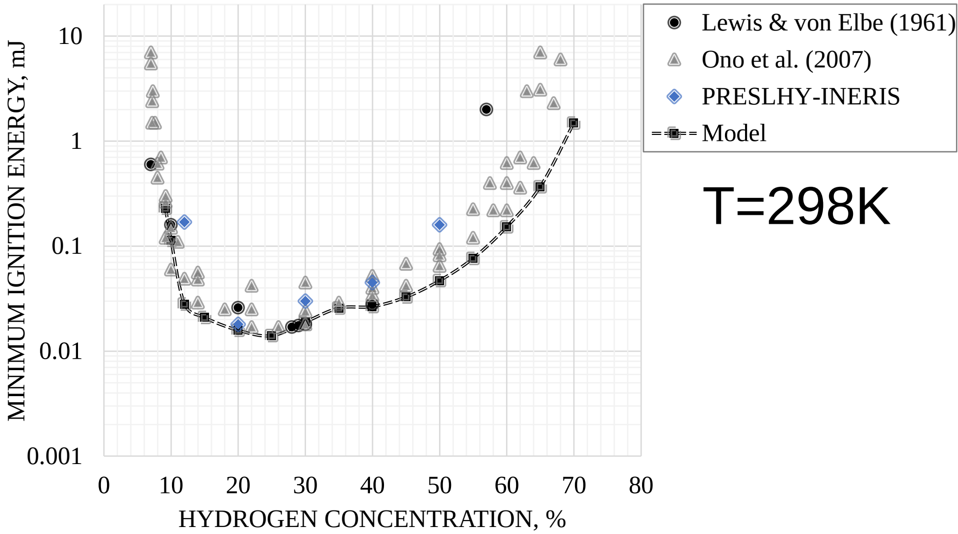
- Q_m: LH_2 mass flowrate;
- Q_{cond}: thermal exchange between the pool and the ground;
- L_{vap}: heat of vaporization of LH_2;
- k: thermal conductivity of the ground;
- a_{diff}: thermal diffusivity of the ground;
- t: time elapsed since the start of the release;
- A_{pond} is linked to the characteristic radius r_{pond} of the pond as $A_{pond} = \pi \cdot r_{pond}^2$.

Ignition

Ignition Energy for hydrogen-air mixtures (UU)

Aim: determine the Minimum Ignition Energy (MIE) by spark ignition in hydrogen-air mixtures with arbitrary concentration and initial temperature. Novelties:

- Use of the laminar flame thickness to determine the critical flame kernel instead of experimental data not available for low T
- Account of flame stretch and preferential diffusion



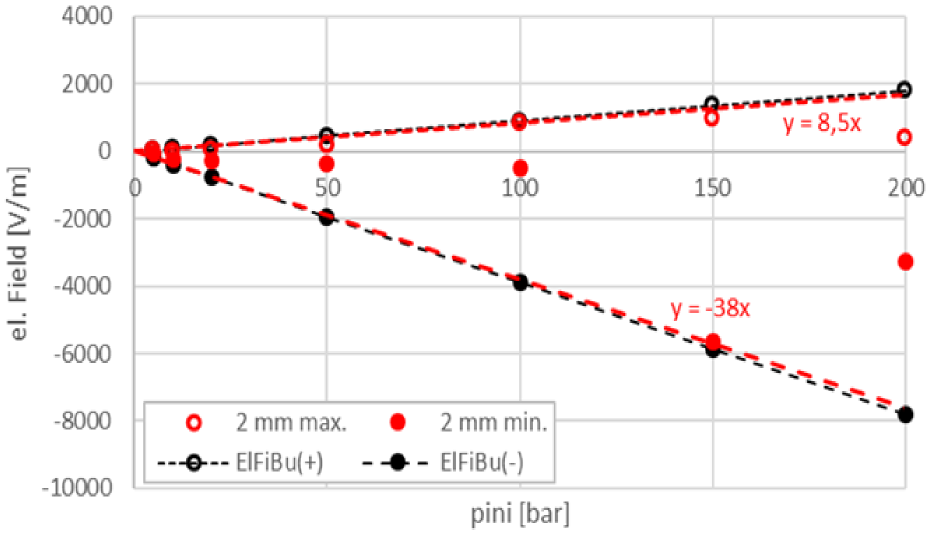
T=298K

Electrostatic field built-up generated during H2 releases (PS)

Aim: assess the electrostatic field built-up during hydrogen releases through a nozzle with circular aperture. The ElFiBU-correlation consists of two formulas:

Positive Field Built-up: $E(+) \leq (4 \cdot dNz + 1) \cdot p_{ini}$

Negative Field Built-up: $E(-) \leq (-14 \cdot dNz - 11) \cdot p_{ini}$



dNz=2mm, T=80K

Combustion

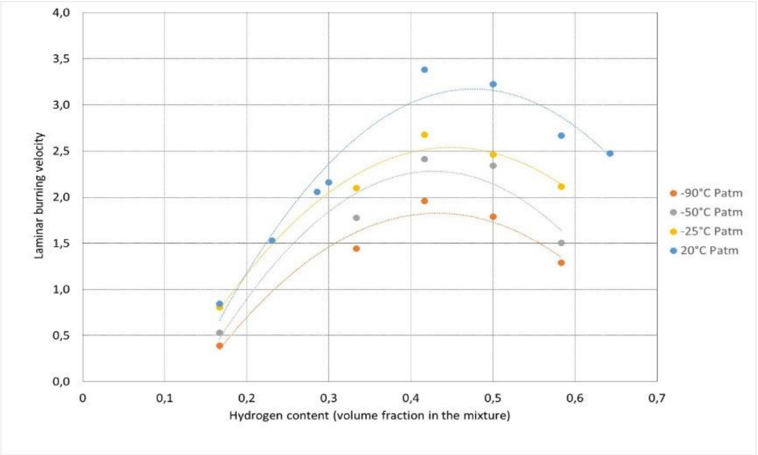
Laminar burning velocity and expansion ratios for hydrogen-air mixtures (INERIS)

Aim: provide graphical information and correlations to estimate the influence of temperature on laminar burning velocity and expansion ratio for combustion of H_2-air mixtures at ambient pressure.

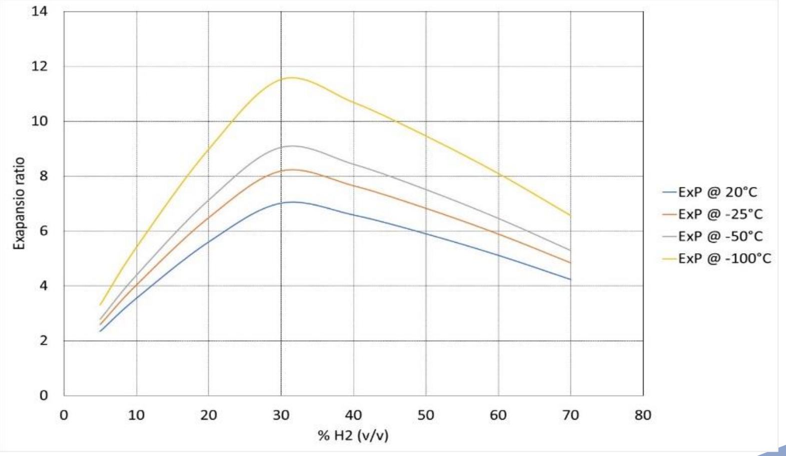
- Measurements of laminar burning velocity were used to assess the evolution of the laminar burning velocity, which well correlates as:

$$\frac{Slmax_T}{Slmax_{Tref}} = \left(\frac{T}{T_{ref}}\right)^{1.48}$$

  where $Slmax_T$ is the max laminar burning velocity at temperature T (in K) and $Slmax_{Tref}$ at reference temperature Tref (in K).



- The thermodynamic equilibrium code by (Gordon and McBride, 1994) was used to assess the evolution of the expansion ratio as function of temperature.



Thermal hazards from jet fires

Flame length correlation and hazard distances for jet fires (UU)

The dimensionless correlation for hydrogen jet flames calculates the flame length knowing the storage conditions. Hazard distances for people can be defined as:

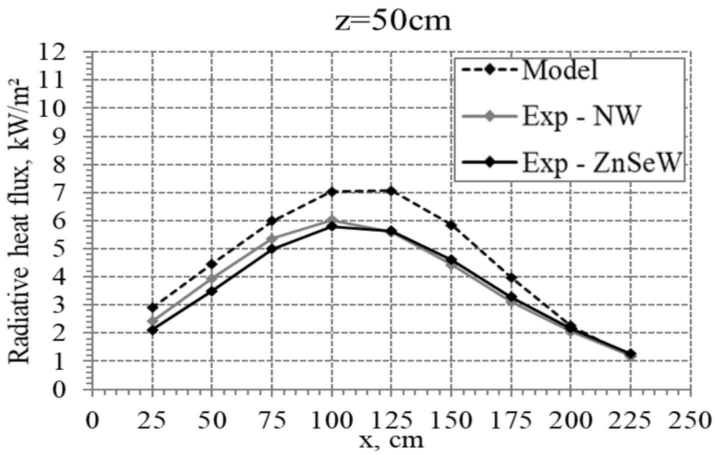
- No harm (70°C) hazard distance, $X_{70} = 3.5L_f$;
- Pain limit (5 mins, 115°C) hazard distance, $X_{115} = 3L_f$;
- Third degree burns (20 sec, 309°C) hazard distance, $X_{309} = 2L_f$.

The tool is available on e-lab platform developed within NET-Tools (https://elab-prod.iket.kit.edu/).

Assessment of thermal load from hydrogen jet fires (UU)

Aim: assess the radiative heat flux from vertical and horizontal hydrogen jet fires.

- The reduced tool is based on the weighted multi source flame radiation model developed by Hankinson and Lowesmith (2012) and further expanded by Ekoto et al. (2014).
- The model was adapted to use the dimensionless correlation to estimate flame length and expand the validation range to cryogenic hydrogen jet fires.



Test: T=80 K, P=3 bar, d=4 mm

Pressure hazards

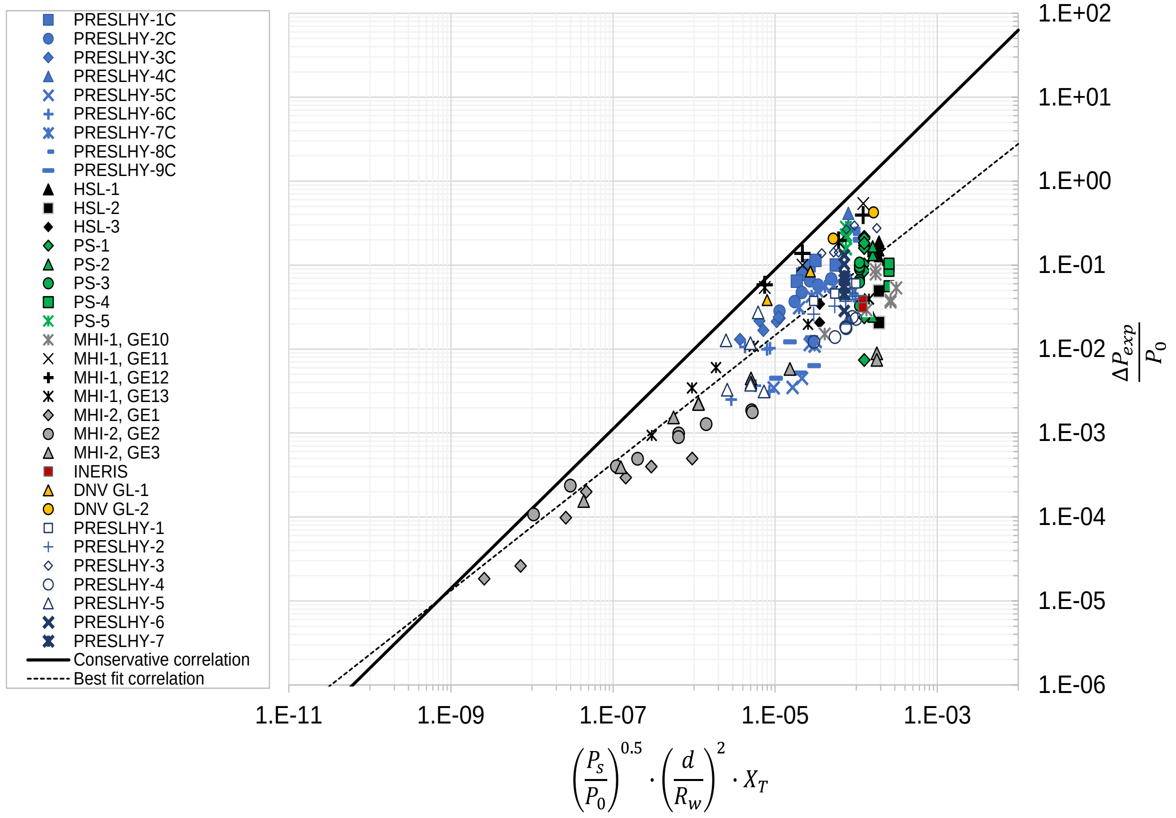
Maximum pressure load from delayed ignition of turbulent jets (UU)

Aim: predict the maximum overpressure generated by delayed ignition of a hydrogen jet at an arbitrary location for known storage pressure, P_s, and release diameter, *d*. The correlation is applicable only to free jets in open atmosphere.

The semi-empirical correlation was built by using overpressure measurements from about 80 experiments and the similitude analysis:

$$\Delta P_t = P_0 \cdot 5000 \cdot \left[\left(\frac{P_s}{P_0}\right)^{0.5} \cdot \left(\frac{d}{R_w}\right)^2 \cdot X_T\right]^{0.95}$$

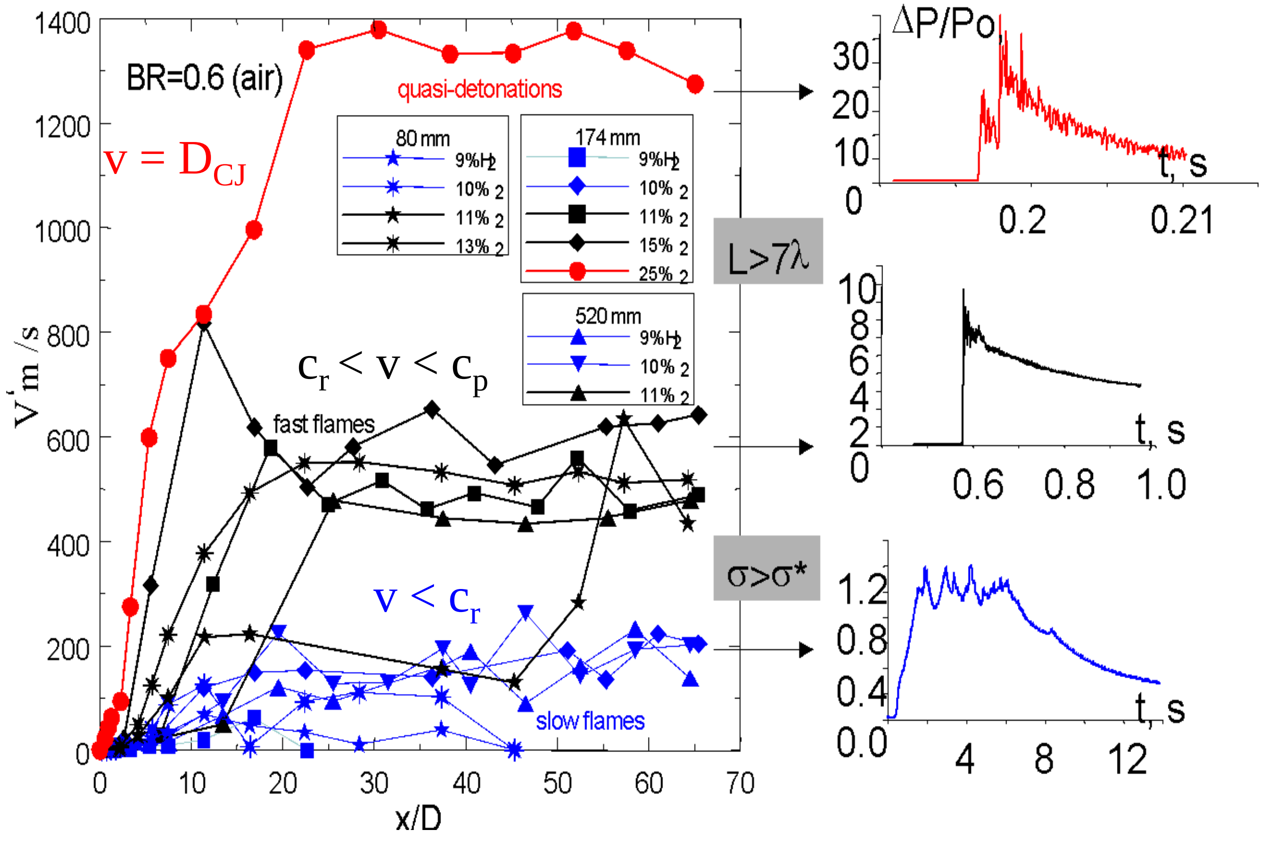
- R_w: distance between the centre of the fast burning mixture (25-35% by volume) and the target location
- $X_T = 1$ for ambient temperature releases
- $X_T = \frac{T_S}{T_0}\frac{E_{i,T_S}}{E_{i,T_0}}$ for cryogenic releases, where E_{i,T_S} is the expansion coefficient at T_S.



Flame acceleration and DDT

Flame acceleration and detonation transition for cryogenic hydrogen-air mixtures (KIT/PS)

Aim: evaluate critical hydrogen concentrations and conditions for effective flame acceleration (FA) and Detonation-to-Deflagration Transition (DDT) of cryogenic H_2-air mixtures.



- Determine conditions for flame acceleration

$$\sigma^* = 2200 \cdot T^{-1.12}$$

- Determine the detonation cell size

$$\lambda = 0.0006724[H_2]^4 - 0.1039[H_2]^3 + 6.0786[H_2]^2 - 159.74[H_2] + 1603.3$$

- Determine the run-up distance to detonation, e.g.

$$X_D = 250\lambda \quad \text{smooth tube (BR = 0)}$$

- Determine the pre-detonation length, L

$$L = \frac{D+S}{2(1-d/D)}$$

- Determine Detonation onset. DDT conditions

$$L/\lambda > N^*$$

Fireball from LH2 spills

Fireball size after liquid hydrogen spill combustion (UU, KIT)

Aim: determine a fireball size after liquid hydrogen spill combustion.

Makarov et al. (2021) built a first correlation to calculate a fireball size from LH_2 spills based on the best fit of experimental data Zabetakis (1961):

$$D_{bf} = 8.16m^{0.45}$$

A second correlation provides a conservative estimation of a fireball size from combustion of LH_2 spills:

$$D_c = 10m^{0.45}$$

Conclusions (1/2)

- Experimental data from literature and from the experimental campaigns carried out within PRESLHY research programme were used to either build semi-empirical and empirical correlations, or to validate theoretical models.
- The engineering correlations and tools aim at characterising the phenomena associated to cryogenic hydrogen and at assessing the hazards and consequences from likely accident scenarios involving releases, ignition and combustion.
- The presented engineering correlations and tools may be used in synergy to provide a full spectrum of the expected hazards and consequences from an initiating event.
- The engineering correlations and tools are described in D6.5 via a unified template to ease future implementation into existing and/or future integrated platforms for hazards and risks assessment.
- The engineering correlations and tools developed and validated within PRESLHY are implemented to support and produce guidelines and recommendations for Regulations Codes and Standards.

Conclusions (2/2)

- The following knowledge gaps are closed and model/tools are made available for hydrogen safety engineering:
  - Modelling of transient cryogenic releases accounting for heat transfer effect.
  - Modelling of steady state releases including a discharge line friction and extra resistances.
  - Characterisation of concentration decay in momentum cryogenic hydrogen jets.
  - Definition of the final state resulting from mixing liquid hydrogen and moist in the air.
  - Prediction of extent of cryogenic pools.
  - Determination of Ignition Energy for hydrogen-air mixtures.
  - Estimation of electrostatic field-up generated during hydrogen releases.
  - Evolution of laminar burning velocity and expansion ratios for cryogenic hydrogen-air mixtures
  - Predictive tools for a flame length and thermal load from hydrogen jet fires.
  - Determination of the maximum pressure load from delayed ignition of turbulent hydrogen jets.
  - Critical conditions for flame acceleration and detonation transition for cryogenic hydrogen-air mixtures.
  - Determination of a fireball size after liquid hydrogen spill combustion.

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Synergy and interconnections

- The engineering correlations developed within work-packages 3, 4 and 5 may be used in synergy to provide a full spectrum of the expected hazards and consequences from an initiating event.
- Example for cryogenic gaseous hydrogen jet: outlook of the applicable engineering correlations to quantify associated hazards.

Release & mixing

- Steady state release rate of hydrogen jets accounting discharge line effects
- Storage tank non-adiabatic blowdown model
- Similarity law for concentration decay in momentum jets

Ignition

- Electrostatic charge generated in hydrogen jets
- Ignition Energy for hydrogen-air mixtures

Combustion

- Flame length and hazard distances of jet fires
- Thermal load from jet fires
- Pressure load from delayed ignition of turbulent jets